INTEGRATED ANALYSIS OF DISASTER MANAGEMENT IN WESTERN HIMALAYAN REGION

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By

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INTEGRATED ANALYSIS OF DISASTER MANAGEMENT IN WESTERN HIMALAYAN REGION

ABSTRACT

The study presented herein delves into an exhaustive examination of Glacial Lake Outburst Floods (GLOFs) within the Chenab Basin, aiming to assess vulnerability, develop mitigation strategies, and enhance preparedness through the implementation of an Early Warning System (EWS). Leveraging remote sensing data and sophisticated algorithms, this research endeavors to classify glacial lakes, analyze temporal changes in glaciers and lakes over the period 1990-2018, and model potential GLOF impacts downstream. Two specific lakes, namely Lake 1 and Lake 2, have been identified as particularly vulnerable, prompting the application of hydrodynamic modeling to predict potential flood scenarios and assess their repercussions on downstream communities. The methodology employed in this study involves the utilization of remote sensing techniques coupled with a decision tree algorithm for the classification of glacial lakes based on specific parameters and spectral characteristics. By systematically analyzing temporal changes in glacier dynamics and lake expansion, researchers can effectively identify evolving patterns and assess potential risks associated with GLOFs. Through this process, Lake 1 and Lake 2 emerged as focal points for vulnerability assessment and subsequent mitigation measures. Hydrodynamic modeling constitutes a pivotal component of the research methodology, enabling the simulation of GLOF scenarios and the estimation of response times for downstream communities. The findings underscore the heightened vulnerability of villages SHANSHA and THOLONG to GLOFs originating from Lake 1 and Lake 2, respectively, with projected response times of 60 minutes and 4 hours 15 minutes. These insights provide valuable input for the development and implementation of an effective Early Warning System tailored to the specific needs and dynamics of the Chenab Basin. The study advocates for the integration of advanced geophysical monitoring systems, remote sensing technologies, and machine learning algorithms within the framework of the proposed EWS. By harnessing real-time data and predictive analytics, authorities can enhance early detection capabilities, facilitate timely communication, and mitigate the potential impact of GLOFs on vulnerable communities. Furthermore, the study emphasizes the importance of community engagement and capacity building initiatives to foster resilience and empower local stakeholders in disaster preparedness and response efforts.

Keywords: Chenab Basin, Glacial Lake Outburst Floods (GLOFs), Early Warning System (EWS), Remote Sensing, Hydrodynamic Modeling, Vulnerability Assessment, Decision Tree Algorithm, Community

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BGreen	Band in the green spectrum
BNIR	Band in the near-infrared spectrum
BSWIR	Band in the short-wave infrared spectrum
DEM	Digital Elevation Model
EWS	Early Warning System
GLOF	Glacial Lake Outburst Flood
HEC-RAS	Hydrologic Engineering Center's River Analysis System
NDWI	Normalized Difference Water Index
PD	Potentially Dangerous
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
T1, T2, T3	Threshold values
USGS	United States Geological Survey

CHAPTER 1

INTRODUCTION

1.1 Background

Glacial lakes in the Himalayan region are becoming increasingly prominent due to the retreat of glaciers. However, despite their importance, the proliferation of glacial lakes poses significant risks, particularly in the form of Glacial Lake Outburst Floods (GLOFs), which have been associated with catastrophic events like the 2013 Kedarnath floods, claiming the lives of over 5,000 individuals (Durga Rao et al., 2014). The retreat of glaciers due to climate change exacerbates the risks associated with GLOFs. As glaciers recede, they give rise to new glacial lakes, thereby amplifying the threat of GLOFs (R. K. Sharma et al., 2022).In recent years, the frequency and intensity of extreme weather events have been linked to global climate change, driven by human activities such as greenhouse gas emissions, deforestation, and land-use change. Climate models project further changes in precipitation patterns, including shifts in the timing and distribution of rainfall, alterations in the frequency and intensity of storms, and changes in the phase and duration of snowfall. These changes are expected to increase the frequency and severity of GLOFs in mountainous regions worldwide, posing significant challenges for disaster risk management and adaptation efforts.

1.2 Spread and Recession of Glaciers

In India alone, the Himalayas boast an extensive network of glaciers, encompassing approximately 16,627 glaciers spanning an area of 40,563 square kilometres (MoEF, 2011).These glaciers play a vital role in global freshwater supply, contributing over 68% of Earth's freshwater resources (Hirabayashi et al., 2010).Glacier recession rates are another critical factor in glacial lake analysis. As glaciers retreat due to climate change, they often leave behind depressions that fill with water to form glacial lakes. The rate of glacier recession can vary widely depending on local climate conditions, topography, and glacier morphology. High rates of glacier recession can lead to the rapid formation of new glacial lakes, increasing the risk of outburst floods and other hazards. By monitoring glacier recession rates, researchers can anticipate changes in glacial lake dynamics and develop strategies to mitigate associated risks.

1.3 Glacial Lakes

Glacial lakes, a product of glacier retreat, are significant features in high-altitude environments, serving as reservoirs of water and supporting diverse ecosystems. These lakes form as glaciers recede, leaving behind depressions in the landscape that fill with meltwater, creating bodies of water surrounded by rugged mountain terrain. Despite their seemingly isolated locations, glacial lakes play vital roles in ecological, geological, and cultural contexts, making them integral components of mountainous regions worldwide. Ecologically, glacial lakes are unique habitats that sustain a variety of plant and animal life adapted to extreme environmental conditions. These ecosystems thrive in the cold, nutrient-poor waters of glacial lakes, where species such as algae, plankton, and cold-water fish have evolved specialized adaptations to survive. The surrounding landscapes of glacial lakes also support diverse vegetation, including alpine meadows, shrubs, and lichens, which provide habitat and forage for mountain wildlife such as birds, mammals, and insects. Additionally, glacial lakes contribute to regional hydrological cycles, serving as important sources of freshwater for downstream rivers, lakes, and wetlands, and supporting agricultural, recreational, and domestic water needs for human communities. Geologically, glacial lakes are dynamic features shaped by the erosive forces of ice and water over millennia. As glaciers advance and retreat, they carve out valleys, cirques, and basins in the landscape, forming depressions that collect meltwater and sediment. Over time, these depressions may fill with water to create glacial lakes, which can vary in size, depth, and shape depending on local topography, glacier dynamics, and climatic conditions. The formation and evolution of glacial lakes are influenced by a complex interplay of factors, including glacier mass balance, meltwater runoff, sediment deposition, and moraine damming, which contribute to the dynamic nature of these environments.

Culturally, glacial lakes hold significant value for indigenous peoples and mountain communities, serving as sacred sites, sources of inspiration, and markers of cultural identity. Many cultures around the world have deep spiritual connections to mountains and glaciers, viewing them as sacred landscapes imbued with cultural meaning and symbolism. Glacial lakes are often associated with myths, legends, and folklore that reflect the spiritual beliefs and traditional practices of local communities. In addition to their cultural significance, glacial lakes also have practical importance for mountain communities, providing essential resources such as water for drinking, irrigation, and livestock grazing, as well as opportunities for fishing, tourism, and recreation. Glacial lakes are dynamic and multifaceted features of high-altitude environments, embodying ecological, geological, and cultural significance. These lakes serve as important habitats for diverse plant and animal life, contribute to regional hydrological cycles, and shape the landscapes of mountainous regions worldwide. Glacial lakes also hold cultural and spiritual significance for indigenous peoples and mountain communities, serving as sacred sites and sources of inspiration. As glaciers continue to retreat in response to climate change, the formation and evolution of glacial lakes will remain dynamic processes, shaping the ecological, geological, and cultural landscapes of mountain environments for generations to come.

1.4 Glacial Lake Outburst Flood (GLOF)

Glacial Lake Outburst Floods (GLOFs) represent a unique and complex phenomenon characterized by the sudden release of impounded water from glacial lakes, posing significant risks to downstream communities and infrastructure. GLOFs are increasingly prevalent in mountainous regions worldwide, driven by glacier recession, changes in precipitation patterns, and other climatic impacts. Moraine-dammed lakes, formed by the deposition of glacial debris, are particularly vulnerable to GLOFs due to their unstable nature and susceptibility to rapid drainage events. The mechanism of GLOFs typically involves the destabilization of moraine dams, which act as natural barriers holding back water from glacial lakes. Glacier recession, induced by rising temperatures and climate change, can lead to the retreat of glaciers and the exposure of moraine-dammed lakes. As glaciers melt and retreat, the volume of water stored in glacial lakes increases, putting pressure on moraine dams and increasing the risk of failure.

Changes in precipitation patterns and the frequency of extreme weather events further exacerbate the risk of GLOFs by triggering rapid glacier melt and enhancing the volume of water flowing into glacial lakes. Heavy rainfall, thunderstorms, and cyclonic disturbances can overwhelm natural drainage systems and accelerate the formation of glacial lakes, increasing the likelihood of moraine dam failure and GLOF occurrence. Understanding the mechanisms and landscape dynamics of GLOFs is crucial for effective risk management and disaster preparedness. Scientists and researchers employ a variety of techniques to study GLOFs, including remote sensing, field observations, and computational modelling. Remote sensing technologies, such as satellite imagery and LiDAR, provide valuable insights into glacier dynamics, moraine dam morphology, and changes in glacial lake volume over time. Field observations, including ice core analysis, ground-penetrating radar surveys, and GPS monitoring, offer detailed information about glacier movement, moraine stability, and potential

GLOF triggers. Computational models are used to simulate and predict the behaviour of glacial lakes and assess the potential impact of GLOFs on downstream communities and infrastructure. These models integrate data on climate variability, glacier dynamics, and hydrological processes to simulate the release of water from glacial lakes and predict the timing, magnitude, and extent of GLOF events. By combining remote sensing data, field observations, and computational modelling, scientists can develop accurate risk assessments and early warning systems to alert communities and authorities to the potential threat of GLOFs. GLOFs represent a significant hazard in mountainous regions, driven by glacier recession, changes in precipitation patterns, and other climatic impacts. Morainedammed lakes are particularly vulnerable to GLOFs due to their unstable nature and susceptibility to rapid drainage events. Understanding the mechanisms and landscape dynamics of GLOFs is essential for effective risk management and disaster preparedness. By employing a combination of remote sensing, field observations, and computational modelling techniques, scientists can develop accurate risk assessments and early warning systems to mitigate the impacts of GLOFs on downstream communities and infrastructure.

1.4.1 Topographical and Geometrical Features Causing GLOF

The analysis of glacial lakes and their surrounding terrain is crucial for understanding and mitigating the hazards associated with these dynamic water bodies. This comprehensive assessment provides valuable insights into various factors that contribute to the risk posed by glacial lakes, including their size, inflow dynamics, glacier recession rates, and spatial relationships with surrounding features. By analysing these parameters, stakeholders can develop effective strategies for hazard assessment, mitigation, and infrastructure planning in vulnerable regions. One key aspect of glacial lake analysis is the assessment of lake size. Glacial lakes vary widely in size, ranging from small, isolated ponds to large, expansive bodies of water. The size of a glacial lake can significantly impact the potential hazard it poses, with larger lakes having the capacity to store and release larger volumes of water. By accurately measuring the size of glacial lakes, researchers can assess their potential for generating catastrophic floods and prioritize mitigation efforts accordingly. In addition to size, the dynamics of inflow into glacial lakes are essential for understanding their behaviour and potential hazards. Inflow dynamics are influenced by various factors, including glacier meltwater, rainfall, and snowmelt. Changes in climate patterns can alter the timing and intensity of these inflows, leading to fluctuations in lake levels and increasing the risk of outburst floods.

By analysing inflow dynamics, researchers can identify patterns and trends that may indicate heightened risk and inform early warning systems to mitigate potential hazards. Spatial relationships between glacial lakes and surrounding terrain are also essential for hazard assessment and mitigation. Glacial lakes are often located in remote, mountainous regions with rugged terrain and limited access. The spatial distribution of glacial lakes relative to nearby communities, infrastructure, and natural features can influence the potential impact of outburst floods and other hazards. By mapping the spatial relationships between glacial lakes and surrounding terrain, researchers can identify areas at greatest risk and prioritize mitigation efforts to protect vulnerable populations and infrastructure. The analysis of glacial lakes and surrounding terrain plays a crucial role in hazard assessment, mitigation, and infrastructure planning in vulnerable regions. By examining factors such as lake size, inflow dynamics, glacier recession rates, and spatial relationships, stakeholders can develop targeted strategies to reduce the risk posed by glacial lakes and enhance the resilience of communities and infrastructure in the face of climate change and other environmental challenges. Through continued research and monitoring, we can better understand the complex dynamics of glacial lakes and work towards sustainable solutions to mitigate their associated hazards.

1.5 Consequences of GLOF in Downstream

Changes in precipitation patterns and the frequency of extreme weather events have profound implications for the occurrence and severity of glacial lake outburst floods (GLOFs), presenting a significant threat to downstream communities and infrastructure in mountainous regions worldwide. This complex phenomenon arises from a combination of climatic, hydrological, and geomorphological factors, with precipitation variability playing a central role in triggering GLOFs and exacerbating their impacts. Precipitation patterns, influenced by global climate systems such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), are subject to dynamic fluctuations over various temporal and spatial scales. In mountainous regions with glaciers, changes in precipitation regimes can lead to alterations in the timing, intensity, and spatial distribution of rainfall and snowfall. Shifts in precipitation patterns may result in more frequent and intense rainfall events, leading to increased meltwater production and runoff from glaciers and snowpack. The increased frequency of extreme weather events, such as heavy rainfall, thunderstorms, and cyclonic disturbances, can overwhelm natural drainage systems and trigger the rapid formation and expansion of glacial lakes. When excessive precipitation exceeds the capacity of glacial lakes or impounds behind unstable moraine dams, it can result in the catastrophic failure of these natural barriers, leading to the sudden release of vast quantities of water downstream. GLOFs represent a unique and complex hazard, characterized by their sudden onset, rapid flow velocities, and destructive power. The release of water from glacial lakes can generate massive flood waves, carrying debris, sediment, and large boulders downstream, causing extensive damage to infrastructure, vegetation, and human settlements in their path. The impacts of GLOFs extend far beyond the immediate flood zone, affecting downstream river systems, agricultural land, and ecosystems, and posing long-term risks to water resources, hydropower facilities, and socio-economic development in affected areas. The severity of GLOFs is further exacerbated by the topographic and geomorphological characteristics of mountainous regions, which often feature steep slopes, narrow valleys, and fragile ecosystems. These factors can amplify the destructive power of floodwaters, increase the likelihood of sedimentation and debris flow, and hinder access for rescue and relief operations in remote and inaccessible areas. Moreover, the presence of existing infrastructure, such as roads, bridges, and hydropower dams, can act as barriers tofloodwaters, leading to localized inundation and exacerbating the impacts of GLOFs on downstream communities and livelihoods.

Addressing the risks associated with GLOFs requires a comprehensive and multi-disciplinary approach that integrates scientific research, risk assessment, early warning systems, and community-based adaptation strategies. Enhanced monitoring and surveillance of glacial lakes, combined with improved modelling and forecasting capabilities, can help identify and assess the potential hazards posed by unstable moraine dams and rapidly growing glacial lakes. Early warning systems, supported by real-time monitoring data and advanced predictive modelling techniques, can provide timely alerts to downstream communities and authorities, enabling them to take proactive measures to mitigate the impacts of GLOFs and minimize the loss of life and property. Community-based adaptation strategies, grounded in local knowledge and traditional practices, can enhance the resilience of vulnerable communities to the impacts of GLOFs. These may include the construction of protective infrastructure, such as flood barriers and embankments, the establishment of emergency evacuation routes and shelters, and the development of sustainable land-use practices that reduce the risk of flooding and erosion. Strengthening institutional capacity, promoting stakeholder engagement, and fostering collaboration between governments, civil society organizations, and the private sector are also essential for effective GLOF risk management and adaptation in mountainous regions. The escalating temperatures induced by climate change play a pivotal role in driving glacier recession, leading to the expansion of glacial lakes (Ankit Kumar et al., 2022). Of particular concern are moraine-dammed lakes, which pose significant hazards to downstream infrastructure, including hydropower dams (R. K. Sharma et al., 2022). To address these pressing challenges, the development of an advanced early warning system for regions such as the Chenab Valley is imperative. Such a system would integrate various monitoring techniques to detect changes in glacial lakes and assess the associated risks (M Singhal, 2022). This is especially crucial given the complex relationship between climatic variations and glacier dynamics, as highlighted by studies such as Komori et al. (2012). The expansion of glacial lakes in the Himalayan region presents a multifaceted challenge, exacerbated by climate change-induced glacier recession. The associated risks, including the threat of GLOFs and the potential hazards posed to downstream infrastructure, necessitate proactive measures to enhance monitoring and early warning systems. By integrating advanced monitoring techniques and understanding the intricate interplay between climate variations and glacier dynamics, stakeholders can better mitigate the risks posed by glacial lake expansion and safeguard vulnerable communities and infrastructure in the region.

The integration of advanced monitoring techniques and a comprehensive understanding of the complex interplay between climate variations and glacier dynamics holds significant promise in mitigating the risks associated with glacial lake expansion and safeguarding vulnerable communities and infrastructure in the Himalayan region. This multifaceted approach involves leveraging cutting-edge technologies and scientific insights to enhance our ability to monitor and predict changes in glacial lakes and their associated hazards. Advanced monitoring techniques encompass a wide range of tools and methodologies, including remote sensing, satellite imagery, ground-based observations, and computational modelling. Remote sensing technologies, such as LiDAR (Light Detection and Ranging) and SAR (Synthetic Aperture Radar), enable researchers to accurately measure glacier mass balance, ice flow velocities, and changes in glacier extent over time. These data provide critical information about the behaviour and dynamics of glaciers, including patterns of retreat, ice melt, and the formation of glacial lakes. Satellite imagery offers a comprehensive view of large-scale glacier dynamics and allows for the detection of changes in surface features, such as the growth of glacial lakes and the formation of ice dams. Ground-based observations complement remote sensing data by providing detailed insights into local glacier conditions and processes. Field measurements, including ice core analysis, ground-penetrating radar surveys, and GPS monitoring of glacier movement, offer valuable information about glacier thickness, internal structure, and flow dynamics. These on-the-ground observations help validate and refine remote sensing data and improve our understanding of glacier behaviour at a finer spatial scale. Computational modelling plays a crucial role in synthesizing data from remote sensing and ground-based observations to simulate and predict future glacier changes. Glacier models, such as numerical ice flow models and hydrological models, simulate the response of glaciers to climate variability and predict changes in glacier extent, volume, and runoff. These models integrate climate data, including temperature, precipitation, and solar radiation, to assess the impact of climate change on glacier dynamics and glacial lake formation. By incorporating advanced monitoring data and model simulations, stakeholders can anticipate future changes in glacial lakes and assess potential risks to downstream communities and infrastructure. Understanding the intricate interplay between climate variations and glacier dynamics is essential for effective risk mitigation strategies. Climate variability, driven by natural processes and human-induced climate change, exerts a significant influence on glacier behaviour and the formation of glacial lakes. Rising temperatures accelerate glacier melt and ice loss, leading to the formation of new glacial lakes and the expansion of existing ones. Changes in precipitation patterns and the frequency of extreme weather events can trigger glacial lake outburst floods (GLOFs), posing a severe threat to downstream communities and infrastructure.

Stakeholders, including policymakers, scientists, local communities, and civil society organizations, play a crucial role in mitigating the risks posed by glacial lake expansion. Collaborative efforts are needed to develop and implement robust monitoring systems, improve data sharing and communication networks, and strengthen early warning mechanisms. Engaging with local communities and incorporating indigenous knowledge systems can enhance the effectiveness of risk management strategies and ensure the resilience of vulnerable populations. Investments in infrastructure development, disaster preparedness, and climate adaptation measures are also essential for enhancing resilience to glacial lake hazards. Building robust flood defences, reinforcing hydropower dams, and relocating vulnerable settlements away from flood-prone areas can reduce the potential impact of GLOFs and protect lives and livelihoods. Sustainable land use planning and natural resource management practices can help mitigate the underlying drivers of glacier retreat and minimize future risks associated with glacial lake expansion. The integration of advanced monitoring techniques and a nuanced understanding of climate-glacier interactions are essential for mitigating the risks posed by glacial lake expansion in the Himalayan region. By combining scientific expertise with local knowledge and community engagement, stakeholders can develop holistic risk management strategies that protect vulnerable communities and infrastructure while promoting sustainable development and resilience in the face of environmental change.

1.5.1 Early Warning System

Early Warning Systems (EWS) play a critical role in mitigating the impact of natural disasters, particularly in vulnerable regions such as the Himalayas. These systems are designed to provide timely and accurate information about impending hazards, allowing communities and authorities to take proactive measures to minimize risk and protect lives and property. The effectiveness of EWS depends on several key components, including risk knowledge, monitoring capabilities, response capability, warning communication, and investment in technology. Risk knowledge forms the foundation of an effective EWS, as it enables stakeholders to understand the nature and magnitude of potential hazards, assess vulnerability and exposure, and prioritize mitigation efforts. In the Himalayas, where a wide range of natural hazards, including floods, landslides, earthquakes, and glacial lake outburst floods (GLOFs), pose significant risks, comprehensive risk assessments are essential for developing targeted early warning systems that address the specific needs of local communities. Monitoring capabilities are critical for detecting and tracking changes in environmental conditions that may indicate the onset of a hazard. In the Himalayas, where rugged terrain and remote locations present challenges for traditional monitoring methods, the use of remote sensing technologies, such as satellite imagery, LiDAR, and drones, has become increasingly important for monitoring glacial lakes, snowmelt, and other indicators of potential hazards. These technologies provide valuable data that can be used to improve the accuracy and reliability of early warning systems. Response capability refers to the ability of communities and authorities to respond effectively to warnings and alerts issued by the EWS. This includes having access to emergency response plans, trained personnel, and adequate resources, such as emergency shelters, medical facilities, and evacuation routes. In the Himalayas, where infrastructure is often limited and access to remote areas can be challenging, building local capacity for disaster response is essential for ensuring the effectiveness of early warning systems. Warning communication is another critical component of EWS, as timely and clear communication of hazard information is essential for ensuring that communities understand the risks they face and know how to respond. In the Himalayas, where many communities are located in remote and isolated areas with limited access to communication networks, it is important to develop alternative communication channels, such as radio broadcasts, SMS alerts, and community outreach programs, to ensure that warnings reach those who need them most. Investment in technology is key to the development and maintenance of effective early warning systems. This includes not only the deployment of monitoring equipment and communication infrastructure but also the development of data analysis tools, predictive models, and decision support systems that can help authorities interpret and act on the information provided by the EWS. In the Himalayas, where resources are often limited, partnerships between governments, international organizations, and the private sector can help mobilize funding and technical expertise to support the development and implementation of early warning systems. Despite the importance of early warning systems in mitigating natural disasters, several challenges persist in their implementation in the Himalayas. Limited resources, both financial and human, can constrain the development and maintenance of EWS, particularly in remote and marginalized communities. Technological constraints, such as limited access to reliable power sources and internet connectivity, can also hamper the effectiveness of early warning systems in the region. Additionally, societal factors, such as cultural beliefs, language barriers, and trust in authorities, can influence community perceptions of risk and willingness to respond to warnings issued by the EWS. Early warning systems are essential for mitigating the impact of natural disasters in vulnerable regions like the Himalayas. By addressing key components such as risk knowledge, monitoring capabilities, response capability, warning communication, and technology investment, stakeholders can develop effective early warning systems that help communities prepare for and respond to hazards. However, challenges such as limited resources, technological constraints, and societal factors must be overcome to ensure the success of early warning systems in the Himalayas and other vulnerable regions.

1.6 Study Area

The present study focuses on the **Western Himalayan Region**, with particular emphasis on the **Chenab Basin**, one of the most dynamic and hazard-prone mountain systems in India. Geographically situated within the high-altitude terrains of Himachal Pradesh and Jammu & Kashmir, the Chenab Basin represents a complex geomorphic and climatic environment characterized by steep slopes, active tectonics, extensive glaciation, and highly variable hydrometeorological conditions. The region hosts a dense network of glaciers and glacial lakes that have evolved significantly due to ongoing climatic shifts, particularly glacier recession and increased meltwater production. As documented in the thesis, the Western Himalaya comprises thousands of glaciers whose meltwater feeds major river systems, including the Chenab, playing an essential role in regional hydrology and downstream water security (Srivastava, 2024). The basin's fragile geomorphology, coupled with rapid glacier retreat, has resulted in the formation and expansion of numerous moraine-dammed lakes, several of which exhibit a high potential for Glacial Lake Outburst Floods (GLOFs). Specifically, two glacial lakes—Lake 1 and Lake 2—were identified as potentially dangerous due to their topographical and geometrical configurations, inflow characteristics, and surrounding instability factors, necessitating further hydrodynamic and vulnerability analysis (Srivastava, 2024).

The Chenab Basin's high-relief terrain amplifies the destructive potential of GLOFs, as the sudden release of glacial water can generate high-velocity flood waves capable of transporting debris, boulders, and sediment over long distances. The downstream communities of **Shansha** and **Tholong** are particularly vulnerable, with estimated flood travel times of 60 minutes and 4 hours 15 minutes, respectively, underscoring the urgency of early detection and preparedness measures. Furthermore, the region's climatic regime is strongly influenced by both the Indian Summer Monsoon and Western Disturbances, resulting in pronounced seasonal variations in precipitation, snowfall, and temperature. These variations directly affect glacier mass balance and lake stability, contributing to increased hazard probability. The remoteness of the terrain, limited accessibility, sparse communication networks, and fragile infrastructure further complicate rapid response efforts, making scientific assessment and early warning systems indispensable.

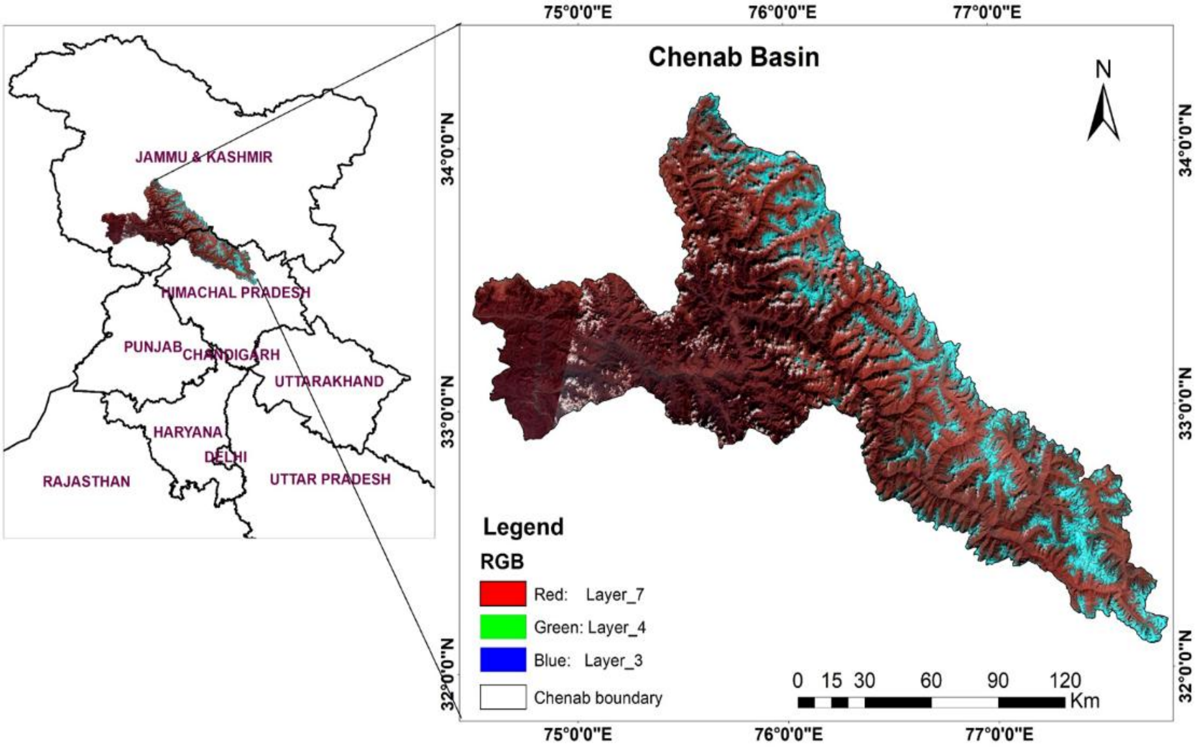


Figure 1.1 Location of the Study Area

From a geomorphological perspective, the basin is shaped by deep, V-shaped valleys, unstable moraines, hanging glaciers, and active periglacial processes. Digital Elevation Models (DEMs) and satellite-derived datasets have revealed ongoing changes in lake area and glacier extent from 1990 to 2018, highlighting significant temporal expansion of several glacial lakes. These environmental changes underscore the Chenab Basin's heightened sensitivity to climate forcing and the urgent need for risk-informed decision-making. The hydrological, ecological, and socio-economic relevance of the basin, combined with escalating cryospheric changes, position the Western Himalaya as a critical landscape for evaluating disaster management strategies. Therefore, this study area serves as an ideal natural laboratory for investigating GLOF hazards, developing hydrodynamic models, and designing region-specific early warning systems aimed at safeguarding vulnerable populations in one of India's most complex and rapidly changing mountain environments.

1.7 Research Gaps

A comprehensive review of literature suggests that, due to paucity of observed data in the Himalayan basins in general, the identification, mapping and inventorisation of potentially dangerous lake(s) has received less attention. It also holds for the analysis of the available scarce data and the evaluation of the effect of GLOF in the downstream areas, essentially required for identification of vulnerable locations downstream and prepare a road map for prevention, warning, mitigation, rescue etc.

1. Previous investigations have largely concentrated on selected basins in Nepal & Eastern Himalayas, while western Himalayan region is less investigated particularly the Chenab basin.
2. Identification of potentially dangerous glacial lakes are primarily based on single parameter like lake area without incorporating integrated topographical, hydrological and glacier-connectivity characteristics.
3. Quantitative estimation of peak discharge, travel time and flood inundation extend for identified potentially dangerous lakes has not been adequately explore in Chenab basin.
4. Downstream vulnerability mapping, risk assessment and the formulation of early warning frameworks are offing insufficiently integrated in case of glacial hazard studies.

1.8 Objectives

1. Analysis of the available data of selected regions of the western Himalayas for identification, mapping and inventorisation of glacial lakes.
2. Identification of potentially dangerous lake(s) based on topographical and geometrical features associated with glacial lakes, moraine dams and mother glacier.
3. To apply the hydrodynamic model on the identified potentially dangerous lake(s) and study the effect of GLOF downstream.
4. To identify the vulnerable locations downstream where GLOF can create disaster and prepare the road map for prevention, warning, mitigation, rescue etc.

Chapter 2

LITERATURE REVIEW

2.1 Significance of Remote Sensing Data

S. Ogras and F. Onen (2020). The utilization of HEC-RAS software in the Chenab Basin underscores the significance of remote sensing data in assessing the risk of Glacial Lake Outburst Floods (GLOFs) and safeguarding vulnerable communities and infrastructure. Developed by the US Land Forces Engineering Group, HEC-RAS serves as a powerful tool for conducting hydraulic computations, particularly for semi-unsteady and unsteady river flows. Its functionality encompasses both one- and two-dimensional unsteady river flow calculations, along with one-dimensional steady hydraulic flow calculations, providing engineers and researchers with a versatile platform for analyzing river dynamics. By integrating satellite imagery, aerial photographs, and other remote sensing datasets, engineers can accurately delineate the extent and characteristics of glacial lakes in the region. This spatial information serves as input for HEC-RAS models, enabling precise identification of vulnerable lakes and assessment of GLOF risk. Remote sensing data enhances the overall resilience of infrastructure and communities in the Chenab Basin by enabling the simulation of flood scenarios with greater accuracy and precision. This interdisciplinary approach underscores the critical importance of remote sensing data in mitigating the impacts of natural hazards and building resilient communities in mountainous regions like the Chenab Basin.

Klimes et al., (2014). The HEC-RAS software plays a crucial role in hydraulic computations, offering capabilities for both steady and unsteady river flow analysis. However, its significance is further underscored by its accommodation of sediment transport, mobile bed modelling, and water temperature analysis. Moreover, HEC-RAS facilitates simulations of water flow through various structures like bridges and culverts, providing comprehensive insights into hydraulic dynamics. Remote sensing data supplements this software by offering topographical input, enhancing the accuracy of modelling. By defining stream geometry through ground surface cross-sections, researchers can analyze flow conditions and make informed modifications. This integrated approach allows for a thorough understanding of river behavior and helps in assessing the risk of natural hazards like Glacial Lake Outburst Floods (GLOFs). Therefore, the combination of HEC-RAS software and remote sensing data holds immense significance in hydraulic engineering, particularly in regions prone to environmental hazards.

R. Panda, S. K. Padhee, and S. Dutta (2014). Remote sensing plays a crucial role in identifying and assessing the risk of Glacial Lake Outburst Floods (GLOFs) in high mountain regions vulnerable to climate change. By utilizing spectral responses and reflectance bands, remote sensing data is employed to create informational layers like NDWI and snow cover maps, enabling the identification of potential water bodies such as glacial lakes. These layers, coupled with GIS analysis, allow for the precise delineation of lakes within the watershed. Parameters including elevation, area, proximity to streams, slope, and water volume are then evaluated to assess the potential danger posed by these lakes. Remote sensing data facilitates the simulation of GLOF scenarios using advanced models like HEC-RAS. By integrating crosssections from Google Earth and field surveys, these models simulate dam break-like scenarios, generating hydrographs to predict flood dynamics and potential impacts on downstream areas. This comprehensive approach highlights the critical significance of remote sensing in identifying, evaluating, and mitigating the risks associated with GLOFs, ultimately contributing to disaster preparedness and resilience in mountainous regions.

P. I. Anacona, A. Mackintosh, and K. Norton (2015). The occurrence of moraine-dammed lake failures, such as Glacial Lake Outburst Floods (GLOFs), presents significant risks to mountain communities, particularly as glaciers retreat and new lakes form. Understanding the dynamics of GLOFs and implementing effective mitigation measures are essential, especially considering the potential increase in frequency due to glacier retreat driven by climate change. In regions like Patagonia, where historical records indicate numerous GLOF incidents, there is a critical need for comprehensive data on their dynamics and impacts. Utilizing a combination of interviews, satellite imagery interpretation, and hydraulic modelling, researchers reconstructed a significant GLOF event in Chilean Patagonia in 1977. This event resulted in the relocation of villages due to severe flooding exacerbated by the lack of land-use planning and awareness about GLOFs. Hydraulic modelling revealed crucial insights into the flood characteristics, highlighting the importance of proactive measures and migration strategies in response to escalating GLOF risks associated with climate-induced glacier retreat. Remote sensing techniques play a pivotal role in this process by providing valuable data for reconstructing past events, assessing current risks, and informing future mitigation efforts.

Khattak et al., (2016). The utilization of remote sensing data, particularly the freely available Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), is pivotal in watershed delineation, sub-catchment definition, and stream network establishment.

Leveraging the SRTM-DEM facilitates accurate analysis of terrain drainage patterns, essential for understanding hydrological processes. Additionally, vibrant images from Google Earth are employed for land use classification, which is integral for estimating Manning's n values—a key parameter in hydraulic computations conducted by HEC-RAS. Remote sensing data enhances the precision and efficiency of these processes, providing valuable insights into landscape characteristics and land use patterns. By utilizing remote sensing technology, researchers can effectively assess the impacts of climate change-induced glacier retreat on river systems and identify potential hazards such as Glacial Lake Outburst Floods (GLOFs). This interdisciplinary approach underscores the significance of remote sensing in environmental analysis and disaster risk management, enabling informed decision-making and proactive measures to mitigate risks associated with changing environmental conditions.

J.C. Rodda, 2021. Remote sensing plays a crucial role in understanding and simulating dam break floods, offering insights into cryosphere processes, hydrological dynamics, and climate change impacts in high-altitude regions. By utilizing remote sensing data, researchers can accurately delineate basin characteristics and assess the risk of floods induced by factors like concentrated rainfall or swift snowmelt. This data aids in the simulation of flood scenarios, contributing to water resource management and disaster risk reduction strategies in mountainous environments. While physical hydraulic models and mathematical simulation models are traditionally used for flood simulation, remote sensing enhances the accuracy and precision of these models by providing spatial information on basin features. Through the analysis of discharge hydrographs, researchers can discern the interplay between runoff and basin attributes, shedding light on the mechanisms driving flood events. Overall, remote sensing serves as a valuable tool for advancing our understanding of flood dynamics and informing mitigation efforts in vulnerable regions.

2.2 Glacier and Glacier Lakes Mapping

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A. B., Sawagaki, T., &Yamanokuchi, T. (2013). The study by Fujita et al. (2013) focused on assessing the flood volume potential of glacial lakes in the Himalayas, particularly emphasizing the risks associated with Glacial Lake Outburst Floods (GLOFs). Their research aimed to provide crucial insights into hazard assessment and risk management strategies for mountainous regions, with a specific emphasis on understanding the volume of water stored in these lakes. This involved a comprehensive approach, likely integrating field observations, remote sensing techniques, and computational modelling. Field observations would have entailed direct measurements of lake dimensions, water levels, and surrounding topography to estimate water volume. Remote sensing methods, including satellite imagery and aerial photography, were likely employed to gather data on lake morphology, glacier dynamics, and changes in lake extent over time. This interdisciplinary approach highlights the significance of glacier and glacier lake mapping in assessing the potential risks posed by GLOFs and informing effective risk mitigation strategies for vulnerable mountainous regions.

Roohani, M. S. (1986). Roohani, M. S.'s (1986) research delves into the hydro-morphometric characteristics and snowmelt runoff patterns within the Chenab catchment area, shedding light on the hydrological dynamics of the region. The study likely encompasses parameters such as river morphology, drainage patterns, and landform characteristics within the catchment. Moreover, it investigates snowmelt runoff, vital for water resource management in mountainous regions like the Himalayas. However, to comprehensively assess glacier and glacier lake mapping in the region, additional research focusing explicitly on these aspects is imperative. By leveraging remote sensing technology and geospatial analysis, researchers can accurately map glaciers and glacier lakes, providing valuable insights into their distribution, dynamics, and potential hazards such as Glacial Lake Outburst Floods (GLOFs). This mapping effort is crucial for understanding the impact of climate change on glacier systems and facilitating informed decision-making for sustainable water resource management in glacieraffected regions like the Chenab catchment.

S. **Aggarwal, S. C. Rai, P. K. Thakur, and A. Emmer(2017**). Glacier and glacier lakes mapping play a pivotal role in this study focused on Sikkim, India, establishing an inventory of 1104 lakes situated above 3500 m. Among these, 472 lakes exceed 0.01 km^2 in area, with 21 identified as susceptible to Glacial Lake Outburst Floods (GLOFs) based on predefined characteristics. Advanced Analytic Hierarchy Process (AHP) techniques further categorize two lakes as highly susceptible to GLOFs. The study highlights the expansion of proglacial lakes from 1972 to 2015, particularly in regions abundant in unconsolidated moraine material. Notably, these lakes are situated at varying distances from settled areas, posing potential risks to nearby Army camps. Future endeavors include risk modelling, detailed field surveys targeting highly susceptible lakes, and ongoing monitoring of lakes with medium and low susceptibility. Emphasizing regional cooperation is crucial for ecosystem preservation. Ultimately, this comprehensive study provides essential data for informed planning and socioeconomic development initiatives in Sikkim, aiding in the mitigation of GLOF-related risks.

Bahadur, J. (2004). The "Himalayan Snow and Glaciers" provides a comprehensive analysis of the dynamics of glaciers and glacier lakes in the Himalayas. Published in 2004, it extensively covers their distribution, melting patterns, and the resulting impact on water resources. This publication significantly enhances our understanding of cryosphere processes in the Himalayan region, making it an invaluable resource for researchers, policymakers, and stakeholders. Through Bahadur's meticulous exploration, readers gain insights into the complex interplay of environmental factors shaping the Himalayan cryosphere. By highlighting glacier and glacier lake mapping, the book facilitates informed decision-making and the development of effective strategies for conservation and management of water resources in the region.

Kouzehgar, K., &Eslamian, S. (2023). The research presented here delves into the precise determination of breach and flow characteristics in embankment or landslide dam failures, crucial for assessing downstream flood risks. Physical model investigations were conducted to explore erosion dynamics and its implications on breach dimensions. Through the utilization of Gene Expression Programming (GEP) and multivariate regression, a novel relationship was developed, encompassing failure time, eroded volume, breach height, and other pertinent breach and dam geometry factors. Relationships for peak outflow discharge were established using a combination of historical, laboratory, and hypothetical dam failure data, with extensions to include landslide dams. A comprehensive range of breach width variations was defined based on parameters such as dam height, water level above the breach, and embankment length. Strong correlations between observed and measured data were evident, particularly in the analysis of breach output hydrograph components for embankment and earth fill dam failures. This study sheds light on the critical aspects of glacier and glacier lakes mapping, offering valuable insights for enhancing flood risk assessment methodologies.

Gupta and M. P. Sah (2008). The study underscores the importance of mapping glaciers and glacier lakes in assessing the risk of glacial lake outburst floods (GLOFs) in the Satluj valley. It highlights the correlation between damages from past GLOFs and the disposition of Quaternary deposits, including lacustrine sediments and debris fans. Notably, toe erosion of these deposits led to significant damage, particularly in areas with wider river courses. Vertical gorge sections experienced minimal damage compared to regions with Quaternary materials like debris fans, indicating the vulnerability of certain geological formations to GLOFs. Given the influence of global warming on Tibetan Plateau temperatures, evaluating the risk of such hazards becomes even more critical. By accurately mapping glaciers and glacier lakes and assessing the distribution of Quaternary deposits, researchers can better understand and mitigate the impacts of GLOFs in the Satluj valley.

Allen, S. K., Schneider, D., & Owens, I. F. (2009). The research by Allen, Schneider, and Owens (2009) delves into the modelling of glacial hazards in New Zealand's Mount Cook region, with a focus on assessing the risks posed by glacial lake outburst floods (GLOFs). Their study employs modelling techniques to deepen the understanding of these hazards and their potential impacts on local communities. Glacial hazards, particularly GLOFs, present significant risks to communities near glacial lakes in mountainous regions. GLOFs occur when water stored by a glacial dam is suddenly released, resulting in a rapid and often devastating flood downstream. Understanding the factors influencing GLOF occurrence and identifying vulnerable areas are crucial for effective hazard management and mitigation strategies. Through their research, Allen, Schneider, and Owens contribute to advancing knowledge in this field by exploring the feasibility of modelling glacial hazards in a specific geographic context. Their work highlights the importance of glacier and glacier lake mapping in assessing and mitigating the risks associated with GLOFs.

2.3 Features of Glacial Lakes

R. Worni, C. Huggel, J. J. Clague, Y. Schaub, and M. Stoffel (2015). Glacial lakes, often formed by the melting of glaciers and trapped behind moraine dams, exhibit distinct features crucial for understanding their stability and associated hazards. The stability of a moraine dam hinges on various factors, including its geometry, internal structure, and material properties. Overtopping flows, where water exceeds the dam's capacity, are common triggers for breaching events, initiating dam erosion. As the breach enlarges, the dam material experiences critical shear forces, leading to the erosion and transport of sediments downstream. This process ultimately culminates in either partial or complete drainage of the lake, posing significant risks to downstream areas. Understanding these features is vital for assessing the stability of glacial lakes and implementing measures to mitigate potential hazards.

S. Wang, Y. Che, and M. Xinggang (2020). Glacial lakes, formed by the melting of glaciers, are prominent features in regions like the Hindu Kush-Himalaya, Patagonia, and Cordillera Blanca. While glaciers offer benefits like recreation and water resources, their associated processes, such as glacier lake outburst floods (GLOFs), can pose significant hazards. Thousands of glacial lakes have been identified, with hundreds classified as potentially dangerous. Climate change exacerbates these risks by accelerating glacier retreat and increasing lake formation, particularly in regions like the Qinghai-Tibetan Plateau (QTP). GLOFs have caused substantial loss of life and property downstream, emphasizing the urgency for ongoing attention and mitigation efforts. Past events in the Cordillera Blanca and Chinese Himalayas highlight the importance of proactive measures to address GLOF risks. Mitigation strategies prove more cost-effective than coping with disasters, especially as GLOF impacts are expected to extend further downstream in the future. Therefore, continued attention and mitigation efforts are imperative to reduce the potential impacts of GLOFs and ensure the safety of communities in glacier-affected regions.

K. Fujita et al (2013). Glacial lakes in the Himalayan region are prone to Glacial Lake Outburst Floods (GLOFs), presenting significant challenges for risk assessment. This study introduces a new index, leveraging remotely sensed digital elevation models (DEMs), to evaluate the risk of GLOFs based on the depression angle from the lakeshore. Testing on lakes across Nepal, Bhutan, and Tibet revealed a steep lakefront area (SLA) with angles exceeding 10°, which disappeared after GLOF events. Additionally, the study calculates potential flood volumes (PFVs) by analyzing lake surface lowering. PFV calculations for over 2000 Himalayan glacial lakes exhibit a power-law distribution, with some lakes having PFVs surpassing 10 million m^3, akin to major GLOFs. This PFV methodology provides an initial approach to identify and prioritize lakes requiring detailed assessment of GLOF hazards and risks. Leveraging remote sensing data and DEMs, this index offers a valuable tool for understanding and mitigating the threats posed by glacial lakes in the Himalayan region.

Agarwal, K. G., Kumar, V., & Das, T. (1983). The study conducted by Agarwal, Kumar, and Das in 1983 provides insights into the dynamics of melt runoff within a sub-catchment of the Beas basin, illuminating key hydrological processes associated with snowmelt. By analysing melt runoff dynamics, the research reveals critical information about the timing, magnitude, and spatial distribution of water released from snowpack during the melting season. This understanding is pivotal for predicting water availability, particularly in regions reliant on snowmelt as a primary freshwater source. The findings offer valuable implications for water resource management practices in mountainous areas, where seasonal variations in snow accumulation and melt significantly impact water availability. Understanding these dynamics enhances the effectiveness of water resource management strategies, ensuring sustainable water supply in mountainous regions.

M. J. Westoby, N. F. Glasser, J. Brasington, M. J. Hambrey, D. J. Quincey, and J. M. Reynolds (2014). Glacial lakes, central to the phenomenon of Glacial Lake Outburst Floods (GLOFs), exhibit distinctive features that contribute to their hazardous nature. These lakes often serve as reservoirs for vast volumes of water and sediment, resulting in sudden and highly mobile mixtures that can trigger catastrophic floods. GLOFs are characterized by peak discharges and volumes significantly larger than typical floods, posing substantial risks to downstream communities and infrastructure. These events can traverse considerable distances, spanning tens to hundreds of kilometers, following established river channels and potentially inundating populated areas. Breach scenarios, simulated through various parameters, include mechanisms such as overtopping waves and mechanical failures of the dam face, illustrating the complex nature of GLOF events and the need for comprehensive risk assessment and mitigation strategies.

2.4 Flood Analysis

Umar, V. S., et al. (1993). The study conducted by Umar, V. S., et al. (1993) centers on snowmelt runoff forecasting in Himalayan basins. Its primary objective is to enhance the accuracy of predicting water discharge during snowmelt periods, a critical aspect for effective water resource management and flood risk mitigation in the region. By focusing on forecasting techniques tailored specifically to Himalayan conditions, the research addresses the unique challenges posed by snowmelt runoff, which is a significant contributor to river flow in these basins. The study likely employs a combination of observational data, hydrological modelling, and statistical analysis to develop and validate snowmelt runoff forecasting models. These models may incorporate factors such as snowpack depth, temperature, precipitation, and topographic characteristics to simulate the timing and magnitude of snowmelt runoff events. By refining and validating these models, the research aims to provide decision-makers with more reliable information for managing water resources and preparing for potential flood events. Ultimately, the findings of this study have practical implications for water resource managers, policymakers, and disaster response agencies operating in Himalayan regions. By improving the accuracy of snowmelt runoff forecasts, the research contributes to betterinformed decision-making processes related to water allocation, reservoir management, and flood preparedness. Additionally, the study may provide valuable insights into the long-term impacts of climate change on snowmelt patterns and river flow dynamics in the Himalayas, informing adaptation strategies for future water resource management challenges.

Hall, D. K., Riggs, G. A., & Salomonson, V. V. (1995). Hall, Riggs, and Salomonson's (1995) study addresses the development of methodologies for mapping global snow cover using remote sensing data. By leveraging Moderate Resolution Imaging Spectro radiometer (MODIS) data, the researchers aimed to enhance the monitoring and assessment of snow cover dynamics at a global scale. The study contributes to the field of earth observation by providing innovative approaches to accurately map and analyse snow cover extent and changes over time. Remote sensing techniques offer valuable insights into snow cover dynamics by capturing high-resolution images of the Earth's surface from space. MODIS data, with its moderate spatial resolution and frequent revisit times, proves to be a valuable resource for monitoring snow cover dynamics on a global scale. By developing robust methods for processing and analysing MODIS data, the researchers enable comprehensive mapping of snow cover extent, distribution, and changes over time. The findings of Hall, Riggs, and Salomonson's study have significant implications for various sectors, including climate science, hydrology, and natural resource management. Accurate mapping of snow cover dynamics facilitates the assessment of water resources, weather forecasting, and climate modelling. Moreover, it supports decisionmaking processes related to agriculture, water management, and disaster preparedness in regions prone to snow-related hazards. The study contributes to advancing our understanding of snow cover dynamics and highlights the importance of remote sensing technologies in monitoring and managing snow-covered regions worldwide. By providing valuable insights into global snow cover dynamics, the research contributes to efforts aimed at enhancing environmental sustainability and resilience in snow-affected regions.

Gupta, V., & Sah, M. P. (2008). The study conducted by Gupta and Sah (2008) focuses on the impact of Landslide Lake Outburst Floods (LLOFs) within the Satluj catchment area of Himachal Pradesh, India. The research underscores the hazards posed by glacial lakes and the subsequent implications for local communities inhabiting the region. LLOFs, triggered by the sudden release of water from landslide-dammed lakes, can result in devastating floods that pose significant risks to human life, infrastructure, and ecosystems. By examining the specific case of the Satluj catchment area, the study provides valuable insights into the dynamics of LLOFs and their socio-economic and environmental consequences. The findings of the research contribute to a better understanding of the complex interactions between geological processes, glacial lake formation, and the occurrence of catastrophic flood events in mountainous regions. Gupta and Sah's study sheds light on the urgent need for comprehensive risk assessment and management strategies to address the growing threat of LLOFs in the Himalayan region. By highlighting the vulnerabilities of local communities and infrastructure to these natural hazards, the research underscores the importance of proactive measures to enhance resilience and minimize the potential impacts of future flood events.

J.C. Rodda, 2021. Modelling Glacial Lake Outburst Floods (GLOFs) is comparable to the examination of dam breaks in moraine dams. This involves evaluating the flood hydrograph resulting from the discharge due to dam breaches and the subsequent time series of discharge at various points downstream of the dam, considering the propagation of flood waves. The simulation of dam break floods can be conducted using either scaled physical hydraulic models or mathematical simulation models. The discharge hydrograph delineates the chronological interplay among runoff and various elements within the basin water balance, accounting for adjustments influenced by the basin's physical attributes. The initial surge in the hydrograph is ascribed to channel precipitation—water directly precipitating onto interlinked water surfaces within the basin. The primary elevation in discharge is predominantly attributed to surface runoff. While certain floods stem from occurrences like dam ruptures, geological shifts, and elevated tides, these events are infrequent in comparison to floods induced by concentrated rainfall or swift snowmelt.

Agarwal, K. G., Kumar, V., & Das, T. (1983). By gaining a deeper understanding of melt runoff dynamics, policymakers and water resource managers can make more informed decisions regarding water allocation, irrigation planning, and hydropower generation, among other uses. Furthermore, the insights derived from this study can inform the development of sustainable water management practices that account for the impacts of climate change on snowpack dynamics and melt runoff patterns. This research contributes to the growing body of knowledge aimed at enhancing the resilience of water systems in mountainous regions, ultimately supporting the long-term sustainability of freshwater resources and the communities that depend on them.

K. Fujita et al., (2013). Glacial lakes in the Himalayan region pose significant risks of Glacial Lake Outburst Floods (GLOFs), but assessing their potential for such events has been challenging. This study introduces a novel index based on the depression angle from the lakeshore, utilizing remotely sensed digital elevation models (DEMs). Testing on lakes in

Nepal, Bhutan, and Tibet, pre-GLOF events revealed a steep lakefront area (SLA) with angles exceeding 10°, which disappeared post-event. The study also calculates potential flood volumes (PFVs) based on lake surface lowering. PFV calculations for over 2000 Himalayan glacial lakes showed a power-law distribution, with some lakes having PFVs exceeding 10 million m^3, akin to major GLOFs. This PFV approach offers a preliminary means to identify and prioritize lakes necessitating detailed investigation of GLOF hazards and risks.

2.5 Importance of Early Warning System

Singh (1994) conducted a study to examine the distribution of snow with altitude in the Chenab basin. By analysing the spatial variability of snow accumulation, the research offers valuable insights into hydrological processes and snowmelt dynamics in mountainous regions. Understanding the distribution of snow at different elevations is crucial for assessing water resources, as snowpack acts as a natural reservoir that contributes to streamflow during the melting season. The findings of this study contribute to improved water resource management and flood forecasting in the Chenab basin, where snowmelt plays a significant role in the hydrological cycle. Additionally, the research provides valuable data for climate change studies, as changes in snow distribution patterns can have significant implications for regional water availability, ecosystem dynamics, and the livelihoods of local communities. Overall, Singh's study enhances our understanding of the complex interactions between climate, topography, and hydrology in mountainous areas, thereby informing sustainable water management practices and adaptation strategies in the face of environmental change.

S. Wang, Y. Che, and M. Xinggang (2020). Glaciers offer various benefits like recreation, climate regulation, and water resources, but their associated processes can pose hazards, potentially worsened by climate change. Numerous studies have examined glacier-related risks, identifying thousands of glacial lakes, including hundreds of potentially dangerous ones, particularly in regions like the Hindu Kush-Himalaya, Patagonia, and Cordillera Blanca. Glacier lake outburst floods (GLOFs) exemplify these risks, causing significant loss of life and property downstream. The Qinghai-Tibetan Plateau (QTP) has experienced notable warming, accelerating glacier retreat and lake formation, heightening GLOF risks. Past events, like those in Peru's Cordillera Blanca and the Chinese Himalayas, underscore the urgency for ongoing attention and mitigation efforts as glacier retreat persists. Mitigation proves more cost-effective than coping with disasters, and as GLOF impacts are expected to extend downstream in the future, continued attention is imperative.

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A. B., Sawagaki, T., &Yamanokuchi, T. (2013). Remote sensing techniques, such as satellite imagery and aerial photography, may have been utilized to gather data on lake morphology, glacier dynamics, and changes in lake extent over time. Computational modelling, such as hydrological modelling, could have been employed to simulate potential flood scenarios and assess the downstream impacts of GLOFs. The findings of this research are crucial for understanding the magnitude and potential consequences of GLOFs in the Himalayan region. By quantifying the potential flood volume of glacial lakes, the study provides valuable information for risk assessment and the development of effective risk management strategies. This research contributes to our broader understanding of the complex interactions between glaciers, glacial lakes, and downstream communities, ultimately aiming to enhance the resilience of mountainous regions to the impacts of GLOFs.

Kulkarni, A. V., Mathur, P., Rathore, B. P., Alex, S., Thakur N., & Kumar, M. (2002). The study conducted by Kulkarni et al. (2002) explores the impact of global warming on snow ablation patterns in the Himalayas, with a specific focus on changes in snowmelt dynamics. By investigating how rising temperatures influence the timing, intensity, and spatial distribution of snowmelt across the Himalayan region, the study sheds light on the broader implications of climate change for mountain ecosystems. The findings of this research are significant for several reasons. Firstly, they provide valuable insights into the vulnerability of high-altitude environments to climate change, highlighting the potential consequences of warming temperatures for snowpack dynamics and water resources in mountainous regions. As snowmelt plays a crucial role in regulating water availability, changes in snow ablation patterns can have far-reaching implications for downstream water supplies, hydrological processes, and ecosystem functioning. Additionally, by elucidating the mechanisms driving changes in snowmelt dynamics, the study enhances our understanding of the complex interactions between climate, glaciers, and water resources in the Himalayas. This knowledge is essential for developing effective adaptation strategies to mitigate the impacts of climate change on vulnerable communities and ecosystems in the region. The research conducted by Kulkarni et al. (2002) contributes to the growing body of scientific literature on climate change impacts in mountainous regions and underscores the urgent need for proactive measures to address the challenges posed by global warming in the Himalayas.

Roohani, M. S. (1986). By analysing snowmelt runoff patterns, Roohani's research contributes valuable information for hydrological modelling, which is essential for predicting water availability, managing water resources, and planning for water-related infrastructure development. Overall, Roohani's thesis provides essential insights into the hydro morphometric characteristics and snowmelt runoff patterns in the Chenab catchment area. The findings of this study are likely to be valuable for policymakers, water resource managers, and researchers involved in hydrological modelling and water management strategies in the region.

N. Islam and P. P. Patel (2022). In the North Sikkim district of India, where the Teesta River flows through the Eastern Himalayas, Glacial Lake Outburst Floods (GLOFs) pose a recurring danger to downstream communities. This study utilizes multi-temporal satellite imagery to monitor lake formation in the region. Results show the emergence of 203 new lakes between 2000 and 2018, with 82 lakes forming from 2011 to 2018 alone, indicating significant glacial retreat and lake expansion, coinciding with rising temperatures. By analyzing various geometric and geomorphic parameters, the study identifies the 36 most hazardous lakes, pinpointing the 10 posing the highest GLOF risk. These lakes, predominantly located along the primary snowline and Great Himalayan water-divide in northeastern Sikkim, require continuous monitoring.

Allen, S. K., Schneider, D., & Owens, I. F. (2009).By assessing the risks associated with GLOFs in the Mount Cook region, they provide valuable insights that can inform decisionmaking processes related to land use planning, infrastructure development, and disaster preparedness. This research serves as an important first step towards developing strategies to mitigate the impacts of glacial hazards in the Southern Alps of New Zealand. By increasing awareness of these risks and providing tools for risk assessment and management, the study contributes to efforts aimed at safeguarding local communities and enhancing their resilience to natural hazards.

2.6 Conclusion

Research on glacial lake outburst floods (GLOFs) underscores the grave dangers faced by mountain communities due to heightened flooding, especially in areas where glaciers are receding. Past events in Patagonia highlight the pressing need to comprehend GLOF dynamics and deploy preventative measures. Through the use of freely available Digital Elevation Models (DEMs) and analysis of satellite imagery, scientists delineate watershed boundaries and evaluate terrain drainage patterns essential for calculating flood volumes and gauging flood risks in at-risk regions. These assessments stress the necessity of proactive actions to address escalating GLOF threats. Investigations into glacial hazards in the Himalayas and New Zealand's Southern Alps contribute to our understanding of cryospheric processes and their repercussions, aiding in hazard evaluation and risk management approaches. By scrutinizing the attributes of glacial lakes and the stability of moraine dams, researchers pinpoint factors influencing GLOF occurrences and the mechanisms triggering dam failures. The development of innovative indices for estimating potential flood volumes of glacial lakes helps prioritize lakes for thorough GLOF hazard assessments. Furthermore, analyses of melt runoff dynamics within sub-catchments furnish valuable insights for managing water resources in mountainous regions reliant on snowmelt. Together, these studies deepen our grasp of hydrological dynamics, cryospheric processes, and the ramifications of climate change in high-altitude areas, providing crucial guidance for water resource management, hazard evaluation, and strategies for mitigating disaster risks.

CHAPTER 3

IDENTIFICATION OF POTENTIALLY DANGEROUS LAKE(S) BASED ON TOPOGRAPHICAL AND GEOMETRICAL FEATURES ASSOCIATED WITH GLACIAL LAKES, MORAINE DAMS, MOTHER GLACIER

3.1 Introduction

Glacial lakes are dynamic features of high-altitude landscapes, formed by the melting of glaciers in mountainous regions. While these lakes provide critical water resources and contribute to the unique ecosystems of these environments, they also pose significant hazards, particularly when dammed by moraine or other natural barriers. The potential for catastrophic glacial lake outburst floods (GLOFs) threatens downstream communities, infrastructure, and ecosystems, making the identification and assessment of potentially dangerous lakes imperative for risk management and disaster preparedness. In recent years, research efforts have intensified to identify and evaluate the hazards associated with glacial lakes, employing advanced remote sensing techniques and geographic information systems (GIS). By analysing the topographical and geometrical features of glacial lakes, researchers aim to assess the stability of moraine-dammed lakes and estimate the likelihood of GLOFs. This approach allows for the prioritization of high-risk lakes and the implementation of targeted mitigation measures to reduce the potential impacts of GLOFs. It poses significant risks to mountainous regions, particularly in the Himalayas, where the impacts of climate change are accelerating glacier melt. Identifying and assessing potentially dangerous glacial lakes is crucial for mitigating the risks associated with GLOFs. Remote sensing and geographic information systems (GIS) have emerged as powerful tools for studying glacial lakes and their dynamics. This review aims to provide an overview of remote sensing studies focused on the identification and assessment of potentially dangerous glacial lakes in the Himalayas.

Wang et al. (2012) developed an approach for estimating the breach probabilities of morainedammed lakes in the Chinese Himalayas using remote sensing data. Their study focused on analysing the topographical and geometrical features of moraine-dammed lakes to assess their vulnerability to breaching and potential GLOF hazards. By combining remote sensing techniques with statistical modeling, they were able to identify high-risk lakes and prioritize mitigation efforts in the region. Mergili and Schneider (2011) conducted a regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Their study utilized satellite imagery and digital elevation models (DEMs) to identify and characterize glacial lakes and moraines in the region. By analysing the topographical features and geomorphological characteristics of these features, they assessed the susceptibility of moraine-dammed lakes to outburst floods and identified potential hazard zones. Duan et al. (2023) conducted a case study of Bienong Co, a moraine-dammed lake in the southeastern Tibetan Plateau, to assess its volume and potential hazards. Their study integrated field surveys, remote sensing data, and numerical modeling techniques to analyse the topographical and geometrical features of the lake and its surrounding moraines. By quantifying the volume of the lake and evaluating its stability, they provided valuable insights into the potential risks of GLOFs in the region. Wang et al. (2012) developed methods for assessing regional glacial lake variation and hazard in the south-eastern Tibetan Plateau, focusing on the Boshula mountain range in China. Their study utilized remote sensing data and GIS techniques to analyse the topographical features and morphological changes of glacial lakes and moraines in the region. By quantifying lake variations and assessing potential hazard zones, they provided valuable information for GLOF risk management and mitigation. Iribarren Anacona et al. (2014) conducted a study of moraine-dammed lake failures in Patagonia and assessed outburst susceptibility in the Baker Basin. Their research focused on analysing the topographical and geometrical features of moraines and glacial lakes to identify potential hazard zones and assess the vulnerability of downstream communities. By combining field surveys with remote sensing data analysis, they provided valuable insights into GLOF risk assessment in the region. Dubey and Goyal (2020) assessed glacial lake outburst flood hazard, downstream impact, and risk over the Indian Himalayas. Their study utilized remote sensing data and GIS techniques to identify and assess the hazards posed by glacial lakes and moraines in the Indian Himalayas. By analysing the topographical and geometrical features of these features, they provided valuable information for GLOF risk management and mitigation in the region. Chowdhury et al. (2022) conducted a study of potential glacial lake outburst flood assessment in the Chhombo Chhu Watershed, Sikkim Himalaya, India. Their research focused on analysing the topographical and geometrical features of glacial lakes and moraines to identify potential hazard zones and assess the vulnerability of downstream communities. By combining field surveys with remote sensing data analysis, they provided valuable insights into GLOF risk assessment in the region.

Lamsal et al. (2016) assessed glacial lake development and prospects of outburst susceptibility in the Chamlang South Glacier, eastern Nepal Himalaya. Their study utilized remote sensing data and GIS techniques to analyse the topographical and geometrical features of glacial lakes and moraines in the region. By quantifying lake development and assessing potential hazard zones, they provided valuable information for GLOF risk management and mitigation in the region. Allen et al. (2008) developed satellite remote sensing procedures for glacial terrain analyses and hazard assessment in the Aoraki Mount Cook region, New Zealand. Their study focused on analysing the topographical and geometrical features of glacial lakes and moraines to identify potential hazard zones and assess the vulnerability of downstream communities. By combining field surveys with remote sensing data analysis, they provided valuable insights into GLOF risk assessment in the region.

Bolch et al. (2008) conducted a study in the Mt. Everest region of Nepal, where they utilized spaceborne imagery to identify glacier motion and potentially dangerous glacial lakes. Their research emphasized the importance of analysing topographical features to assess the stability and potential risk of GLOFs. Similarly, Wang et al. (2012) developed an approach to estimate breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote sensing data. Their study highlighted the significance of remote sensing techniques in evaluating the potential hazard posed by glacial lakes. Jain et al. (2015) contributed to the identification of glacial lakes and potentially dangerous ones in the Himalayan basin. Their research underscored the importance of understanding the dynamics of climate change and its impact on water resources in the region. Additionally, Osti and Egashira (2009) focused on the hydrodynamic characteristics of the Tam Pokhari glacial lake outburst flood in the Mt. Everest region of Nepal, shedding light on the complexities of GLOFs and the need for comprehensive risk assessment measures. Rongali et al. (2022) conducted a study on potentially dangerous glacial lake risk mapping and assessment in the Satluj River Basin of Himachal Pradesh, utilizing remote sensing and GIS techniques. Their research emphasized the integration of advanced technologies for accurate mapping and assessment of glacial lake hazards. Tang et al. conducted a comprehensive study on the Tibetan Plateau to identify hidden dangers associated with ice avalanches and GLOFs. Through systematic inventorying and mapping of hazardous features, such as glacial lakes and unstable slopes, they provided valuable insights into the distribution and potential impacts of these hazards. Their research emphasized the importance of considering multiple hazard sources in risk assessment and management strategies. Dasgupta focused on GLOFs in the Indian Himalayas, emphasizing the need for geotechnical resilience in hazard assessment. By analysing geological and topographical characteristics, the study highlighted the complex interplay of factors contributing to GLOFs and underscored the importance of proactive measures to enhance community resilience. In their study in the Swiss Alps, Huggel et al. demonstrated the utility of remote sensing techniques in assessing hazards from glacier lake outbursts. By integrating remote sensing data with field observations, they developed hazard maps and risk assessments, providing practical tools for policymakers and planners to mitigate GLOF risks. Liu et al. conducted an inventory of glacial lakes in the Bhote Koshi Basin following the Gorkha earthquake. Their research highlighted the dynamic nature of glacial lakes and the increased risk of outburst floods and debris flows in post-earthquake environments. The study emphasized the importance of continuous monitoring and risk assessment in such contexts. Zhang et al. utilized high-frequency glacial lake mapping techniques in the south-eastern Tibetan Plateau. By analysing Sentinel-1A/1B SAR imagery, they tracked the temporal evolution of glacial lakes and identified potentially hazardous lakes. Their findings contributed to a better understanding of lake dynamics and informed risk management strategies in the region. Budhathoki et al. assessed the risk of Imja Glacier Lake outburst floods in the Dudh Koshi River Basin using remote sensing techniques. Their study demonstrated the applicability of remote sensing in identifying and evaluating GLOF risks, providing actionable insights for policymakers and stakeholders. Gupta et al. conducted a quantitative prioritization of potentially critical glacial lakes in the Indus River basin using satellite-derived parameters. Through their assessment, they identified high-risk areas and provided guidance for implementing targeted risk reduction measures to safeguard vulnerable communities. The literature reviewed highlights the diverse approaches and methodologies employed in identifying and assessing dangerous glacial lakes. Remote sensing techniques, including satellite imagery and SAR data, have emerged as valuable tools for mapping and monitoring glacial lakes and associated hazards. The studies emphasize the importance of considering multiple factors, such as glacier dynamics, topographical features, and geological conditions, in comprehensive risk assessments. The utilization of remote sensing, Geographic Information Systems (GIS), and topographical analysis is paramount in identifying and assessing potentially hazardous glacial lakes in the Himalayan region. Through the integration of space borne imagery and remote sensing data, researchers have gained the ability to monitor glacier motion, detect moraine-dammed lakes, and evaluate the risk of Glacial Lake Outburst

Floods (GLOFs). This comprehensive approach allows for a more accurate understanding of the dynamics of glacial lakes and the potential hazards they pose to surrounding communities and infrastructure. Remote sensing studies, such as those conducted by Tang et al. (2023) and Zhang et al. (2020), have demonstrated the effectiveness of satellite imagery in mapping glacial lakes and monitoring their changes over time. By analysing high-resolution imagery, researchers can identify changes in glacier morphology, track the expansion of glacial lakes, and assess the likelihood of GLOF events. This information is crucial for early warning systems and disaster preparedness efforts in vulnerable regions.

Besides remote sensing, GIS technology plays a key role in spatial analysis and modeling of glacial lake hazards. Studies like those by Huggel et al. (2002) and Budhathoki et al. (2010) have utilized GIS techniques to develop hazard maps, assess risk levels, and prioritize mitigation measures. By integrating various geospatial datasets, including topographical maps, elevation models, and land cover data, researchers can identify areas prone to GLOFs and target interventions where they are most needed. Topographical analysis is essential for evaluating the stability of glacial lakes and predicting potential breach scenarios. Studies by Dasgupta (2021) and Liu et al. (2020) have highlighted the importance of considering geological and morphological factors in assessing GLOF risks. Factors such as lake volume, dam stability, and proximity to downstream communities are critical considerations in determining the potential impact of a GLOF event.

Therefore, identification of potentially dangerous glacial lakes based on topographical and geometrical features is necessary to enhance the resilience of mountain communities and infrastructure in the face of GLOF hazards. The findings of the aforementioned studies underscore the critical role of remote sensing, GIS, and topographical analysis in assessing the risks associated with glacial lakes and GLOFs. By leveraging these advanced technologies and spatial analysis techniques, researchers can accurately map glacial lakes, evaluate their stability, and prioritize high-risk areas for targeted interventions. The insights gained from these studies provide valuable information for stakeholders involved in disaster risk management and mitigation efforts. By identifying potentially hazardous lakes and assessing their hazards, stakeholders can develop effective risk management strategies to mitigate the impacts of GLOFs on mountain communities and infrastructure. Early warning systems, evacuation plans, and infrastructure upgrades are examples of measures that can help reduce the vulnerability of communities to GLOF events.

Remote sensing and GIS play a crucial role in this process by enabling the identification and monitoring of glacial lakes and the assessment of their hazards. By analysing topographical and geometrical features associated with glacial lakes, researchers can identify potential triggers for GLOFs, such as moraine instability or rapid lake expansion. This information allows for the development of targeted mitigation measures to reduce the risks posed by potentially dangerous lakes. The use of advanced technologies allows for the creation of comprehensive risk maps, which can be used to inform decision-making and prioritize resource allocation for GLOF risk reduction. By integrating remote sensing data with ground-based observations and modelling techniques, researchers can provide valuable insights into the dynamics of glacial lake systems and the potential impacts of GLOFs on downstream areas. The continued research in this field is essential to further enhance our understanding of glacial lake dynamics and improve the resilience of mountain communities to natural hazards. By advancing our knowledge of the processes driving GLOFs and refining our methods for identifying and assessing potentially dangerous lakes, we can better prepare for and mitigate the impacts of these catastrophic events. Through collaboration between researchers, policymakers, and local communities, we can work towards building safer and more resilient mountain environments in the face of increasing glacial lake hazards.

3.2 Features Associated with Glacial Lakes

3.2.1 Topographical Features

Identification of Dangerous Lakes: The identification of dangerous lakes based on topographical features is crucial for assessing and mitigating the risks associated with glacial lake outburst floods (GLOFs) in mountainous regions like the Himalayas. Glacial lakes are inherently unstable due to their formation from melting glaciers, and when these lakes breach or experience sudden drainage, they can trigger catastrophic flooding downstream, posing significant threats to human lives, infrastructure, and ecosystems. Topographical features play a pivotal role in determining the stability and potential hazards of glacial lakes. By analysing the topography of the surrounding landscape, researchers can identify key indicators of lake instability, such as steep slopes, loose sediments, and proximity to active glaciers. These features can increase the likelihood of moraine dam failure or landslide-induced lake drainage, leading to GLOFs. One of the primary reasons for identifying dangerous lakes based on topographical features is to prioritize risk assessment and management efforts. Not all glacial lakes pose the same level of threat, and limited resources necessitate the identification of highrisk lakes for targeted interventions. By focusing on lakes with characteristics conducive to instability, such as those situated in steep valleys or with large moraine dams, stakeholders can allocate resources more effectively to monitor, mitigate, or even engineer solutions to reduce the risk of GLOFs. It also enables proactive measures to be implemented to reduce the impact of potential GLOFs. Early warning systems can be established in downstream communities to alert residents of imminent flood events, giving them valuable time to evacuate to safer areas. The infrastructure improvements, such as reinforced riverbanks or diversion channels, can help mitigate the effects of flooding and protect vulnerable communities and assets.

1. **Steep Slope**

   Steep slopes play a critical role in the dynamics of Glacial Lake Outburst Floods (GLOFs), often serving as a contributing factor to the initiation and severity of such events. Understanding the relationship between steep slopes and GLOFs requires a comprehensive examination of the geological, glaciological, and hydrological processes involved.

   Firstly, it's essential to comprehend the formation of glacial lakes and the influence of steep slopes on their stability. Glacial lakes typically form in depressions created by the erosive action of glaciers. When glaciers retreat or melt due to rising temperatures, depressions left behind can accumulate water, forming lakes. Steep slopes around these lakes can exacerbate the vulnerability of moraine dams that hold them in place. Moraine dams are composed of loose sediments and debris deposited by glaciers, and their stability depends on various factors, including slope angle, material composition, and hydrological conditions. The steepness of slopes around glacial lakes affects the stability of moraine dams in several ways. Firstly, steep slopes can increase the erosive forces acting on the moraine dam. When water levels in the lake rise due to glacial meltwater inputs or heavy rainfall, the hydraulic pressure exerted against the dam can lead to erosion of the dam material. Steep slopes facilitate rapid runoff, amplifying the erosive power of flowing water and increasing the likelihood of dam failure.

Secondly, the angle of the slope influences the stability of the moraine dam against gravitational forces. Steeper slopes result in higher gravitational forces acting on the dam material, potentially leading to slope instability or failure. Additionally, steep slopes can increase the likelihood of landslides or rockfalls, which can directly impact the integrity of the moraine dam. The presence of loose sediments and debris on steep slopes makes them susceptible to mass movement, especially under the influence of external triggers such as seismic activity or intense rainfall. Furthermore, the relationship between steep slopes and GLOFs is intricately linked to the mechanism of lake drainage during an outburst event. When a moraine dam fails due to overtopping, erosion, or structural instability, it results in the rapid release of water stored in the glacial lake. Steep slopes surrounding the lake can accelerate the flow velocity of the released water, leading to higher peak discharges and more extensive flood inundation downstream.

Moreover, the topographical features of steep slopes can influence the trajectory and reach of GLOFs. In mountainous terrain characterized by steep slopes, GLOFs can travel long distances downstream at high velocities. The steep gradient provides the necessary energy for the floodwaters to travel rapidly, potentially causing extensive damage to infrastructure, settlements, and natural habitats along the flood path. The relationship between steep slopes and GLOFs underscores the complex interplay between geological, glaciological, and hydrological processes in highmountain environments. Steep slopes increase the vulnerability of moraine dams to erosion and failure, contributing to the initiation and severity of GLOFs. Understanding the role of steep slopes in GLOF dynamics is crucial for assessing hazards, implementing risk reduction measures, and enhancing the resilience of communities vulnerable to glacial lake outburst floods.

2. **Loose and Unconsolidated Material and GLOF**:

Loose or unconsolidated sediments in the area play a crucial role in the context of Glacial Lake Outburst Floods (GLOFs), serving as significant indicators of potential hazards and contributing factors to the initiation and severity of such events. Understanding the relationship between loose sediments and GLOFs requires delving into the geological processes that shape glacial landscapes, the dynamics of glacial lakes, and the mechanisms of dam failure. Glacial environments are inherently dynamic, characterized by the constant movement of ice and the erosion and deposition of sediments. Glaciers erode rocks as they move, producing a mix of fine-grained and coarse-grained sediments. When glaciers retreat, they leave behind moraines, which are accumulations of unconsolidated sediments deposited along their margins. These moraines can act as natural dams, impounding meltwater to form glacial lakes. However, the stability of these moraine dams is often compromised by the loose, unconsolidated nature of the sediments comprising them. Several factors contribute to the instability of loose sediments in glacial environments. First, the deposition of sediments by glaciers is often haphazard, resulting in variable sediment characteristics and stratigraphy within moraine dams. This variability can weaken the structural integrity of the dam, making it susceptible to failure under hydraulic pressure. Second, the presence of ice within moraine dams, known as ice-cored moraines, further complicates their stability. Ice cores can melt or degrade over time, leading to the collapse of the dam and the sudden release of impounded water. The relationship between loose sediments and GLOFs is particularly evident during the process of dam failure. When the structural integrity of a moraine dam is compromised, either through overtopping, erosion, or mechanical failure, the impounded water is released rapidly downstream. The loose, unconsolidated nature of the sediments allows water to infiltrate and destabilize the dam, accelerating the breach process. Once the dam breaches, a catastrophic flood event ensues, characterized by a surge of water, sediment, and debris traveling downstream at high velocities. The consequences of GLOFs can be devastating, impacting both human communities and the surrounding environment. The rapid onset and high magnitude of these events pose significant risks to downstream infrastructure, including roads, bridges, and hydropower facilities. Additionally, GLOFs can result in loss of life, displacement of populations, and destruction of agricultural land and natural habitats. The sediment-laden floodwaters can cause extensive erosion and sediment deposition along their path, altering river channels and landscapes in their wake. Mitigating the risks associated with GLOFs requires a comprehensive understanding of the relationship between loose sediments and dam failure mechanisms. Monitoring and assessing the stability of moraine dams, as well as implementing early warning systems, are essential components of risk management strategies. Remote sensing technologies, such as satellite imagery and LiDAR (Light Detection and Ranging), offer valuable tools for mapping and monitoring glacial lakes and their surrounding landscapes, allowing researchers to identify areas prone to instability and assess the potential hazards posed by loose sediments. The presence of loose or unconsolidated sediments in glacial environments is a critical factor in the initiation and severity of Glacial Lake Outburst Floods. The dynamic nature of glaciers and the variable characteristics of moraine dams contribute to the instability of these sediments, increasing the likelihood of dam failure and catastrophic flood events. Understanding the relationship between loose sediments and GLOFs is essential for effective risk management and disaster preparedness in glacial regions.

3.2.2 Geometrical Features:

Moraine-dammed Lakes: Moraine-dammed lakes, nestled within glacierized landscapes, represent both natural marvels and potential hazards to downstream communities. These lakes, formed by the gradual accumulation of meltwater behind natural dams composed of glacial debris, often exhibit a serene facade that belies the latent dangers they harbor. While their tranquil appearance may suggest a peaceful coexistence with their surroundings, the reality is far more complex, as these lakes can pose significant risks that have the potential to culminate in catastrophic events if not adequately managed. At the heart of the risks associated with moraine-dammed lakes lies the condition of their associated mother glaciers. These glaciers serve as the primary water source for the lakes, supplying them with meltwater generated from the gradual melting of ice and snow. As such, the dynamics of the glaciers directly influence the stability of the landscape surrounding the lakes, thereby impacting the potential hazards they pose to downstream communities. One of the key factors influencing the hazards posed by moraine-dammed lakes is the rate of glacier retreat. Glacier retreat, driven primarily by climate change, results in the exposure of unstable ice fronts that are susceptible to calving events. As glaciers retreat, chunks of ice may break off and fall into the lakes below, contributing to increased water volume and generating waves that can destabilize the natural dams. Rapid glacier retreat exacerbates this risk, as it exposes larger areas of unstable ice fronts, increasing the likelihood of calving-induced hazards. The proximity of hanging glaciers to moraine-dammed lakes further amplifies the potential for instability and catastrophic events. Hanging glaciers, perched on steep slopes and unsupported by the underlying terrain, are inherently prone to instability. As these glaciers melt or undergo calving events, ice masses can directly fall into the lakes, triggering waves and potentially causing dam breaches. The combination of hanging glaciers and moraine-dammed lakes creates a precarious situation, where the slightest disturbance can lead to cascading hazards downstream. The size of the glacier area feeding the moraine-dammed lakes also plays a crucial role in determining the magnitude of the associated hazards. Lakes fed by larger glacier areas have the potential to accumulate significant volumes of meltwater, leading to rapid water level rise and increased pressure on the natural dams. This heightened pressure increases the likelihood of overflow or breach events, posing serious risks to downstream areas and infrastructure. The presence of debris cover at glacier tongues further complicates the dynamics of moraine-dammed lakes. Debris cover acts as insulation, accelerating the melting of underlying ice and increasing water flow into the lakes. As debris-covered glaciers melt, the resulting influx of sediment-laden meltwater alters the characteristics of the lakes, potentially destabilizing the natural dams and increasing the risk of overflow or breach events. Moraine-dammed lakes are complex features of glacierized landscapes that can pose significant hazards to downstream communities if not properly managed. The risks associated with these lakes are intricately linked to the condition of their associated mother glaciers, glacier retreat rates, proximity to hanging glaciers, glacier area size, and the presence of debris cover at glacier tongues. Understanding and mitigating these hazards require comprehensive monitoring, risk assessment, and proactive management strategies to ensure the safety and resilience of downstream communities in the face of evolving glacier dynamics and climate change.

1. **Hanging Glacier Proximity:** The proximity of hanging glaciers to moraine-dammed lakes presents a significant risk factor for potential instability and catastrophic events. Hanging glaciers are situated on steep slopes and lack support from the underlying terrain, making them inherently unstable. As these glaciers undergo melting or calving processes, ice masses can directly fall into the lake below. The impact of ice masses entering the lake can generate powerful

waves, which, in turn, can pose threats such as erosion of the moraine dam or trigger breach events. The instability of hanging glaciers, coupled with their proximity to the lake, amplifies the risk of sudden ice inputs and associated hazards, necessitating comprehensive monitoring and risk assessment strategies to mitigate potential impacts on downstream communities and infrastructure.

2. **Larger Glacier Area:** Moraine-dammed lakes that are fed by larger glacier areas have the potential to accumulate significant volumes of meltwater, thereby increasing the risk of rapid water level rise and outburst events. The size of the glacier directly influences the amount of water stored in the lake, with larger glaciers capable of producing larger volumes of meltwater. As glaciers melt, especially under the influence of climate change, the inflow of meltwater into the lake can raise water levels, exerting greater pressure on the moraine dam. This heightened pressure increases the likelihood of overflow or breach, posing serious risks to downstream areas. Therefore, the size of the glacier area feeding the lake serves as a crucial determinant of the potential hazard posed by moraine-dammed lakes, emphasizing the importance of monitoring glacier dynamics and implementing proactive measures to mitigate associated risks.

4. Fast Retreating Glaciers: Glaciers experiencing rapid retreat are particularly susceptible to calving events, where chunks of ice break off and fall into the lake. Rapid glacier retreat, driven primarily by climate change, exposes unstable ice fronts that are prone to collapse. Calving events not only contribute to increased water volume in the lake but also generate waves that can further destabilize the moraine dam. The retreat of glaciers at an accelerated pace underscores the urgent need for monitoring and risk assessment efforts to understand the evolving hazards associated with moraine-dammed lakes. Additionally, proactive measures such as early warning systems and infrastructure upgrades may be necessary to mitigate the impacts of calving-induced hazards on downstream communities and infrastructure**.**

4. **Debris Cover at Glacier Tongue:** The presence of debris cover at the glacier tongue can significantly influence melting rates, leading to enhanced water flow into the lake. Debris cover acts as insulation, trapping heat and accelerating the melting of underlying ice. As debriscovered glaciers melt, the resulting meltwater carries sediment and debris into the lake, altering its characteristics and potentially destabilizing the moraine dam. The influx of sediment-laden meltwater can lead to increased sedimentation within the lake, affecting its

capacity and increasing the risk of overflow or breach events. Consequently, assessing the presence and extent of debris cover at glacier tongues is crucial for understanding the dynamics of morainedammed lakes and implementing effective mitigation measures to address associated hazards.

5. **Steep Gradient at Glacier Tongue**: Glaciers characterized by steep gradients at their tongues are particularly prone to ice destabilization and mass movement, increasing the risk of hazards associated with glacial lakes. The steep slope of these glaciers amplifies the potential for ice collapse and calving events, where large sections of ice detach and fall into the surrounding water body. The steep gradient accentuates gravitational forces acting on the ice mass, making it more susceptible to sudden movements and structural instability. As a result, ice blocks and icebergs can detach from the glacier's terminus and rapidly enter the adjacent lake. Upon entering the lake, these ice masses can have significant impacts. The sudden introduction of large volumes of ice can generate powerful waves, leading to increased water levels and potential flooding downstream. The waves produced by the impact of falling ice can propagate across the lake, posing risks to infrastructure, communities, and ecosystems located along its shores. The increased water volume resulting from ice inputs can exacerbate the risk of glacial lake outburst floods (GLOFs). The influx of ice can raise water levels, potentially exceeding the capacity of the lake's natural or engineered barriers, leading to breaches and uncontrolled release of water downstream. Given the heightened risks associated with glaciers characterized by steep gradients at their tongues, monitoring and assessing these features are essential for hazard mitigation efforts. Understanding the dynamics of ice destabilization and mass movement can inform early warning systems and emergency preparedness strategies aimed at protecting downstream communities and infrastructure from the impacts of glacial lake-related hazards. Additionally, incorporating this knowledge into land use planning and infrastructure development can help minimize risks and enhance resilience in areas vulnerable to glacial lake outburst floods and related events.

6. **Presence of Crevasses and Ponds:** Crevasses and ponds on the surface of glaciers serve as indicators of structural weaknesses and areas of heightened meltwater accumulation. Crevasses are fractures that develop in glaciers due to ice deformation and movement, representing zones where the glacier's integrity is compromised. These fractures weaken the

glacier structure and contribute to its overall instability. Meanwhile, ponds form as a result of the accumulation of meltwater on the glacier surface, creating small bodies of water that collect in depressions or low-lying areas. These ponds serve as reservoirs of water that can eventually find their way into the glacial lake.

Both crevasses and ponds play significant roles in the dynamics of glacial lakes. Crevasses represent potential pathways for meltwater to penetrate deep into the glacier, reaching its base and contributing to basal sliding, which can further destabilize the glacier. Additionally, the presence of crevasses indicates regions of stress concentration within the glacier, making them susceptible to fracturing and calving events. Similarly, ponds act as sources of water input into the lake, as the meltwater they collect eventually drains into the glacier's internal hydrological system or directly into the lake itself. The combination of crevasses and ponds increases the likelihood of ice collapse events into the lake. As meltwater accumulates within these features, it can further weaken the surrounding ice and exacerbate the formation of fractures and crevasses. Ultimately, this heightened instability increases the risk of large ice masses breaking off from the glacier and entering the lake, potentially triggering glacial lake outburst floods (GLOFs) and other related hazards. Therefore, monitoring and assessing the presence and characteristics of crevasses and ponds are crucial for understanding the dynamics of glacial lakes and mitigating associated risks to downstream communities and infrastructure.

7. Toppling/Collapses of Glacier Masses: The toppling or collapse of glacier masses represents a significant mechanism for introducing ice into glacial lakes. This phenomenon, often triggered by melting, calving, or other destabilizing factors, leads to the release of ice blocks into the lake's waters. These ice blocks can exhibit a wide range of sizes, from small chunks to massive masses, depending on the scale of the event. Upon entering the lake, these ice blocks can cause immediate disturbances, generating waves and increasing water volume. The sudden influx of ice into the lake poses significant risks to downstream infrastructure and communities, as it can lead to flooding, erosion, and other hazards. Monitoring and assessing the potential for glacier mass toppling or collapse is essential for understanding and mitigating the risks associated with glacial lake outburst floods (GLOFs) and other related events. By identifying areas prone to such phenomena and implementing appropriate risk management strategies, stakeholders can work towards reducing the vulnerability of downstream areas to these dynamic natural processes.

8. Ice Blocks Draining to Lake: The drainage of ice blocks into glacial lakes presents a significant hazard, supplementing the direct collapse of ice into the water. As meltwater carves channels within the glacier, ice blocks can detach and flow into the lake, augmenting its water volume and posing downstream risks. This process may unfold gradually as channels deepen over time, or it can occur abruptly due to sudden changes in glacier dynamics. The influx of ice blocks contributes to the overall instability of the lake and exacerbates the potential for glacial lake outburst floods (GLOFs). Monitoring these processes is crucial for assessing the evolving hazards associated with glacial lakes and implementing effective risk mitigation measures to protect downstream communities and infrastructure.

Understanding these characteristics is crucial for assessing the risk posed by moraine-dammed lakes and implementing proactive mitigation measures. Monitoring glacier dynamics, lake water levels, and signs of instability informs early warning systems and disaster preparedness efforts. Community engagement and collaboration are essential for developing effective risk management strategies and enhancing resilience to glacial lake outburst floods and related hazards in vulnerable mountainous regions. Beyond the immediate features like moraines, mother glaciers, and lake conditions, various other factors contribute to the potential hazards associated with these water bodies. These include climatic conditions, such as temperature and precipitation patterns, which influence glacier melt rates and the frequency of extreme events. Geological factors, such as the composition of moraine materials and underlying bedrock, also play a role in determining the stability of moraine dams and the likelihood of failure. The human activities, such as infrastructure development and land use changes, can alter the natural dynamics of glacierized landscapes and increase the vulnerability of downstream communities to glacial lake outburst floods. Therefore, the hazards associated with moraine-dammed lakes are multifaceted and require a comprehensive understanding of the physical, environmental, and socio-economic factors at play. By recognizing the interconnectedness of glacier dynamics, moraine stability, and downstream risks, stakeholders can work together to develop adaptive strategies that enhance resilience and minimize the potential impacts of glacial lake outburst floods in vulnerable mountainous regions. These conditions are paramount for assessing the risk posed by glacial lakes and implementing effective mitigation strategies. The hazards associated with glacial lakes extend beyond the immediate features of the lakes themselves. Surrounding environmental conditions and geological phenomena can significantly contribute to the risks posed by these dynamic hydrological features. Here are some additional factors to consider:

1. **Potential Rockfall/Slide Sites:** Glacial lakes situated in regions prone to rockfall or landslides face significant threats due to mass movements. These events can occur suddenly, dislodging large volumes of debris into the lake, triggering waves and surges that may result in flooding or outburst events. The steep slopes surrounding many glacial lakes make them susceptible to such events, especially during periods of heavy precipitation or rapid glacial retreat. The potential for rockfall or landslides to impact glacial lakes is heightened by the dynamic nature of glacier environments. As glaciers melt and retreat, they leave behind loose debris and unstable slopes, increasing the likelihood of mass movements. Additionally, the presence of ice within the debris can act as a lubricant, further facilitating slope instability and enhancing the risk of rockfall or landslides. Monitoring and mitigation efforts in areas prone to rockfall or landslides are crucial for reducing the hazards posed to glacial lakes and downstream communities.

2. **Snow Avalanches:** The presence of large snowfields surrounding glacial lakes increases the risk of snow avalanches, which can pose significant threats to lake stability. Snow avalanches occur when a mass of snow detaches from a slope and cascades downhill, often with considerable force. If triggered near a glacial lake, a snow avalanche can enter the lake suddenly, displacing water and causing disturbances to the lake's equilibrium. The impact of a snow avalanche can create waves that disturb the stability of the lake and potentially lead to overflow or outburst events, posing dangers to downstream communities and infrastructure. The risk of snow avalanches is influenced by various factors, including slope angle, snowpack stability, and weather conditions. Areas with steep slopes and heavy snowfall are particularly susceptible to snow avalanches, highlighting the

importance of comprehensive risk assessments and mitigation measures in snowprone regions near glacial lakes.

3. **Neo-tectonic and Earthquake Activities:** Glacial lakes located in regions prone to neo-tectonic activity or frequent earthquakes face additional risks due to potential ground shaking and landslides. Seismic events can induce ground shaking or trigger landslides, potentially destabilizing the surrounding terrain and leading to catastrophic outcomes for the lake and downstream areas. The combination of seismic activity and glacial dynamics can increase the likelihood of moraine dam failures or landslides, exacerbating the hazards associated with glacial lakes. Neotectonic activity refers to the ongoing geological processes that result in the deformation of the Earth's crust, often leading to earthquakes, faulting, and folding.

   Regions characterized by neo-tectonic activity are inherently unstable, with the potential for sudden changes in topography and landscape features. In such environments, glacial lakes are at greater risk of destabilization, as seismic events can trigger landslides or ground subsidence, leading to breaches or overflow events. Effective risk management strategies for glacial lakes located in neo-tectonically active regions should consider the combined impacts of seismic activity and glacial dynamics, incorporating measures to mitigate the potential consequences of ground shaking and landslides.

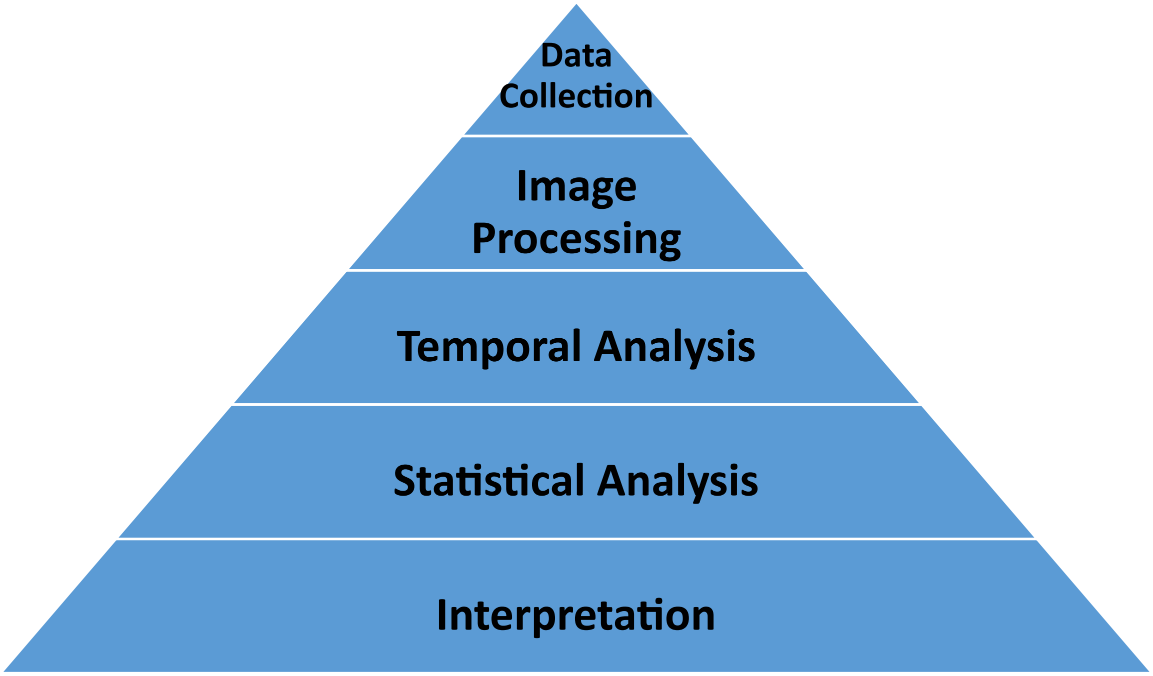
4. **Climatic Conditions:** Climatic variability plays a crucial role in influencing the stability of glacial lakes, with changes in precipitation patterns and temperature fluctuations affecting water input, glacier dynamics, and moraine dam stability. Successive years of wet and cold weather followed by hot and wet or hot and arid conditions can accelerate glacial melting and increase water input into the lake. This heightened input can raise water levels, leading to overflow or outburst events that pose risks to downstream areas. Changes in precipitation patterns, such as increased rainfall or snowmelt, can also impact glacier dynamics, potentially leading to increased ice melt and moraine dam instability. Additionally, temperature fluctuations can influence the rate of glacier melt and the stability of the surrounding terrain, further amplifying the hazards associated with glacial lakes.

Effective management of glacial lake hazards in response to climatic conditions requires comprehensive monitoring and modelling efforts to assess the potential impacts of changing climate patterns on lake stability and downstream risks.

5. **Glacial Dynamics:** The movement of glaciers towards their lower tributaries or mother glaciers can pose significant hazards to glacial lakes due to increased pressure on containment structures and destabilization of the surrounding terrain. If a glacier harbours a well-developed lake at its tongue, sudden advances can exert pressure on the lake's containment structures, leading to breaches or increased water levels that threaten downstream areas. Additionally, glacier movements can destabilize the surrounding terrain, increasing the risk of landslides or rockfall events that can impact the stability of the lake and its surroundings. The dynamic nature of glaciers, influenced by factors such as climate change, snowfall, and topographical features, complicates hazard assessment and management efforts for glacial lakes. Continuous monitoring of glacier dynamics, combined with comprehensive risk assessments and mitigation measures, is essential for reducing the hazards posed by glacier-related events to downstream communities and infrastructure.

Assessing the hazards associated with glacial lakes involves a multifaceted analysis of various indicators that illuminate the potential risks posed by these dynamic hydrological features. Understanding factors such as the rise in lake water level, the presence and activity of supraglacial lakes, the positioning of lakes, and the conditions of the dam are all critical components in evaluating the hazard potential of glacial lakes (Bajracharya et al., 2007; Ives et al., 2010; Aggarwal et al., 2017; Wang et al., 2020; Anacona et al., 2015; Islam & Patel, 2022; Gurung et al., 2017).The rise in lake water level serves as one of the primary indicators of potential hazard associated with glacial lakes (Bajracharya et al., 2007). It has been observed that lakes with volumes exceeding 0.01 km3 often have historical events associated with them (Bajracharya et al., 2007). A rapid increase in lake water volume, particularly in deeper lakes with a substantial portion near the dam rather than the glacier tongue, signals a potentially dangerous situation (Ives et al., 2010). This sudden rise can lead to the overtopping or breaching of the moraine dam, triggering catastrophic glacial lake outburst floods (GLOFs). Supraglacial lakes, characterized by groups of closely spaced smaller lakes at glacier tongues, also play a significant role in assessing hazard potential (Aggarwal et al., 2017). These lakes can coalesce over time to form larger lakes, amplifying the risk of glacial lake outburst floods (Wang et al., 2020). The evolving activity of these supraglacial lakes is indicative of increasing potential hazard, especially as they merge and expand, potentially destabilizing the surrounding glacier ice and contributing to the overall volume of water stored in the lake. Besides monitoring water levels and supraglacial lake activity, the positioning of glacial lakes within their respective glacier systems is crucial in assessing hazard potential. Lakes located in close proximity to hanging glaciers or steep glacier tongues face an increased risk of instability and potential collapse into the lake (Anacona et al., 2015). The presence of crevasses and ponds further indicates structural weaknesses in the glacier, which can exacerbate the risk of ice destabilization and mass movement into the lake (Islam & Patel, 2022). The condition of the moraine dam that holds back the glacial lake is a critical factor in determining hazard potential. Larger glacier areas can contribute significant meltwater, raising the potential for rapid water level rise and outburst events (Gurung et al., 2017). Fast-retreating glaciers are particularly prone to calving events, which can add to the volume of water in the lake and increase the pressure on the moraine dam (Bajracharya et al., 2007). Debris cover at the glacier tongue enhances melting rates, further increasing water flow into the lake (Ives et al., 2010). Additionally, a steep gradient at the glacier tongue can exacerbate ice destabilization potential, increasing the likelihood of ice collapse into the lake (Aggarwal et al., 2017). Besides these, the toppling or collapses of glacier masses can release ice blocks into the lake, raising water volume and posing downstream hazards (Wang et al., 2020). Ice blocks draining into the lake can also contribute to increased water volume and the potential for glacial lake outburst floods (Anacona et al., 2015). Understanding these various indicators and their interactions is crucial for assessing risk and implementing proactive mitigation measures. Continuous monitoring of glacier dynamics, lake water levels, and signs of instability informs early warning systems and disaster preparedness efforts (Gurung et al., 2017). Moreover, community engagement and collaboration are essential for developing effective risk management strategies and enhancing resilience to glacial lake outburst floods and related hazards in vulnerable mountainous regions (Bajracharya et al., 2007). Therefore, the assessment of hazards associated with glacial lakes requires a comprehensive understanding of the complex interplay of factors such as lake water level rise, supraglacial lake activity, glacier positioning, moraine dam condition, and glacier dynamics. By integrating data from various sources and employing advanced monitoring techniques, researchers and policymakers can develop proactive measures to mitigate the risks posed by glacial lake outburst floods and enhance the resilience of communities in vulnerable mountainous regions.

3.3 Methodology



1. **Data Collection**: The surface area measurements of Lake 1 and Lake 2 were collected from satellite imagery spanning multiple years, including 2008, 2014, 2016, and 2018. High-resolution satellite images were obtained from reputable sources with appropriate spatial and temporal resolutions to ensure accuracy in the measurements.

2. **Image Processing**: The satellite images were processed using geographic information system (GIS) software to extract the surface area of each lake. This process involved digitizing the boundaries of the lakes from the satellite imagery and calculating the corresponding surface area in square kilometres.

3. **Temporal Analysis**: The surface area measurements of Lake 1 and Lake 2 were analyzed over the specified time periods (2008-2018) to assess changes in their hydrological regime and environmental conditions. The rate of change per year was calculated for each lake by comparing surface area measurements between consecutive years.

4. **Statistical Analysis**: The rate of change per year was subjected to statistical analysis to identify trends and variability over time. This involved calculating the mean rate of change and assessing its significance using appropriate statistical tests.

5. **Interpretation**: The results of the temporal analysis and statistical analysis were interpreted to understand the evolving dynamics of Lake 1 and Lake 2. Fluctuations in the rate of change were analyzed to discern patterns and implications for water resource management and environmental conservation.

6. **Applying Dam Breach Model:** Cross-sections are to be prepared with the help of DEM at regular intervals along the drainage system of the lake. These cross-sections can be used as input for the Dam Breach Model. The Dam Breach Model HEC-RAS is applied here to find out the hydrological parameters at different locations in case of GLOF.

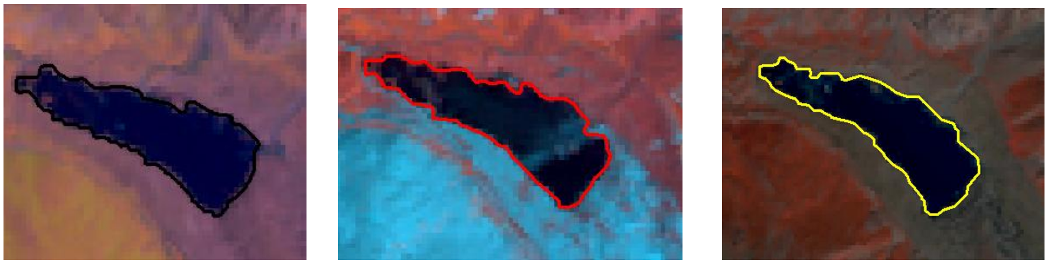
7. **Identifying the vulnerable locations:** Based on the hydrological parameters in case of GLOF and the uses of the locations i.e. infrastructure live stockes, habitation, agricultural products, the vulnerable locations are identified.

8. **Recommendation of Early Warning System**

In the present study for identification of dangerous lake, criteria/factors of consequence specially evaluating area/volume of lake, breaching evidences, condition of lake and its surrounding etc. have been studied.

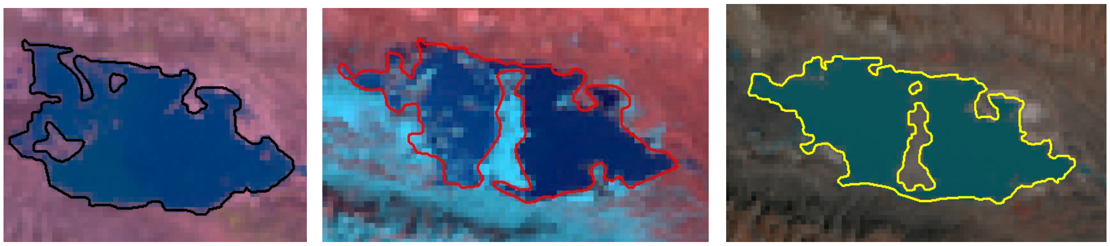
As per the assessment from some of the criteria's, two Lake have been identified to have a relatively higher potential for occurrence of GLOF in Chenab basin. It was found that the lake is connected directly with the snout of the mother glacier, whereas apart from mother glacier, it is also fed from adjacent glaciers. From interpretations of multi spectral satellite imagery it was found that Lake are of moraine dammed type with its position in ablation zone.

Chenab Potentially Dangerous Lake



Chenab PD Lake 1 (Black-2000, Red-2008, Yellow-2014)

Figure 3.1 Chenab PD Lake 1



Chenab PD Lake 2 (Black-2000, Red-2008, Yellow-2014)

Figure 3.2 Chenab PD Lake 2

3.4 Satellite Data Used:

Table 3.1 Satellite Data Used

Date of acquisition	Sensor	Spatial resolution (m)
3 December 1990	Landsat 4-5TM	30
19 October 2000	Landsat 4-5TM	30
22 August 2008	Landsat 4-5TM	30
16 August 2014	Landsat 8 OLI	30
6 October 2016	Landsat 8 OLI	30
14 September 2018	Landsat 8 OLI	30

3.5 Statistical Analysis:

There are total 57 lakes and the area under all lakes is 3.00 sq. km. The lakes were further classified on the basis of area and elevation. Out of 57 lakes, 14 lakes have area less than 0.01 sq km, 38 lakes area are between 0.01 and 0.1 sq km and among all these lakes, 5 lakes are having area more than 0.1 sq km. In addition, glacial lakes are located at different altitudinal ranges. Most of the lakes are situated above 4500m.Total 26 lakes are situated at an elevation more than 4500 m, 23 lakes are below 4200 m, while 8 lakes are situated between 4200 and 4500 m. All this statistic is summarized in Table 1.

Table 3.2 Nos of Lakes at Different Altitude

Year	Lake	E<4200	4200<E<4500	E>4500
1990	57	23	8	26
2000	89	36	15	38
2008	86	37	20	29
2014	89	36	18	35

Table 3.3 Nos of Lakes of Different Area

Year	Lake	A<0.01	0.01<A<0.1	A>0.1
1990	57	14	38	5
2000	89	10	71	8
2008	86	8	69	9
2014	89	10	71	8

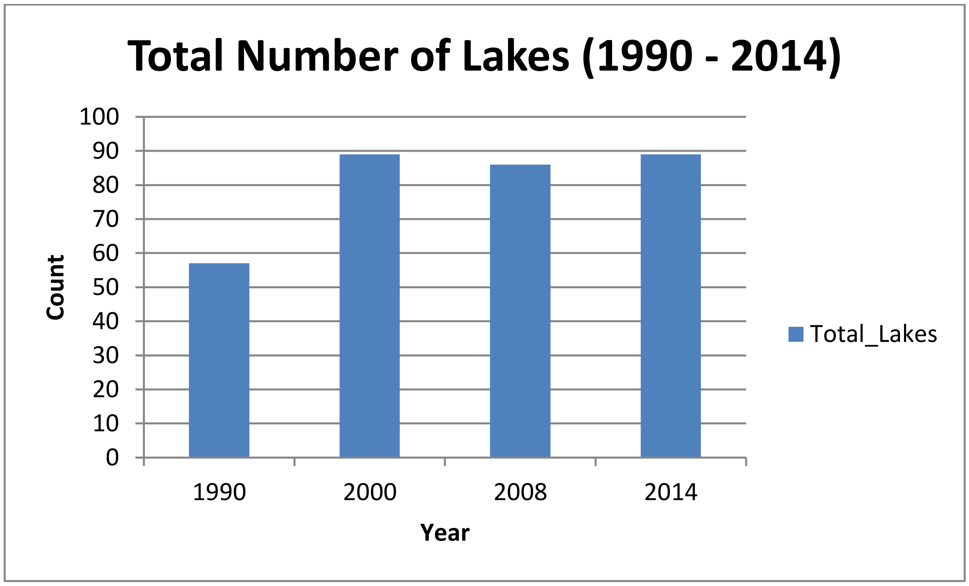


Figure: 3.3 Total Numbers of Lakes (1990-2014)

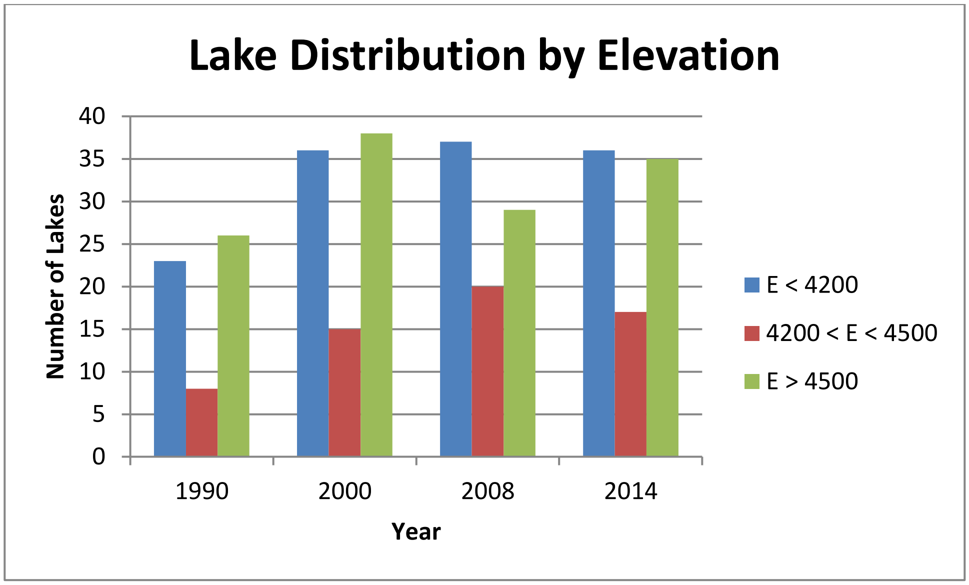


Figure: 3.4 (a) Distribution of Lakes by Elevation (year wise)

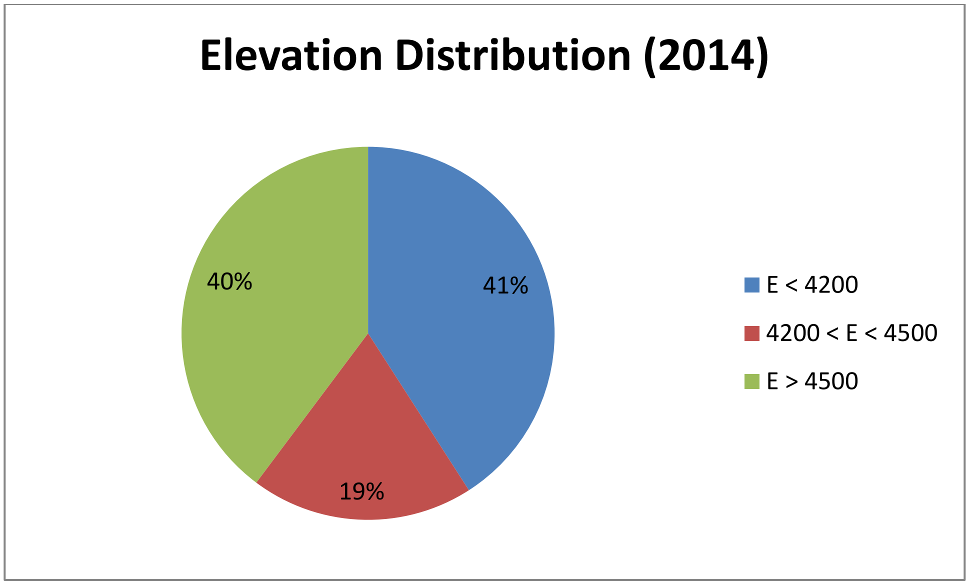


Figure: 3.4 (b) Distribution of Lakes by Elevation in 2014

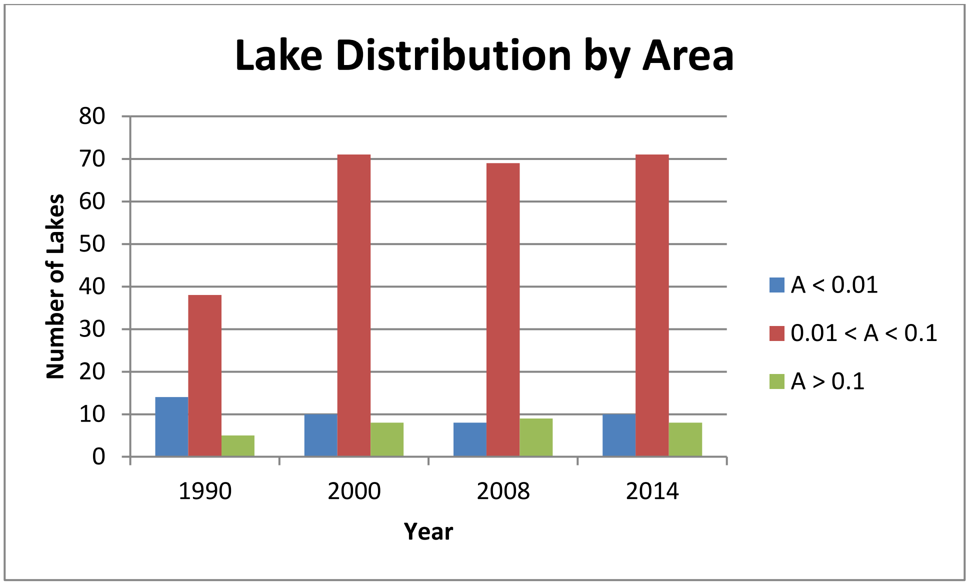


Figure: 3.5 (a) Distribution of Lakes by Area (year wise)

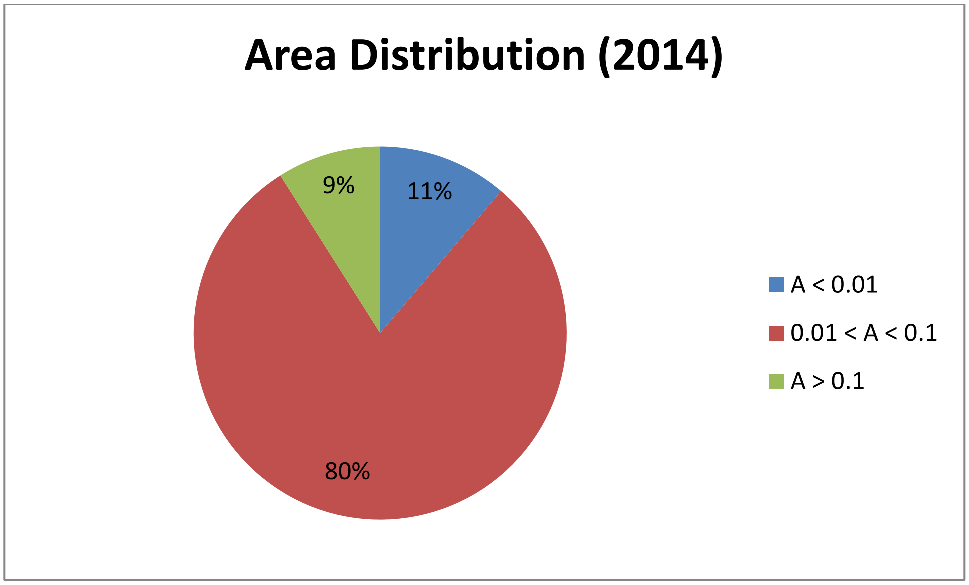


Figure: 3.5 (b) Distribution of Lakes by Area in 2014

3.6 Result and Discussion

Table 3.4 Areas (sq. km.) of Lakes and Rate of Change Per Year

		1990	2000	2008	2014	2016	2018					
								1990-2000	2000-2008	2008-2014	2014-2016	2016-2018
	PD Lake1	0.5112	0.5221	0.5980	0.8128	0.9028	0.9192	0.001	0.01	0.035	0.01125	0.01
	PD Lake2	1.0356	1.0738	1.0085	1.2151	1.3078	1.3384	0.003	-0.0075	0.035	0.0225	0.015

Table 3.1 provides a comprehensive analysis of the rates of change per year (Aa-1) for two potentially hazardous lakes spanning nearly three decades, from 1990 to 2018. These rates offer a detailed view of the annual fluctuations in the surface area (A) of the lakes, providing valuable insights into their dynamic behaviour over time. Understanding these fluctuations is crucial for monitoring and understanding the potential risks associated with these water bodies.

For Potentially Dangerous Lake 1, the rate of change in surface area from 1990 to 2000 is reported as 0.001 Aa-1. This relatively low rate suggests minimal expansion or contraction of the lake during this period. However, there is a notable increase in the rate of change to 0.01 Aa-1 from 2000 to 2008, indicating a significant growth in the lake's surface area during these years. This trend continues with a further rise to 0.035 Aa-1 from 2008 to 2014, suggesting accelerated expansion. Subsequent periods witness slight fluctuations, with rates ranging from 0.01125 Aa-1 (2014-2016) to 0.01 Aa-1 (2016-2018), indicating relatively stable conditions or minor changes in surface area during these years.

Similarly, Potentially Dangerous Lake 2 exhibits a comparable trend in surface area changes over the same period. The rate of change starts at 0.003 Aa-1 from 1990 to 2000, indicating modest expansion or contraction. However, there is a significant fluctuation in the rate to -0.0075 Aa-1 from 2000 to 2008, suggesting a decrease in surface area during this period. This is followed by a notable surge in the rate to 0.035 Aa-1 from 2008 to 2014, indicating rapid expansion. Subsequent periods see a decline in the rate to 0.0225 Aa-1 from 2014 to 2016 and further to 0.015 Aa-1 from 2016 to 2018, suggesting a slowdown in the expansion rate.

These figures provide invaluable insights into the changing dynamics of the lakes' surface areas, which are essential for monitoring and understanding the potential risks associated with these water bodies over time. By tracking these fluctuations, researchers and policymakers can better assess the evolving hazards posed by these lakes and develop appropriate mitigation strategies to safeguard surrounding communities and infrastructure.

The observed trends in surface area changes reflect the complex interplay of various factors, including glacier melt rates, precipitation patterns, and local geomorphology. Rapid glacier retreat and increased meltwater runoff can lead to the formation and expansion of glacial lakes, while changes in precipitation patterns and sedimentation rates can influence their size and stability. Additionally, geological factors such as tectonic activity and moraine composition can affect the stability of moraine-dammed lakes, potentially increasing the risk of outburst events.

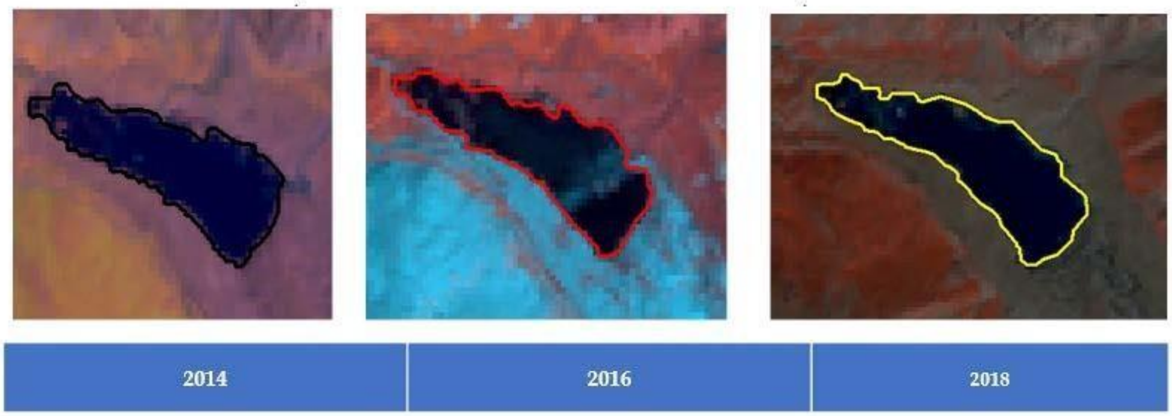


Figure 3.6 Chenab PD Lake 1 (Black 2014, Red 2016 and Yellow 2018)

Lake 1 has exhibited notable expansion in its surface area, as evidenced by measurements of 0.8128, 0.9028, and 0.9192 square kilometers in 2014, 2016, and 2018, respectively. This significant growth underscores the dynamic nature of the lake over time, indicating potential changes in its hydrological regime and environmental conditions. Furthermore, the rate of change per year for Lake 1 has shown variability across different periods. From 2008 to 2014, the rate stood at 0.035, reflecting a period of rapid expansion. However, this rate decreased to 0.01125 from 2014 to 2016, suggesting a slower growth rate during this interval. Subsequently, the rate stabilized at 0.01 from 2016 to 2018, indicating a period of relative stability in the lake's expansion. These fluctuations in the rate of change provide valuable insights into the evolving dynamics of Lake 1 and highlight the importance of continuous monitoring and adaptive management strategies to understand and address potential implications for water resource management and environmental conservation**.**

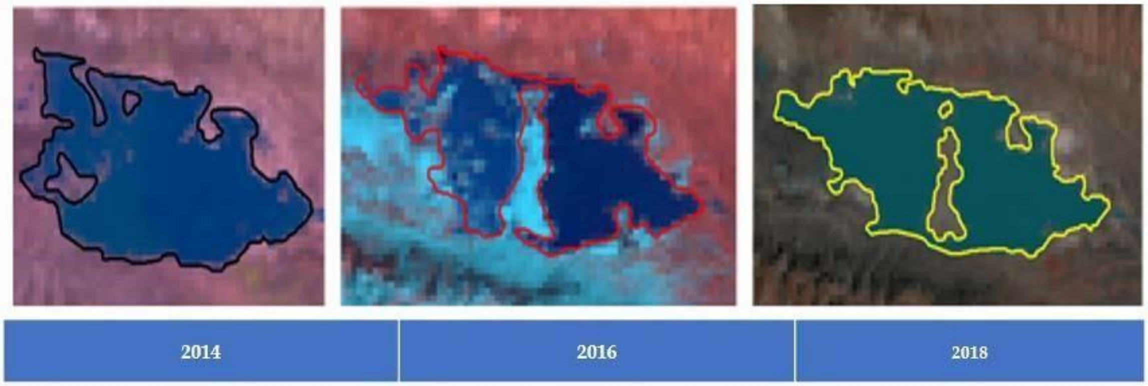


Figure 3.7 Chenab PD Lake 2 (note to scale) (Black 2014, Red 2016 and Yellow 2018)

Lake 2 has demonstrated significant expansion in its surface area, with measurements indicating growth from 1.2151 square kilometres in 2014 to 1.3384 square kilometres in 2018. This considerable increase underscores the dynamic nature of the lake over the specified period, suggesting potential changes in its hydrological regime and environmental conditions. Furthermore, the rate of change per year for Lake 2 exhibits a consistent pattern. From 2008 to 2014, the rate remained steady at 0.035, indicating a period of relatively rapid expansion. Subsequently, this rate decreased to 0.0225 from 2014 to 2016, reflecting a slower growth rate during this interval. Further decline was observed from 2016 to 2018, where the rate stabilized at

0.015. These consistent trends in the rate of change provide valuable insights into the evolving dynamics of Lake 2 and highlight the importance of continuous monitoring and adaptive management strategies to understand and address potential implications for water resource management and environmental conservation**.**

3.7 Conclusion

The positioning of lakes within glacier landscapes plays a critical role in assessing the potential hazards they pose. Glacial lakes, particularly those considered potentially dangerous, are often located in strategic areas within the glacier landscape. Typically, these lakes are situated in the lower part of the ablation area near the terminal moraine, where they are vulnerable to various environmental factors. Lakes positioned within 0.5 kilometers of sizable mother glaciers present heightened risks, especially if they exceed 0.1 square kilometers in size. Additionally, cirque lakes, smaller than 0.1 square kilometers and located near steep hanging glaciers, are also precarious due to their proximity to potential sources of instability. The condition of the dam is a crucial factor in determining the stability of moraine-dammed lakes. Dams with narrow crests, poor drainage systems, steep slopes, ice cores, and considerable height pose significant risks, especially when compounded by past breaches and seepage flows. Assessing both the dynamics of the lake itself and the condition of its dam provides valuable insights into the functioning of high-altitude lake ecosystems. The observed trends in the dynamics of Lake 1 and Lake 2 further underscore the complex interplay between environmental factors in glacier landscapes. Both lakes exhibited significant increases in surface area over time, indicative of dynamic changes in their hydrological regimes. Furthermore, variations in the annual rates of change highlight the dynamic nature of these ecosystems, with fluctuations likely influenced by factors such as glacier melt rates, precipitation patterns, and local geomorphology. These findings emphasize the importance of vigilant monitoring and proactive risk management strategies in glacier lake ecosystems. Continuous monitoring of glacial lakes and their associated dams is essential for early detection of potential hazards and timely implementation of mitigation measures. Proactive risk management strategies, such as regular dam inspections, early warning systems, and community preparedness programs, are crucial for safeguarding downstream communities and ecosystems from the potential impacts of glacial lake outburst events. Therefore, the stability of moraine-dammed lakes in glacier landscapes depends on various intrinsic factors related to the dam structure and external environmental conditions. Understanding these factors and their interplay is essential for effective risk assessment and management in glacier lake ecosystems. Through continuous monitoring, proactive risk management, and community engagement, stakeholders can work together to mitigate the risks posed by potentially dangerous glacial lakes and enhance the resilience of downstream communities and ecosystems to glacial lake outburst events.

CHAPTER 4

DAM BREACH MODEL

4.1 INTRODUCTION

A DAM breach, or Data Access Management breach, is a significant cybersecurity incident wherein unauthorized individuals or entities gain access to sensitive or confidential data stored within a digital asset management (DAM) system. DAM systems are designed to store, organize, and distribute digital assets such as images, videos, documents, and other media files. These systems are commonly used by organizations across various industries to manage their digital content efficiently. When a DAM breach occurs, it typically involves the compromise of the security measures put in place to protect the digital assets stored within the system. This breach can result from a variety of factors, including vulnerabilities in the DAM software, inadequate security protocols, insider threats, or targeted cyberattacks by malicious actors. The consequences of a DAM breach can be severe and far-reaching. Firstly, there is the risk of sensitive information falling into the wrong hands. This could include proprietary business data, intellectual property, customer information, or other confidential materials. If this data is exposed or stolen, it can lead to financial losses, reputational damage, and legal repercussions for the affected organization. Moreover, a DAM breach can also disrupt business operations and undermine trust in the organization's ability to safeguard data. Depending on the nature and extent of the breach, organizations may face downtime as they work to mitigate the damage, investigate the incident, and implement remediation measures. During this time, productivity may suffer, and customers, partners, and stakeholders may lose confidence in the organization's ability to protect their information. In addition to the immediate impacts, a DAM breach can have long-term consequences for an organization. It can erode customer loyalty and tarnish its reputation in the marketplace. Customers who have their personal information compromised may become wary of doing business with the organization in the future, leading to a loss of revenue and market share. Similarly, partners and suppliers may reconsider their relationships with the organization if they perceive it as a security risk. Furthermore, a DAM breach can trigger regulatory scrutiny and legal action. Many industries are subject to strict regulations governing the handling and protection of sensitive data, such as the General Data Protection Regulation (GDPR) in the European Union or the Health Insurance Portability and Accountability Act (HIPAA) in the United States. In the event of a breach, organizations may face fines, penalties, and lawsuits for non-compliance with these regulations, further compounding the financial and reputational damage. Preventing DAM breaches requires a multi-faceted approach to cybersecurity. Organizations must invest in robust security measures, including encryption, access controls, authentication mechanisms, and intrusion detection systems, to protect their DAM systems from unauthorized access. Regular security assessments and audits can help identify vulnerabilities and weaknesses that could be exploited by attackers. Employee training and awareness programs are essential for promoting a culture of cybersecurity within the organization. Employees should be educated about the risks of cyber threats, such as phishing attacks and social engineering tactics, and trained on best practices for safeguarding sensitive data. This includes proper password management, recognizing suspicious emails or messages, and reporting any security incidents promptly. Additionally, organizations should have a comprehensive incident response plan in place to effectively respond to and mitigate the impacts of a DAM breach should one occur. This plan should outline the steps to take in the event of a breach, including notifying affected parties, containing the damage, conducting forensic investigations, and restoring systems and data integrity. A DAM breach poses significant risks to organizations, including the exposure of sensitive data, disruption of business operations, and damage to reputation and trust. Preventing such breaches requires a proactive approach to cybersecurity, including robust security measures, employee training, and incident response planning. By prioritizing cybersecurity and implementing appropriate safeguards, organizations can reduce the likelihood of a DAM breach and minimize its impact if one occurs.

The concept of a "DAM Breach Model" typically refers to a predictive model or framework used to assess the potential impacts of a dam breach on surrounding ecosystems, communities, and infrastructure. Such models are essential tools for risk assessment, emergency preparedness, and disaster management, particularly in areas vulnerable to dam breaches, such as the mountain ecosystem of the Chenab Valley. The Chenab Valley, located in the Indianadministered union territory of Jammu and Kashmir, is characterized by its rugged terrain, steep slopes, and the presence of several dams and reservoirs. These dams play a crucial role in hydroelectric power generation, irrigation, and water supply for agriculture and domestic use. However, they also pose inherent risks, particularly in the event of a dam breach. A DAM breach in the mountain ecosystem of the Chenab Valley could have devastating consequences due to the high population density, presence of critical infrastructure, and ecological sensitivity of the region. Therefore, it is imperative to have a robust DAM Breach Model tailored to the unique characteristics of this ecosystem. Here's why:

1. **Risk Assessment**: A DAM Breach Model allows stakeholders to assess the potential risks associated with dam breaches in the Chenab Valley. By considering factors such as dam size, reservoir capacity, downstream population density, and topographical features, the model can quantify the likelihood and magnitude of different scenarios, ranging from minor leaks to catastrophic breaches.

2. **Emergency Preparedness**: Understanding the potential impacts of a dam breach enables authorities to develop comprehensive emergency preparedness plans. These plans can include evacuation procedures, disaster response protocols, communication strategies, and resource allocation strategies to mitigate the impacts on human lives, property, and the environment.

3. **Infrastructure Protection**: The Chenab Valley is home to critical infrastructure such as roads, bridges, power transmission lines, and agricultural facilities. A DAM Breach Model helps identify vulnerable infrastructure and prioritize measures to protect it from the effects of a dam breach. This could involve strengthening existing structures, relocating infrastructure out of flood-prone areas, or implementing early warning systems to alert authorities and residents.

4. **Environmental Impact Assessment**: Dam breaches can have significant ecological consequences, including habitat destruction, loss of biodiversity, soil erosion, and water contamination. By incorporating ecological data into the DAM Breach Model, stakeholders can assess the potential environmental impacts and develop mitigation measures to minimize harm to sensitive ecosystems and wildlife habitats.

5. **Community Resilience**: In mountainous regions like the Chenab Valley, communities are often isolated and vulnerable to natural disasters. A DAM Breach Model facilitates community engagement and empowerment by raising awareness about the risks of dam breaches and empowering residents to take proactive measures to enhance their resilience. This may include training in disaster preparedness, establishing community-based early warning systems, and fostering local partnerships for emergency response and recovery.

6. **Policy Development**: Effective risk management requires evidence-based policymaking informed by scientific data and analysis. A DAM Breach Model provides policymakers with the information they need to develop and implement regulations, standards, and guidelines for dam safety, land use planning, emergency response, and infrastructure development in the Chenab Valley and other vulnerable regions.

A DAM Breach Model is a vital tool for assessing and managing the risks associated with dam breaches in the mountain ecosystem of the Chenab Valley. By providing insights into the potential impacts on human lives, infrastructure, and the environment, this model enables stakeholders to develop proactive strategies for emergency preparedness, infrastructure protection, environmental conservation, community resilience, and policymaking. By integrating scientific data, stakeholder input, and local knowledge, the DAM Breach Model can help build a safer, more resilient future for the Chenab Valley and other vulnerable regions worldwide.

4.2 METHODOLOGY

Stage	Description
1. Literature Review	Review existing literature, research papers, and case studies related to dam breach modeling, hydrology, topography, risk assessment, and emergency management. Identify relevant methodologies, models, and data sources.
2. Stakeholder Engagement	Identify key stakeholders, including government agencies, dam operators, local communities, environmental organizations, and academic institutions. Conduct interviews, focus groups, surveys, and workshops to gather input on model objectives, parameters, assumptions, and data needs.
3. Data Collection	Compile relevant data sources, including topographic maps, hydrological data, dam specifications, reservoir characteristics, land use/land cover data, population demographics, infrastructure maps, and environmental datasets. Ensure data quality, accuracy, and compatibility.
4. Model Development	Develop a conceptual framework for the DAM Breach Model based on input from the literature review and stakeholder engagement. Select appropriate modeling techniques, such as hydraulic modeling, GIS-based analysis, statistical modeling, or agent-based modeling, depending on the research objectives and available data. Develop algorithms, equations, and computational procedures to simulate dam breach scenarios and assess potential impacts.
5. Calibration and Validation	Calibrate the model parameters using historical dam breach data or laboratory experiments. Validate the model outputs against observed dam breach events or benchmark datasets to ensure accuracy and reliability.
	Adjust model parameters as needed to improve performance and reduce uncertainty.

6. Scenario Analysis	Conduct scenario analysis to evaluate the potential impacts of dam breaches under different conditions, such as varying reservoir levels, dam failure modes, rainfall intensities, and land use scenarios. Assess the spatial extent of flooding, flood depths, evacuation routes, infrastructure damage, environmental consequences, and socioeconomic impacts for each scenario.
7. Sensitivity Analysis	Perform sensitivity analysis to identify the most influential parameters and factors affecting the model outputs. Evaluate the uncertainties associated with input data, model assumptions, and modeling techniques. Assess the robustness of the model and identify areas for further improvement or refinement.
8. Documentation and Reporting	Document the methodology, assumptions, data sources, and model algorithms in a comprehensive report or technical documentation. Present the findings, conclusions, and recommendations to stakeholders through technical reports, presentations, workshops, and peer-reviewed publications. Provide guidelines for model implementation, maintenance, and future research directions.

4.3 DIGITAL ELEVATION MODEL OF BASIN

A high-resolution Digital Elevation Model (DEM) of the basin surrounding a glacial lake is undeniably a cornerstone for accurately modeling flood dynamics, particularly in the context of Glacial Lake Outburst Floods (GLOFs). This digital representation of the terrain offers a wealth of essential information about the topography, including elevation, slope, aspect, and terrain roughness, all of which play integral roles in governing the behavior of floodwaters in mountainous regions. At the core of GLOF modelling efforts lies the utilization of advanced spatial analysis techniques to harness the wealth of information embedded within the DEM data. By leveraging sophisticated Geographic Information System (GIS) tools and hydraulic modeling software, researchers can simulate various aspects of flood dynamics, including flow paths, inundation extents, velocity distributions, and potential hazard zones. This analytical framework enables stakeholders to gain invaluable insights into the potential impacts of GLOF events and develop robust risk mitigation strategies to safeguard vulnerable communities and infrastructure. One of the primary functions of a high-resolution DEM in GLOF modeling is to provide detailed information about the topographic characteristics of the basin surrounding the glacial lake. Elevation data derived from the DEM allow researchers to accurately delineate the spatial extent of the watershed and identify key topographic features such as ridgelines, valleys, and drainage channels. This spatial context is essential for understanding the natural pathways that floodwaters are likely to follow as they cascade downstream from the glacial lake, guiding the development of realistic flood simulations. Furthermore, the DEM facilitates the computation of slope gradients across the basin, which exert a profound influence on the velocity and flow dynamics of floodwaters during a GLOF event. Steeper slopes generally result in faster flow velocities and more rapid flood propagation, while gentler slopes may attenuate the speed of floodwaters and influence the extent of inundation downstream. By integrating slope information derived from the DEM into hydraulic models, researchers can accurately predict the spatial distribution of flow velocities and assess the associated hazards posed by fast-moving floodwaters. In addition to slope analysis, the DEM provides valuable insights into terrain roughness, which refers to variations in surface elevation at a smaller scale. Terrain roughness influences flow resistance and channel morphology, thereby impacting the spatial distribution of floodwaters and the extent of inundation. High-resolution DEM data enable researchers to quantify terrain roughness parameters such as surface roughness coefficients or fractal dimensions, which can be incorporated into hydraulic models to refine predictions of flood flow patterns and inundation extents. Another critical application of the DEM in GLOF modelling is the simulation of flow paths and inundation extents using hydrological modelling techniques. By combining elevation data with information about precipitation, snowmelt, and glacier dynamics, researchers can simulate the generation and propagation of floodwaters through the basin, tracking their movement over time and space. Advanced spatial analysis techniques, such as hydrological modelling and hydraulic routing algorithms, enable the generation of predictive flood maps that depict the areas likely to be inundated during a GLOF event, along with estimates of flood depths and velocities. Furthermore, the DEM serves as a foundational dataset for the development of accurate hydraulic models that simulate the behaviour of floodwaters in complex terrain. By coupling the DEM with hydraulic equations governing fluid flow, researchers can generate detailed simulations of flood propagation, accounting for factors such as channel geometry, flow velocity, and sediment transport. These hydraulic models allow stakeholders to assess the potential impacts of GLOF events on infrastructure, agriculture, and ecosystems, facilitating informed decision-making and risk management strategies. The integration of high-resolution DEM data with advanced spatial analysis techniques has revolutionized the field of GLOF modelling, enabling researchers to conduct detailed assessments of flood hazards and vulnerabilities in mountainous regions. By leveraging the wealth of information embedded within the DEM, stakeholders can develop comprehensive flood risk maps, identify high-risk areas, and prioritize mitigation efforts to reduce the potential impacts of GLOF events.

Moreover, ongoing advancements in remote sensing technologies and spatial analysis methodologies continue to enhance the accuracy and precision of GLOF modeling, empowering communities to build resilience in the face of this increasingly significant natural hazard.

Breach Model Used The dam breach simulation in this study was carried out using the **Froehlich (1995) empirical breach model**, which is integrated within the HEC-RAS dam-breach analysis module. This approach is widely applied for simulating breaches of earthen and moraine-dammed lakes, making it appropriate for the glacial lakes identified in the Chenab Basin. The Froehlich model estimates breach parameters such as breach width, breach depth, and breach formation time based on the lake volume, water depth above the breach base, and the physical characteristics of the dam material. Its empirical formulation allows for a realistic representation of moraine dam failure under rapid drawdown conditions, which closely align with the expected mechanism of Glacial Lake Outburst Floods (GLOFs) considered in this study. The model's reliability and extensive use in high-mountain hazard studies support its suitability for simulating potential breach scenarios for Lake 1 and Lake 2.

4.4 CROSS-SECTION AT DOWN-STREAM OF LAKES

Cross-sectional profiles of river channels, meticulously measured at regular intervals downstream of a glacial lake, represent a crucial dataset in the realm of hydraulic modeling and flood propagation analysis, particularly concerning Glacial Lake Outburst Floods (GLOFs) [7]. These profiles offer invaluable insights into the intricate geometrical features of the river channel, including width, depth, cross-sectional area, and bed characteristics, all of which exert profound influences on flow dynamics and the behavior of floodwaters as they traverse downstream. The systematic acquisition of cross-sectional profiles along the length of the river downstream of the glacial lake is essential for capturing the spatial variability in channel morphology and hydraulic characteristics. By sampling the channel geometry at regular intervals, researchers can create detailed profiles that accurately depict the cross-sectional shape of the riverbed, banks, and water surface under various flow conditions. These profiles serve as foundational data for hydraulic modeling efforts aimed at simulating flood propagation and assessing the associated hazards posed by GLOF events. One of the primary functions of cross-sectional profiles in hydraulic modeling is to provide comprehensive information about channel geometry. By measuring parameters such as channel width, depth, and bank slope at each cross section, researchers can characterize the spatial variability in channel dimensions and identify key hydraulic features such as pools, riffles, and meanders. This detailed understanding of channel geometry is essential for accurately simulating flow dynamics and predicting the behavior of floodwaters as they interact with the riverbed and banks downstream of the glacial lake. Furthermore, cross-sectional profiles offer insights into the hydraulic roughness properties of the river channel, which play a critical role in governing flow resistance and energy dissipation. By assessing bed roughness characteristics such as grain size, bedforms, and vegetation cover, researchers can estimate the Manning's roughness coefficient, a key parameter in hydraulic models used to simulate flow velocities and shear stresses within the channel. Incorporating accurate roughness data derived from cross-sectional profiles enhances the fidelity of hydraulic simulations and improves the accuracy of flood forecasts and hazard assessments. In addition to channel geometry and roughness properties, cross-sectional profiles provide information about the vertical distribution of flow velocities and depths across the river channel. By measuring water surface elevations relative to the riverbed at multiple locations along each cross section, researchers can construct stage-discharge relationships that relate water levels to discharge rates under different flow conditions. These relationships serve as essential inputs for hydraulic models, enabling researchers to simulate flood propagation and estimate flood volumes and velocities at various points along the river downstream of the glacial lake. Moreover, cross-sectional profiles facilitate the identification of critical hydraulic control points such as constrictions, expansions, and hydraulic jumps, which can significantly influence flow dynamics and flood routing processes. Narrow sections of the river channel, for example, may act as hydraulic bottlenecks that increase flow velocities and elevate water levels during flood events, while wider sections may attenuate flow velocities and dissipate energy, reducing the risk of downstream inundation. By analyzing cross-sectional profiles in conjunction with hydraulic modeling techniques, researchers can identify these hydraulic features and assess their implications for flood hazard mitigation and risk management strategies. Furthermore, cross-sectional profiling enables researchers to monitor changes in channel morphology and hydraulic conditions over time, providing valuable insights into the dynamic nature of river systems in glacial environments. In regions where glacial retreat and sediment transport processes are prevalent, river channels may undergo significant adjustments in response to changes in sediment supply, flow regime, and channel incision. By periodically surveying cross-sectional profiles, researchers can track these morphological changes and assess their implications for flood hazards, channel stability, and ecosystem dynamics.

4.4.1 Cross-Section at Regular Interval to the Down-Stream of Lake- 1

To understand the significance of the given information, let's delve into the context of river morphology, particularly in relation to the river's longitudinal profile, cross-sectional analysis, and how variations in distance between cross sections can reflect changes in the river's slope. The longitudinal profile of a river represents its elevation gradient along its course from its source (in this case, the lake) to its outlet point. It provides valuable insights into the river's behaviour, including its energy state, erosional and depositional processes, and potential hazards such as rapids or waterfalls. The distance between cross sections refers to the spacing between points where measurements or observations are taken perpendicular to the river's flow. These cross sections are essential for understanding the river's morphology, hydraulic characteristics, and sediment transport dynamics. In this scenario, the total length from the lake to the outlet point is 273 km. This length encompasses the entire course of the river, from its origin at the lake to where it empties into another body of water or the sea. It serves as the baseline for analysing the river's longitudinal profile and cross-sectional variations. The variation in the distance between cross sections along the river's course is indicative of changes in the river's slope or gradient. At the inlet, where the river originates from the lake, the average distance between cross sections is 30 meters. This shorter spacing suggests steeper terrain or more pronounced changes in elevation, requiring closer monitoring and analysis to capture rapid variations in flow velocity, channel morphology, and sediment transport. As the river progresses downstream, away from the lake, the average distance between cross sections increases to 500 meters for the remaining length of the river. This wider spacing indicates gentler slopes or more gradual changes in elevation, allowing for less frequent measurements while still capturing essential characteristics of the river's morphology and behaviour. The transition from shorter to longer distances between cross sections reflects the evolving nature of the river as it meanders through different landscapes and geological formations. Factors such as topography, geology, climate, and human activities can influence the river's slope and, consequently, the spacing of cross sections along its course. In practical terms, the variation in distance between cross sections informs the design and implementation of monitoring and management strategies for river systems. Closer spacing near the inlet facilitates detailed assessments of the river's headwaters, where rapid changes in flow dynamics and channel morphology may pose risks to downstream areas. On the other hand, wider spacing downstream allows for efficient data collection while still capturing the overall behaviour of the river and identifying potential areas of concern, such as channel instability, sediment deposition, or floodplain inundation. The information provided about the variation in distance between cross sections along the river's course offers valuable insights into the spatial and temporal dynamics of river systems. It underscores the importance of considering longitudinal profiles and cross-sectional variations in understanding and managing rivers for sustainable use and conservation.

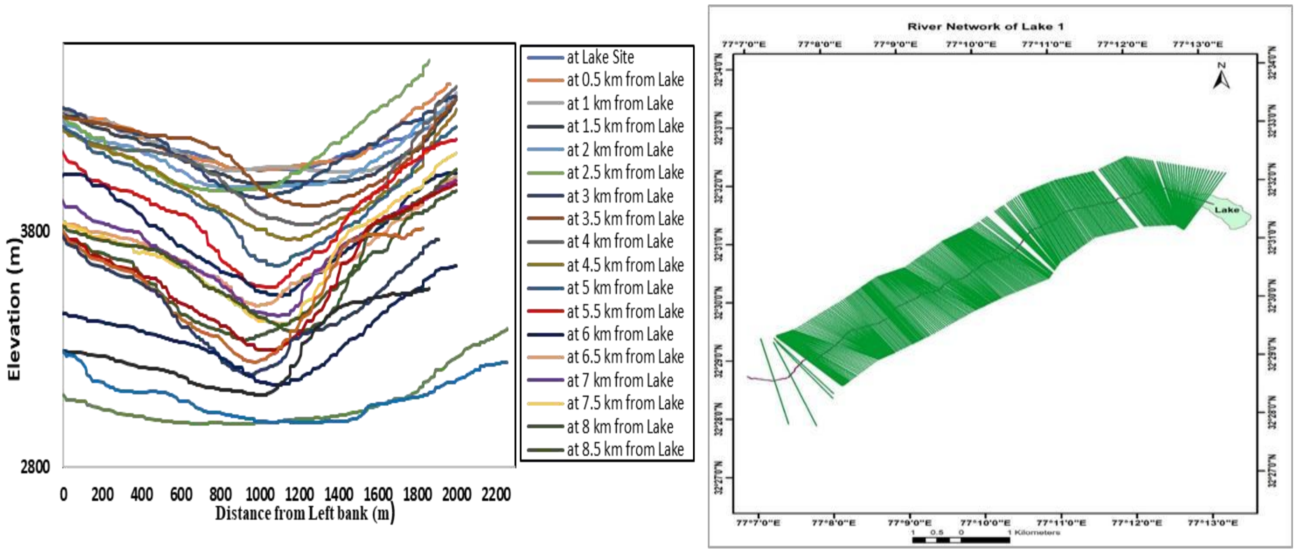


Figure 4.1 Cross Section Layout of Lake 1

4.4.2 Cross-Section at Regular Interval to the Down-Stream of Lake- 2

Understanding the dynamics of a river system requires a comprehensive analysis of its longitudinal profile, cross-sectional variations, and the relationship between these factors and the river's slope. The provided information pertains to a river originating from Lake 2 and flowing downstream to its outlet point, covering a total distance of 343 kilometres. This information offers valuable insights into the spatial characteristics of the river and the variations in cross-sectional spacing along its course. The longitudinal profile of a river represents its elevation gradient from its source to its outlet point. It provides crucial information about the river's energy state, erosional and depositional processes, and potential hazards such as rapids or waterfalls. In this context, the total length of the river from Lake 2 to the outlet point is 343 kilometres. This length serves as the baseline for analysing the river's longitudinal profile and understanding its behaviour over its entire course. The distance between cross sections refers to the spacing between points where measurements or observations are taken perpendicular to the river's flow. These cross sections are essential for analysing the river's morphology, hydraulic characteristics, and sediment transport dynamics. In the case of Lake 2, the spacing between cross sections varies based on the slope of the river.

At the inlet, or the point where the river originates from Lake 2, the average distance between cross sections is 500 meters. This shorter spacing suggests steeper terrain or more pronounced changes in elevation near the lake's shoreline. Closer spacing of cross sections allows for detailed assessments of the river's headwaters, capturing rapid variations in flow velocity, channel morphology, and sediment transport dynamics. As the river progresses downstream from Lake 2, the average distance between cross sections increases to 1000 meters for the remaining length of the river. This wider spacing indicates gentler slopes or more gradual changes in elevation as the river flows away from the lake. Wider spacing between cross sections downstream allows for efficient data collection while still capturing essential characteristics of the river's morphology and behaviour. The transition from shorter to longer distances between cross sections reflects the changing dynamics of the river as it meanders through different landscapes and geological formations. Factors such as topography, geology, climate, and human activities influence the river's slope and, consequently, the spacing of cross sections along its course. Practically, the variation in the distance between cross sections informs the design and implementation of monitoring and management strategies for river systems. Closer spacing near the inlet facilitates detailed assessments of the river's headwaters, where rapid changes in flow dynamics and channel morphology may pose risks to downstream areas. Wider spacing downstream allows for efficient data collection while still capturing the overall behaviour of the river and identifying potential areas of concern, such as channel instability or floodplain inundation The provided information about the variation in crosssectional spacing along the river's course offers valuable insights into the spatial dynamics of the river system. It underscores the importance of considering longitudinal profiles and crosssectional variations in understanding and managing rivers for sustainable use and conservation, highlighting the intricate relationship between slope, cross-sectional spacing, and river behaviour.

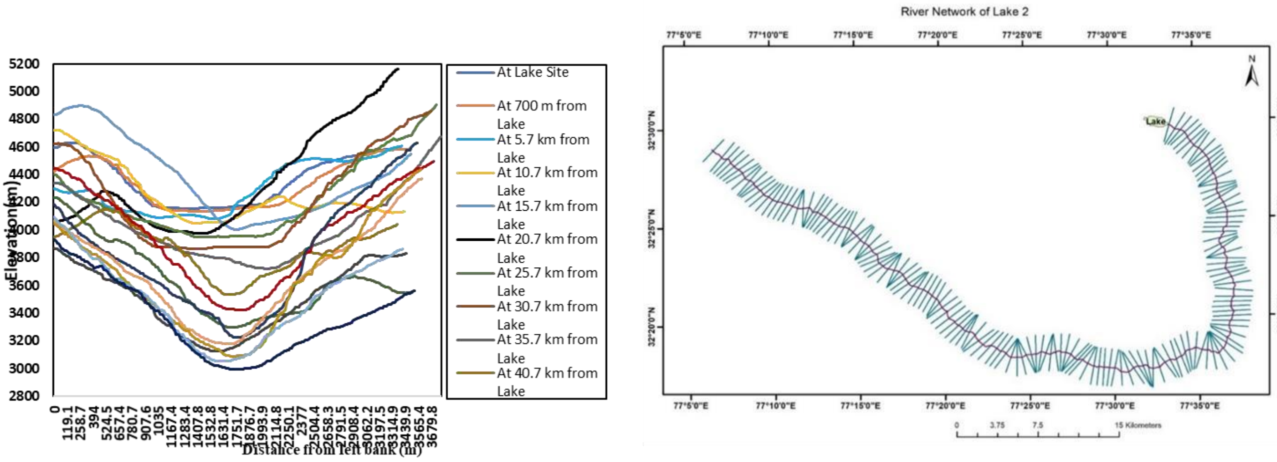


Figure 4.2 Cross Section Layout for Lake 2

Lake Volume Estimation

The volume of each glacial lake was estimated using a **Digital Elevation Model (DEM)–based elevation–area integration method**. Initially, the lake boundary was delineated using satellite imagery, after which elevation contours were extracted from the DEM. The area of the lake at successive elevation intervals was calculated, and the change in volume between two adjacent contours was obtained by multiplying the contour interval with the average of the two corresponding surface areas. This contour-based volumetric integration method is consistent with standard hydrological and glaciological practice, allowing an accurate approximation of total lake storage. The resulting volume estimates serve as critical input parameters for the dam breach simulation, influencing computed breach discharge and peak flood magnitude.

Estimation of Breach Width and Breach Depth

The breach width and breach depth for both lakes were estimated using **empirical equations provided by Froehlich (1995)** and implemented in HEC-RAS. These relationships calculate breach geometry as a function of lake volume, water depth above breach bottom, and dam material characteristics. The **breach width (B)** is computed empirically as:

$$B = 0.180 \cdot Q_p^{0.32} \cdot H^{0.19}$$

where $Q_p$is the peak breach discharge and $H$is the depth of water above the breach base. Similarly, the **breach formation time (t_f)** is determined using:

$$t_f = 0.00254 \cdot V_w^{0.53} \cdot H^{-0.90}$$

where V_w is the lake volume.

These physically meaningful empirical equations allow estimation of realistic breach geometries for moraine-dammed lakes, thereby providing more accurate peak discharge and hydrograph predictions for potential GLOF events.

4.5 AREA AND VOLUME OF LAKES

The precise estimation of a glacial lake's area and volume represents a fundamental aspect of assessing the potential magnitude and impact of a Glacial Lake Outburst Flood (GLOF) event.

Accurate measurement of the lake's extents and depths is essential for understanding its storage capacity, potential discharge rates, and the scale of potential inundation downstream. To achieve this, remote sensing techniques, including satellite imagery and Light Detection and Ranging (LiDAR) surveys, have emerged as invaluable tools for capturing detailed information about glacial lake dynamics and morphology. Satellite imagery, acquired through various sensors orbiting the Earth, offers a comprehensive view of glacial lakes and their surrounding environments with high spatial resolution. By analyzing multispectral and high-resolution optical imagery, researchers can delineate the boundaries of glacial lakes and accurately measure their surface areas. This process involves the identification of water bodies based on spectral signatures and the application of image processing techniques to extract lake extents from satellite imagery. Additionally, the use of Synthetic Aperture Radar (SAR) data allows for lake monitoring in all weather conditions and can provide valuable information on water surface dynamics, such as changes in water level and ice cover. Furthermore, LiDAR surveys, which involve the emission of laser pulses from an aircraft or satellite to measure surface elevation, offer unparalleled precision in capturing the three-dimensional structure of glacial landscapes, including the depth of glacial lakes. LiDAR data provide detailed elevation information with high vertical accuracy, allowing researchers to create highly accurate digital elevation models (DEMs) of the lake basin and its surroundings. By differencing pre- and postevent LiDAR data, researchers can quantify changes in lake volume over time, providing insights into lake dynamics and potential GLOF hazards. Once the area and volume of the glacial lake have been accurately estimated using remote sensing techniques, this data serves as crucial input parameters for hydrological models used to simulate GLOF events. Hydrological models, such as the Hydrological Engineering Centre’s River Analysis System (HEC-RAS) and the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model, rely on information about lake geometry and inflow characteristics to simulate the release of water during a GLOF event and predict downstream flood impacts. In hydrological modelling the estimated volume of water stored in the glacial lake serves as an initial condition for simulating the outburst scenario. By inputting the lake volume and specifying the breach characteristics (e.g., breach width, depth, and location), researchers can simulate the sudden release of water from the lake and track its propagation downstream. Hydrological models utilize principles of fluid dynamics to simulate the flow of water through the river network, accounting for factors such as channel geometry, flow resistance, and topographic features. The accurate estimation of the glacial lake's area and volume is essential for improving the reliability of GLOF simulations and enhancing the predictive capabilities of hydrological models. By incorporating precise lake geometry data into simulations, researchers can more accurately predict the magnitude, timing, and spatial extent of flood inundation downstream. This information is invaluable for assessing the potential impacts of GLOF events on downstream communities, infrastructure, and ecosystems and informing risk management and disaster preparedness efforts. Furthermore, remote sensing techniques offer the ability to monitor changes in glacial lake dynamics over time, providing insights into long-term trends in lake expansion, retreat, and stability. Repeat satellite imagery and LiDAR surveys allow researchers to track changes in lake area, volume, and water level, providing early warning of potential GLOF hazards and facilitating adaptive management strategies in vulnerable regions.

4.5.1. Area and Volume of Lake 1

Understanding the characteristics of a vulnerable lake, particularly its area and volume, is essential for assessing its ecological significance, potential risks, and management strategies. In this context, Lake 1 serves as a prime example, with its defined area and volume offering valuable insights into its dynamics and environmental implications. Lake 1 covers a total area of 0.9192 square kilometres (km^2). This measurement represents the surface extent of the lake, providing a quantitative understanding of its spatial footprint within its surrounding landscape. The area of the lake serves as a fundamental parameter for various analyses, including habitat assessment, hydrological modelling, and environmental impact studies. Beyond its surface area, Lake 1 also possesses a distinct volume, denoted as (V_{L1}), which measures 29,155.24 cubic meters (m^3). The volume of the lake represents the total amount of water it contains and plays a crucial role in understanding its hydrological dynamics, water balance, and ecological function. The volume measurement offers insights into the lake's capacity to store water, its seasonal variations in water level, and its contribution to downstream flow regimes. Analysing the relationship between the area and volume of Lake 1 provides valuable information about its depth characteristics and water retention capacity. By dividing the lake's volume by its area, one can calculate the average depth of the lake, representing the vertical dimension of its water column. This average depth serves as a key indicator of the lake's ecological health, as deeper lakes typically offer more habitat diversity and support a wider range of aquatic organisms. In addition to its intrinsic characteristics, the area and volume of Lake 1 also have broader implications for ecosystem services, human livelihoods, and environmental management. Lakes play critical roles in regulating local climates, supporting biodiversity, and providing ater resources for various purposes, including irrigation, drinking water supply, and recreational activities. Understanding the area and volume of vulnerable lakes like Lake 1 is therefore crucial for sustainable water resource management and conservation efforts. The vulnerability of Lake 1, as implied by its designation, underscores the importance of proactive measures to address potential risks and threats to its ecological integrity. Vulnerable lakes are often susceptible to various stressors, including pollution, habitat degradation, climate change, and anthropogenic activities. Monitoring and management strategies aimed at protecting vulnerable lakes typically involve a combination of regulatory measures, community engagement, and ecosystem restoration initiatives. For Lake 1 specifically, the area and volume measurements provide baseline data for assessing changes over time and evaluating the effectiveness of conservation interventions. Long-term monitoring programs can track fluctuations in the lake's water level, changes in its shoreline, and alterations in water quality parameters, providing valuable insights into ongoing trends and potential impacts. Furthermore, the area and volume of Lake 1 serve as inputs for hydrological modelling efforts aimed at predicting future scenarios and assessing the resilience of the lake to external pressures. By integrating spatial data, hydrological parameters, and environmental variables, researchers and resource managers can simulate different scenarios and evaluate the potential outcomes of management actions.

4.5.2 Area and Volume of Lake 2

Lake 2, with an area denoted as \(A_2\) of 1.3384 square kilometres (km^2) and a corresponding volume (V_{L2}) of 59,760.40 cubic meters (m^3), presents a distinct aquatic ecosystem with its own set of characteristics, implications, and management considerations. The area measurement of Lake 2, spanning 1.3384 km^2, delineates the surface extent of the lake within its surrounding landscape. This quantitative parameter serves as a fundamental descriptor of the lake's spatial footprint and provides essential information for various ecological, hydrological, and management analyses. Understanding the spatial extent of Lake 2 is crucial for assessing its ecological significance, habitat diversity, and potential impacts on surrounding ecosystems. Complementing its area, Lake 2 possesses a distinct volume, \(V_{L2}\), measuring 59,760.40 m^3. This volume represents the total amount of water contained within the lake and plays a pivotal role in shaping its hydrological dynamics, water balance, and ecological function. The volume measurement offers insights into the lake's capacity to store water, its seasonal variations in water level, and its contribution to downstream flow regimes.

Analysing the relationship between the area and volume of Lake 2 provides valuable information about its depth characteristics, water retention capacity, and hydrological resilience. By dividing the lake's volume by its area, one can calculate the average depth of the lake, offering insights into its vertical dimension and habitat suitability for aquatic organisms. In addition to its intrinsic characteristics, the area and volume of Lake 2 have broader implications for ecosystem services, human livelihoods, and environmental management. Lakes play critical roles in regulating local climates, supporting biodiversity, and providing water resources for various purposes, including irrigation, drinking water supply, and recreational activities. Understanding the area and volume of Lake 2 is therefore crucial for sustainable water resource management and conservation efforts. The vulnerability of Lake 2, as indicated by its designation, underscores the importance of proactive measures to address potential risks and threats to its ecological integrity. Vulnerable lakes are often susceptible to various stressors, including pollution, habitat degradation, climate change, and anthropogenic activities. Monitoring and management strategies aimed at protecting vulnerable lakes typically involve a combination of regulatory measures, community engagement, and ecosystem restoration initiatives. For Lake 2 specifically, the area and volume measurements serve as baseline data for assessing changes over time, evaluating the effectiveness of conservation interventions, and predicting future scenarios. Long-term monitoring programs can track fluctuations in the lake's water level, changes in shoreline morphology, and alterations in water quality parameters, providing valuable insights into ongoing trends and potential impacts. Furthermore, the area and volume of Lake 2 serve as inputs for hydrological modelling efforts aimed at stimulating different scenarios and assessing the resilience of the lake to external pressures. By integrating spatial data, hydrological parameters, and environmental variables, researchers and resource managers can develop informed management strategies to safeguard Lake 2 and promote its sustainable use for the benefit of both ecosystems and human communities.

4.6 Breach Width and Depth of Glacial Lakes

Glacial Lake Outburst Floods (GLOFs) are catastrophic events that occur when water stored in a glacial lake is suddenly released, leading to a rapid surge of water downstream. One crucial aspect influencing the magnitude and impact of a GLOF is the breach width, which refers to the size of the opening or breach through which the glacial lake water is discharged. Understanding the breach width is essential for assessing the potential hazards associated with GLOFs and implementing appropriate mitigation measures. The breach width plays a pivotal role in determining the rate at which water is released from the glacial lake and the volume of water that can be discharged during a GLOF event. A wider breach allows for a more rapid release of water, resulting in a higher flow velocity downstream. This increased flow velocity can lead to greater erosive power, causing more significant damage to infrastructure, vegetation, and landscapes in the path of the floodwaters. Additionally, a wider breach facilitates the release of a larger volume of water in a shorter period, exacerbating the intensity and extent of flooding downstream. Several factors influence the width of the breach and its evolution over time. One key factor is the type of dam or barrier that holds back the glacial lake water. Natural dams, such as moraines formed by glacial debris, often have irregular shapes and may exhibit varying degrees of stability. The breach width in such cases can be unpredictable and may change rapidly as the dam structure undergoes erosion or collapse. In contrast, artificial dams, such as those constructed for hydroelectric projects, may have more regular shapes and engineered features designed to control the release of water. The breach width in these cases may be more predictable but can still be influenced by factors such as dam design, materials, and maintenance. The size and morphology of the glacial lake also influence the breach width. Larger lakes tend to have larger breach widths due to the greater volume of water they contain and the potentially larger dam structures holding them back. Additionally, the shape of the lake basin and the topography surrounding it can affect the distribution of water pressure on the dam and influence the location and size of breaches that may form. Steeper slopes and deeper water may exert greater pressure on the dam, increasing the likelihood of larger breaches occurring. The geological and environmental conditions surrounding the glacial lake also play a role in determining the breach width. For example, the presence of weak or poorly consolidated materials in the dam structure can make it more susceptible to erosion and failure, leading to wider breaches. Similarly, the presence of permafrost or ice within the dam can influence its stability and contribute to changes in breach width over time. Climate factors such as temperature fluctuations, precipitation patterns, and glacier melt rates can also affect the stability of the dam and the likelihood of breaches occurring. The breach width is not a static parameter but can change dynamically over time in response to various factors. For example, the gradual melting of ice or permafrost within the dam structure can weaken its integrity, leading to the gradual widening of existing breaches or the formation of new ones. Similarly, changes in water levels within the glacial lake, such as those caused by glacier melt or precipitation events, can exert additional pressure on the dam and influence breach formation. Seismic activity or glacial surges may also trigger sudden changes in breach width by inducing dam collapse or other structural failures. Understanding the breach width is crucial for assessing the potential hazards posed by glacial lakes and developing effective mitigation strategies. Hydrological models and risk assessments can help estimate the potential magnitude and extent of flooding downstream based on factors such as breach width, lake volume, and topographical characteristics. Early warning systems can provide timely alerts to downstream communities in the event of a GLOF, allowing them to evacuate to safer areas and minimize the risk of loss of life and property.

4.6.1 Breach width and Depth of Glacial Lake-1

Lake 1 Depth (D_L1) is a crucial parameter in hydrological and environmental studies, providing insights into the characteristics and dynamics of the water body. This depth measurement, specified as 32.78 meters, offers valuable information about the volume, habitat, and ecological conditions of Lake 1, facilitating various scientific analyses and management efforts. Understanding the depth of Lake 1 is fundamental for assessing its hydrological characteristics and water storage capacity. The depth measurement indicates the vertical distance from the water surface to the lake bed, representing the volume of water contained within the lake basin. In hydrological studies, this information is essential for estimating water balance components such as inflow, outflow, and storage changes, aiding in water resource management and planning.

Lake depth also plays a crucial role in determining the lake's thermal structure and stratification patterns. The vertical distribution of temperature within the water column is influenced by factors such as solar radiation, air temperature, and water circulation. Deeper lakes like Lake 1 tend to exhibit distinct thermal layers, with warmer water near the surface and colder water at greater depths. This thermal stratification affects aquatic ecosystems, nutrient cycling, and the distribution of aquatic organisms. The depth of Lake 1 is a key factor in determining its ecological characteristics and habitat suitability for aquatic organisms. Deeper lakes typically offer a wider range of habitats and environmental conditions, accommodating diverse aquatic species. Different depth zones within the lake support various organisms adapted to specific temperature, light, and oxygen conditions. Understanding the depth distribution of habitats within Lake 1 is essential for assessing biodiversity, ecological health, and conservation priorities. Lake depth also influences water quality parameters such as light penetration, dissolved oxygen levels, and nutrient availability. In deeper lakes like Lake 1, light attenuation with depth limits the growth of aquatic plants and algae in the deeper regions, impacting primary productivity and ecosystem dynamics. Dissolved oxygen concentrations decrease with depth due to reduced surface exchange and microbial respiration, affecting the distribution of aerobic organisms and nutrient cycling processes. The depth of Lake 1 is a critical factor in assessing its vulnerability to various environmental stressors and anthropogenic impacts. Shallow lakes are more susceptible to eutrophication, sedimentation, and pollution, as they have smaller water volumes and shorter water residence times. Deeper lakes like Lake 1 may have greater resilience to certain disturbances but can still be affected by factors such as nutrient loading, habitat alteration, and invasive species introductions. The bathymetric mapping of Lake 1, which involves measuring and charting its depth contours, provides detailed information about the lake's morphology and subaqueous features. Bathymetric surveys help identify underwater topography, submerged structures, and habitat complexity, aiding in habitat mapping, navigation, and resource management. Accurate depth data enables the creation of bathymetric maps that are valuable tools for researchers, resource managers, and recreational users.

Lake depth measurements are essential for monitoring changes in water levels over time, which may occur due to natural processes such as precipitation, evaporation, and groundwater inflow, as well as human activities such as water extraction and dam operations. Long-term monitoring of Lake 1 depth provides valuable data for assessing hydrological trends, climate change impacts, and water availability for various uses such as irrigation, drinking water supply, and recreation.

4.6.2 Breach width and Depth of Glacial Lake-2

Lake 2 Depth (D_L2) is a significant parameter in hydrological and environmental studies, offering crucial insights into the characteristics and dynamics of the water body. With a measurement of 40.53 meters, Lake 2 depth provides valuable information about the volume, habitat, and ecological conditions of the lake, enabling various scientific analyses and management efforts. Understanding the depth of Lake 2 is fundamental for assessing its hydrological characteristics and water storage capacity. This depth measurement represents the vertical distance from the water surface to the lake bed, indicating the volume of water contained within the lake basin. In hydrological studies, this information is essential for estimating water balance components such as inflow, outflow, and storage changes, aiding in water resource management and planning. Lake depth also plays a crucial role in determining the lake's thermal structure and stratification patterns. The vertical distribution of temperature within the water column is influenced by factors such as solar radiation, air temperature, and water circulation. Deeper lakes like Lake 2 tend to exhibit distinct thermal layers, with warmer water near the surface and colder water at greater depths. This thermal stratification affects aquatic ecosystems, nutrient cycling, and the distribution of aquatic organisms. The depth of Lake 2 is a key factor in determining its ecological characteristics and habitat suitability for aquatic organisms. Deeper lakes typically offer a wider range of habitats and environmental conditions, accommodating diverse aquatic species. Different depth zones within the lake support various organisms adapted to specific temperature, light, and oxygen conditions. Understanding the depth distribution of habitats within Lake 2 is essential for assessing biodiversity, ecological health, and conservation priorities.

Lake depth also influences water quality parameters such as light penetration, dissolved oxygen levels, and nutrient availability. In deeper lakes like Lake 2, light attenuation with depth limits the growth of aquatic plants and algae in the deeper regions, impacting primary productivity and ecosystem dynamics. Dissolved oxygen concentrations decrease with depth due to reduced surface exchange and microbial respiration, affecting the distribution of aerobic organisms and nutrient cycling processes. The depth of Lake 2 is a critical factor in assessing its vulnerability to various environmental stressors and anthropogenic impacts. Shallow lakes are more susceptible to eutrophication, sedimentation, and pollution, as they have smaller water volumes and shorter water residence times. Deeper lakes like Lake 2 may have greater resilience to certain disturbances but can still be affected by factors such as nutrient loading, habitat alteration, and invasive species introductions. The bathymetric mapping of Lake 2, which involves measuring and charting its depth contours, provides detailed information about the lake's morphology and subaqueous features. Bathymetric surveys help identify underwater topography, submerged structures, and habitat complexity, aiding in habitat mapping, navigation, and resource management. Accurate depth data enables the creation of bathymetric maps that are valuable tools for researchers, resource managers, and recreational users. Lake depth measurements are essential for monitoring changes in water levels over time, which may occur due to natural processes such as precipitation, evaporation, and groundwater inflow, as well as human activities such as water extraction and dam operations. Long-term monitoring of Lake 2 depth provides valuable data for assessing hydrological trends, climate change impacts, and water availability for various uses such as irrigation, drinking water supply, and recreation.

4.7 DAM Breach Model

A dam breach model is a computational tool used to simulate the breach process and resulting flood hydrograph when a dam fails or breaches. It is a critical component of dam safety and risk assessment, providing valuable insights into the potential impacts of dam failures on downstream areas. In this discussion, we will delve into the components, principles, and applications of dam breach models.

4.7.1. Components of a Dam Breach Model:

A typical dam breach model consists of several key components:

a. **Geometry**: This includes the physical characteristics of the dam, such as height, crest width, downstream slope, and reservoir storage capacity. These parameters define the initial conditions of the breach process.

b. **Breach Parameters**: These parameters describe the breach geometry, including breach width, depth, and shape. They influence the rate and extent of water release during the breach process.

c. **Hydrological Inputs**: These inputs include rainfall, snowmelt, or other inflows into the reservoir. They drive the hydrological processes leading to dam failure, such as overtopping or piping.

d. **Hydraulic Properties**: These properties define the flow characteristics of the breach, including Manning's roughness coefficient, conveyance capacity, and flow resistance.

e. **Downstream Topography**: This includes the topographic profile of the downstream area, which affects the propagation and inundation of floodwaters following the dam breach.

f. **Computational Algorithm**: The model utilizes mathematical equations, numerical methods, or computational algorithms to simulate the breach process and predict the resulting flood hydrograph.

4.7.2. Principles of Dam Breach Modelling:

Dam breach modelling is based on hydraulic and hydrological principles, including:

a. **Continuity Equation**: The model applies the principle of conservation of mass, known as the continuity equation, to simulate the flow of water through the breach opening. This equation relates the rate of change of water volume to the inflows, outflows, and storage changes within the reservoir.

b. **Energy Equation**: The model considers the energy balance of the flowing water, accounting for changes in kinetic energy, potential energy, and friction losses as water flows through the breach and downstream channels.

c. **Flow Resistance**: The model incorporates parameters that quantify the resistance to flow, such as Manning's roughness coefficient or the Weir equation for open-channel flow, to simulate the hydraulic behavior of water as it exits the breach and propagates downstream.

d. **Breach Formation**: The model may include empirical or mechanistic approaches to simulate the breach formation process, considering factors such as erosion, scour, piping, or structural failure of the dam.

4.7.3. Applications of Dam Breach Models:

Dam breach models have diverse applications in dam safety, risk assessment, emergency planning, and flood management:

a. **Dam Safety**: Engineers use dam breach models to assess the structural integrity of dams and identify potential failure modes and failure scenarios. By simulating various breach scenarios, they can evaluate the likelihood and consequences of dam failures and prioritize risk reduction measures.

b. **Emergency Planning**: Dam breach models support emergency preparedness and response efforts by providing early warning systems, evacuation planning, and flood inundation mapping. By predicting the timing, extent, and severity of downstream flooding, authorities can implement timely evacuation orders and deploy resources effectively.

c. **Risk Assessment**: Dam breach models are integral to quantitative risk assessment methodologies, such as Probable Maximum Flood (PMF) analysis and dam safety risk analysis. These models help quantify the potential loss of life, property damage, economic impacts, and environmental consequences associated with dam failures.

d. **Land Use Planning**: Urban planners and land use managers utilize dam breach models to inform land development decisions, zoning regulations, and infrastructure design standards in flood-prone areas. By incorporating flood risk assessments into land use planning, they can mitigate the exposure of communities and infrastructure to dam failure hazards.

e. **Climate Change Adaptation**: With the increasing frequency and intensity of extreme weather events due to climate change, dam breach models play a vital role in assessing the resilience of dams to changing hydrological conditions. Engineers use these models to evaluate the adequacy of existing dams and design new dams with climate change considerations.

4.8 HEC-RAS Model

HEC-RAS is an integrated, open-source system of software that has been designed to use in a multi-tasking environment and is frequently applied to carry out glacial hazard studies. It is a user-friendly reliable model that has the dynamic capability of performing complex flow simulations in design, management and operation of river systems. The model is based on one-dimensional St. Venant equations that are used to simulate flood scenarios generated by Glacial Lake outburst. In the present study, we have used the 2-D hydrodynamic model i,e Hydrologic Engineering Centres River Analysis System (HEC-RAS) version 5.3.1 to simulate the GLOF event in the basin.

CAPABILITIES OF HEC-RAS

HEC-RAS can perform one-dimensional and two-dimensional river analysis. The main capabilities of HEC-RAS are:

1. Steady flow water surface profile computations
2. One Dimensional and Two-Dimensional Unsteady flow simulation
3. Moveable boundary sediment transport computations
4. Water quality analysis
5. RAS Mapper

Steady flow water surface profile computations

This component of the modelling system is intended for calculating water surface profiles for steady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modelling subcritical, supercritical, and mixed flow regimes water surface profiles.

One-Dimensional and Two-Dimensional Unsteady flow simulation

This component of the HEC-RAS modelling system can simulate one-dimensional; two-dimensional; and combined one/two-dimensional unsteady flow through a full network of open channels, floodplains, and alluvial fans. The unsteady flow component can be used to perform subcritical, supercritical, and mixed flow regimes (subcritical, supercritical, hydraulic jumps, and drawdowns) calculations in the unsteady flow computations module.

Moveable boundary sediment transport computations

This component of the modeling system is intended for the simulation of one-dimensional sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods.

Water quality analysis

This component of the modeling system is intended to allow the user to perform riverine water quality analyses. An advection-dispersion module is included within HEC–RAS, adding the capability to model water temperature.

RAS Mapper

HEC-RAS has the capability to perform inundation mapping of water surface profile results directly from HEC-RAS. Using the HEC-RAS geometry and computed water surface profiles, inundation depth and floodplain boundary datasets are created through the RAS Mapper.

4.9 Risk & Uncertainty Analysis

There are number of uncertainties in Glacial Lake Outburst Flood (GLOF) modelling and it is a critical issue because GLOFs are complex, and data-scarce events. The uncertainty propagates from lake characterization to breach modelling and downstream flood routing. As such no uncertainty analysis has been carried in the present work. Data related uncertainties are associated with resolution and accuracy of DEM. Computation of volume and depth etc. have been carried out using existing relationships, no actual measurements have been carried out. Other Uncertainty sources are Manning’s roughness coefficient, Sediment load effects, Channel geometry changes during flood and Debris flow transformation GLOFs often transition from clear-water flood to debris flow, which standard hydraulic models may not fully simulate.

4.10 GLOF Hydrograph at Outlet from Lake 1

The table outlines crucial parameters concerning Bridge 1 and its relationship with a nearby lake or water body. Bridge 1 is positioned approximately 11.224 kilometers away from the referenced lake, a distance pivotal for assessing potential flooding impacts on the bridge structure. The data reveals a maximum water depth of 4.61 meters near Bridge 1, indicating the depth of water the bridge may encounter during flood events. Additionally, a maximum water flow velocity of 5.63 meters per second highlights the force exerted by water on the bridge, influencing its structural integrity. The highest Water Surface Elevation (WSE) relative to Mean Sea Level (msl) reaches 3085.61 meters, indicating the peak water level during floods and aiding in flood risk assessment. Furthermore, the table indicates that it takes approximately 51.43 minutes for the flood peak to reach Bridge 1, crucial information for emergency response planning and flood management. Collectively, these insights enable informed decision-making regarding infrastructure resilience and risk mitigation strategies for Bridge 1 in the face of water-related hazards.

Table 4.1 Hydological Parameters of Vulnerable Location Due to GLOF at Lake 1

S No.	Bridge ID	Distance from lake (km)	Depth Maximum (m)	Velocity Maximum(m/s)	WSE Maximum (msl)	Flood Peak Arrival Time (H)
1	Bridge 1	11.224	4.61	5.63	3085.61	0.85714

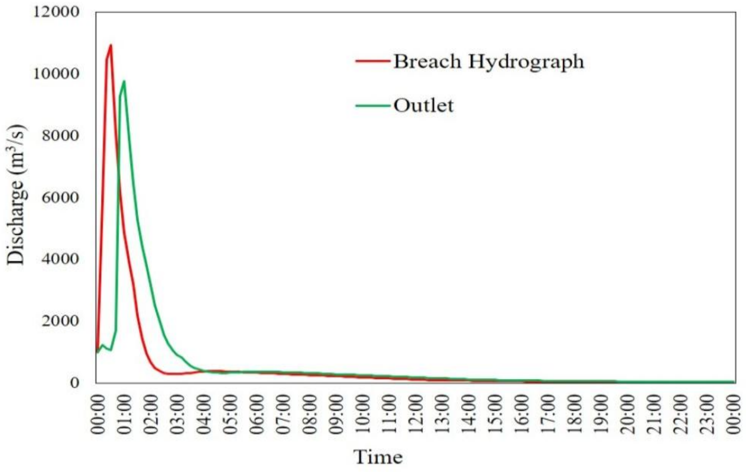


Figure 4.3 GLOF Hydograph at Outlate From Lake 1

4.11 GLOF Hydrograph at Outlet from Lake 2

The table outlines key characteristics of several bridges (Bridge 1 to Bridge 7) concerning their proximity to a nearby lake or water body. Each bridge is identified by a unique ID, with corresponding data detailing their distance from the lake, maximum water depth, maximum flow velocity, maximum Water Surface Elevation (WSE) relative to Mean Sea Level (msl), and flood peak arrival time. Distances from the lake vary across the bridges, with Bridge 1 being the closest at 18.614 km and Bridge 7 the farthest at 80.601 km. Maximum water depths range from 8.17 meters for Bridge 1 to 29.85 meters for Bridge 3, indicating differing flood risk levels. Similarly, maximum flow velocities vary, with Bridge 3 experiencing the lowest at 1.54 m/s and Bridges 1 and 5 encountering the highest at 3.51 m/s. WSE Maximum values range from 3008.80 m for Bridge 7 to 4013.17 m for Bridge 1, highlighting peak water levels during flooding events. Flood peak arrival times range from 1.821 hours for Bridge 1 to 5.224 hours for Bridge 7. This data collectively provides valuable insights into the susceptibility of each bridge to water-related hazards, aiding in infrastructure planning and emergency response strategies.

Table 4.2 Hydological Parameters of Vulnerable Locations Due to GLOF at Lake 2

S No.	Bridge ID	Distance from lake (km)	Depth Maximum (m)	Velocity Maximum(m/s)	WSE Maximum (msl)	Flood Peak Arrival Time (H)
1	Bridge 1	18.614	8.17	3.51	4013.17	1.821
2	Bridge 2	51.062	24.87	1.57	3324.87	3.504
3	Bridge 3	51.089	29.85	1.54	3324.85	3.509
4	Bridge 4	68.423	9.23	3.38	3117.23	4.458
5	Bridge 5	68.501	9.87	3.51	3116.87	4.468
6	Bridge 6	75.838	20.06	2.32	3070.06	5.018
7	Bridge 7	80.601	10.8	3.09	3008.80	5.224

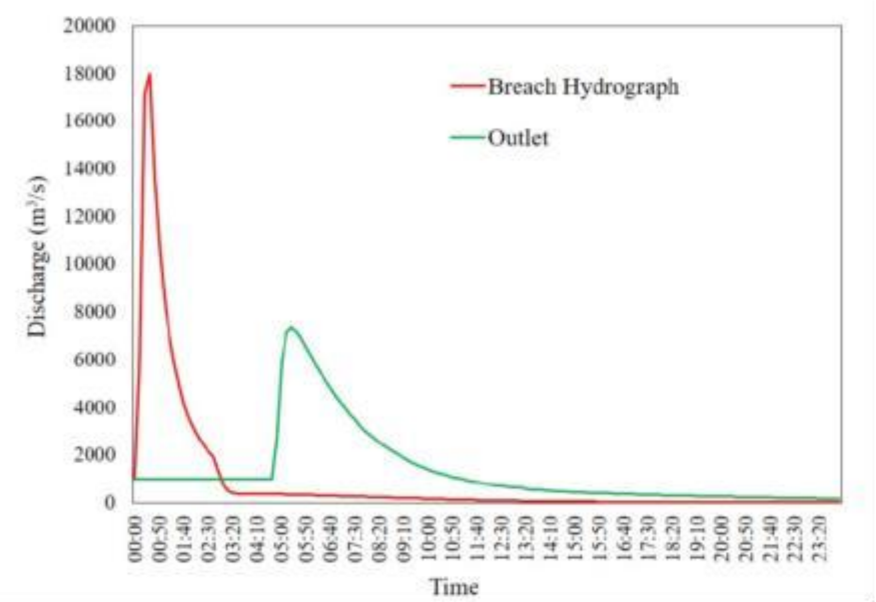


Figure 4.4 GLOF Hydograph at Outlate From Lake 2

Interpretation of Hydrograph Results

The hydrographs generated at the outlets of Lake 1 and Lake 2 represent the temporal variation of discharge following a modeled breach event. For **Lake 1**, the peak discharge was approximately **9,751 m³/s**, occurring shortly after breach initiation due to the relatively smaller lake volume and steeper downstream gradient. This results in a rapid flood wave with a short travel time of **about 1 hour 10 minutes** to the nearest vulnerable settlement. For **Lake 2**, the peak discharge at the outlet was approximately **7,332 m³/s**, reflecting a different breach geometry and larger storage volume. Despite a slightly lower peak discharge, the travel time to downstream vulnerable locations was significantly longer, approximately **5 hours 20 minutes**, indicating a larger catchment influence and greater floodplain propagation distance.

The hydrograph shapes for both lakes exhibit a characteristic sharp rise due to sudden moraine dam failure, followed by a rapid recession as the lake volume drains. These results demonstrate the substantial destructive potential of both lakes, with Lake 1 posing a more immediate hazard and Lake 2 posing a broader, more prolonged downstream risk. The findings underscore the necessity for site-specific early warning systems, evacuation planning, and continuous monitoring of lake evolution.

4.12 Limitations and Findings

The glacial lake outburst flow modelling process is nothing but an approximation of a physical phenomenon through which the physical phenomenon and its effects can be studied for water resource structure design and flood management. In GLOF modelling, assumptions are mainly associated with the breach parameters, especially breach width and depth, which impact flood peak and arrival times. Due to lack of bathymetric information, the volume and depth of the lake has been estimated using available formula, which may lead to different peak discharges. Errors in Digital Elevation Model, especially in the channel region will affect the hydrodynamics of the flood wave. Although the major errors were corrected manually, but few minor terrain errors may have still been neglected due to practical reasons. Dam breach parameters are estimated using Froehlich's regression equations and FERC rather than in-situ observational based data. There are uncertainties associated with regression-based dam breach parameters.

The high velocity of GLOF can cause significant scour of channels associated with the bed and bank erosion. Change in the channel cross-section due to GLOF is neglected due to limitations in modelling process. Generally, GLOF creates a large number of transported debris, and this may accumulate at constricted cross sections, where it acts as a temporary dam and partially or completely restricts the flow, resulting in variation in flood peak arrival time. This aspect has not been considered in the study due to the limitations of modelling such a complicated physical process. These limitations mainly affect the conservative side. Even with the assumptions and limitations outlined above, hydrodynamic modelling serves a very useful purpose, as it provides a reasonable estimate of glacial lake outburst flood.

4.13 Conclusion

In conclusion, the development of a DAM Breach Model is paramount for assessing and mitigating the risks associated with dam breaches, especially in regions like the mountain ecosystem of the Chenab Valley. The diverse range of stakeholders involved, including government agencies, dam operators, local communities, environmental organizations, and academic institutions, underscores the importance of collaborative efforts in research and implementation. Through extensive literature review, stakeholders' engagement, and meticulous data collection, the foundation for a robust DAM Breach Model is established. This model encompasses various parameters, including topography, hydrology, dam specifications, reservoir characteristics, population demographics, infrastructure mapping, and environmental datasets. The integration of these data sources ensures the accuracy, reliability, and comprehensiveness of the model outputs. The model development phase involves the selection of appropriate modeling techniques, such as hydraulic modeling, GIS-based analysis, statistical modeling, or agent-based modeling, depending on the research objectives and available data. The calibration and validation process further refine the model parameters, ensuring alignment with observed dam breach events or benchmark datasets. Sensitivity analysis identifies influential parameters and factors, addressing uncertainties and enhancing the model's robustness. Scenario analysis plays a crucial role in assessing the potential impacts of dam breaches under varying conditions, including reservoir levels, failure modes, rainfall intensities, and land use scenarios. By evaluating the spatial extent of flooding, flood depths, evacuation routes, infrastructure damage, environmental consequences, and socioeconomic impacts, stakeholders gain valuable insights for emergency preparedness and disaster management. The significance of the DAM Breach Model extends beyond its technical aspects, encompassing broader implications for policy development, community resilience, and environmental conservation. Evidence-based policymaking informed by scientific data and analysis is essential for enhancing dam safety, land use planning, emergency response, and infrastructure development in vulnerable regions like the Chenab Valley. Community engagement and empowerment are fundamental for fostering resilience and preparedness at the grassroots level. By raising awareness about dam breach risks and empowering residents to take proactive measures, such as disaster preparedness training and community-based early warning systems, stakeholders can build a more resilient society capable of responding effectively to emergencies. Furthermore, the DAM Breach Model provides valuable insights into environmental impacts, enabling stakeholders to develop mitigation measures that minimize harm to sensitive ecosystems and wildlife habitats. By integrating ecological considerations into dam safety assessments and emergency response plans, stakeholders can promote sustainable development and environmental stewardship in the Chenab Valley and similar regions worldwide. In conclusion, the development and implementation of a DAM Breach Model represent a critical step towards enhancing dam safety, emergency preparedness, and environmental resilience in the mountain ecosystem of the Chenab Valley. Through collaborative efforts, data-driven analysis, and stakeholder engagement, stakeholders can build a safer, more sustainable future for the region, mitigating the risks of dam breaches and safeguarding lives, property, and the environment for generations to come.

CHAPTER 5

IDENTIFICATION OF VULNERABLE LOCATIONS AND EARLY WARNING SYSTEM

5.1 INTRODUCTION

An Early Warning System (EWS) stands as a cornerstone in the realm of disaster management, offering a critical shield against the devastating impacts of natural calamities by furnishing timely alerts and actionable information to vulnerable communities and authorities. In the sphere of environmental hazards, including floods, landslides, and extreme weather events, the efficacy of an EWS hinges upon a sturdy foundation built upon robust data collection mechanisms, cutting-edge technology, and streamlined methodologies geared towards assessing risks and swiftly disseminating warnings. This section elucidates the pivotal role of key data sources and methodologies indispensable for crafting and implementing an Early Warning System tailored to address specific hazards and geographical regions. One pivotal aspect in the establishment of an effective EWS is the utilization of comprehensive data sources spanning various domains pertinent to hazard assessment and monitoring. Geological and geospatial datasets serve as fundamental building blocks, furnishing critical insights into the terrain characteristics, geological formations, and susceptibility to hazards such as landslides and earthquakes (Tharwat, 2020). Additionally, hydrological data encompassing river flow rates, precipitation patterns, and water levels in reservoirs and rivers are vital for assessing flood risks and issuing timely warnings (De Angeli et al., 2022). Moreover, meteorological data, including weather forecasts, satellite imagery, and climate models, play a pivotal role in predicting and monitoring extreme weather events such as hurricanes, cyclones, and severe storms (Abdel-Fattah, 2020). In tandem with data collection, the integration of advanced technologies stands as a linchpin in fortifying the efficacy of an EWS. Geographic Information Systems (GIS) facilitate the analysis and visualization of spatial data, enabling authorities to delineate hazard-prone areas, identify vulnerable populations, and optimize resource allocation for preparedness and response efforts (Bajracharya et al., 2007). Remote sensing technologies, encompassing satellite imagery and aerial surveys, offer invaluable insights into changes in land cover, vegetation dynamics, and environmental conditions, aiding in the early detection of potential hazards and the monitoring of ongoing events (Twigg, 2004). Furthermore, the advent of Artificial Intelligence (AI) and machine learning algorithms enables the automation of data analysis processes, enhancing the speed and accuracy of hazard assessments and warning generation (Sattar et al., 2019). Alongside data collection and technological advancements, the development of efficient methodologies is paramount in ensuring the effectiveness of an EWS. Multi-hazard frameworks, such as those integrating spatial-temporal impact analysis, enable a comprehensive understanding of the cascading effects of multiple hazards, thereby enhancing the resilience of communities to a spectrum of threats (Haemmig et al., 2014). Participatory approaches, involving the active engagement of local communities and stakeholders, foster ownership and empowerment, thereby enhancing the responsiveness and effectiveness of early warning dissemination and response mechanisms (Wamane, 2022). Additionally, the adoption of standardized classification assessment methods aids in streamlining the evaluation of warning messages, ensuring clarity, and consistency in communication to at-risk populations (UNDP, 2018). The establishment of an Early Warning System (EWS) tailored to mitigate the impacts of environmental hazards necessitates a multifaceted approach that draws upon a diverse array of resources and methodologies. At the core of such a system lies the need for robust data collection mechanisms, which serve as the foundation for assessing risks and issuing timely warnings to vulnerable communities and authorities. Geological and geospatial datasets, as highlighted by Abdel-Fattah (2020) and Tharwat (2020), play a pivotal role in this regard, providing crucial insights into terrain characteristics, geological formations, and susceptibility to hazards such as landslides and earthquakes. These datasets serve as fundamental building blocks upon which hazard assessments and risk evaluations are conducted, enabling authorities to identify high-risk areas and allocate resources for preparedness and response efforts effectively. In addition to geological and geospatial data, hydrological information assumes critical importance in the context of an EWS, particularly for assessing flood risks. Data pertaining to river flow rates, precipitation patterns, and water levels in reservoirs and rivers, as emphasized by De Angeli et al. (2022), provide essential inputs for forecasting and monitoring flood events. By analysing hydrological data, authorities can anticipate potential flood scenarios, issue early warnings, and implement mitigation measures to minimize the impact on communities and infrastructure. Meteorological data, encompassing weather forecasts, satellite imagery, and climate models, serve as another key component of an effective EWS. As highlighted by Abdel-Fattah (2020), meteorological information enables the prediction and monitoring of extreme weather events such as hurricanes, cyclones, and severe storms. By leveraging meteorological data, authorities can anticipate the onset of hazardous weather conditions, disseminate timely warnings to atrisk populations, and coordinate response efforts to mitigate the impacts of these events.

The integration of advanced technologies, including Geographic Information Systems (GIS) and remote sensing technologies, further enhances the capabilities of an EWS. GIS enables the analysis and visualization of spatial data, facilitating the identification of hazard-prone areas and the assessment of vulnerability and exposure. As outlined by Bajracharya et al. (2007), GIS-based approaches enable authorities to map hazard zones, delineate evacuation routes, and prioritize resources for disaster preparedness and response. Remote sensing technologies, such as satellite imagery and aerial surveys, provide valuable insights into changes in land cover, vegetation dynamics, and environmental conditions. These technologies enable the early detection of potential hazards and the monitoring of ongoing events, as noted by Twigg (2004), thereby enhancing the effectiveness of early warning systems. Furthermore, the advent of Artificial Intelligence (AI) and machine learning algorithms has revolutionized the field of hazard assessment and warning generation. As highlighted by Sattar et al. (2019), AI-powered algorithms enable the automation of data analysis processes, enhancing the speed and accuracy of hazard assessments and warning dissemination. By leveraging AI technologies, authorities can analyze vast amounts of data, identify patterns and trends, and generate actionable insights to support decision-making in disaster management. In addition to data collection and technological advancements, the development of efficient methodologies is paramount in ensuring the effectiveness of an EWS. Multi-hazard frameworks, such as those integrating spatial-temporal impact analysis, enable a comprehensive understanding of the cascading effects of multiple hazards, thereby enhancing the resilience of communities to a spectrum of threats, as outlined by Haemmig et al. (2014). Participatory approaches, involving the active engagement of local communities and stakeholders, foster ownership and empowerment, thereby enhancing the responsiveness and effectiveness of early warning dissemination and response mechanisms, as emphasized by Wamane (2022). Additionally, the adoption of standardized classification assessment methods aids in streamlining the evaluation of warning messages, ensuring clarity and consistency in communication to at-risk populations, as noted by UNDP (2018). To effectively establish an Early Warning System (EWS) aimed at mitigating the impacts of environmental hazards, it is imperative to adopt a multifaceted approach that integrates robust data collection, advanced technological solutions, and efficient methodologies. The successful implementation of such a system holds the potential to enhance the resilience of communities and reduce the adverse impacts of natural disasters.

One of the foundational pillars of an effective EWS is robust data collection. This entails gathering comprehensive data from various sources, including satellite imagery, ground-based sensors, and meteorological stations. These data sources provide valuable insights into environmental conditions, such as precipitation patterns, temperature fluctuations, and changes in land cover. Additionally, socioeconomic data, such as population density and infrastructure vulnerability, can inform risk assessments and help prioritize response efforts. By leveraging a wide range of data sources, authorities can obtain a comprehensive understanding of potential hazards and their impacts on communities. Advanced technological solutions play a pivotal role in enhancing the capabilities of an EWS. Cutting-edge technologies, such as remote sensing, geographic information systems (GIS), and machine learning algorithms, enable the analysis of vast amounts of data with unprecedented accuracy and efficiency. For example, remote sensing techniques allow for the monitoring of environmental changes over large spatial scales, facilitating early detection of potential hazards such as wildfires, floods, and landslides. GIS platforms provide a spatial framework for integrating diverse datasets and visualizing complex relationships between environmental factors and hazard risks. Machine learning algorithms can analyze historical data to identify patterns and trends, thereby improving the predictive capabilities of the EWS. By leveraging advanced technological solutions, authorities can enhance their ability to detect, monitor, and respond to environmental hazards in a timely manner. Efficient methodologies are essential for the effective operation of an EWS. This involves the development of standardized protocols for data collection, analysis, and dissemination of warnings. Clear communication channels and coordination mechanisms ensure that relevant stakeholders receive timely and accurate information during emergency situations. Moreover, regular training and capacity-building initiatives empower local communities to take proactive measures to mitigate risks and respond effectively to hazards. By implementing streamlined methodologies, authorities can improve the overall efficiency and effectiveness of the EWS, thereby reducing the vulnerability of communities to environmental disasters. The establishment of an Early Warning System tailored to mitigate the impacts of environmental hazards requires a holistic approach that integrates robust data collection, advanced technological solutions, and efficient methodologies. By leveraging comprehensive data sources, harnessing cutting-edge technologies, and employing streamlined methodologies, authorities can strengthen the resilience of communities and minimize the adverse impacts of natural disasters. With the increasing frequency and severity of environmental hazards, investing in a robust EWS is essential for protecting lives, livelihoods, and infrastructure in vulnerable areas. By harnessing comprehensive data sources, leveraging cutting-edge technologies, and employing streamlined methodologies, authorities can bolster the effectiveness of early warning systems, thereby enhancing the resilience of communities and minimizing the adverse impacts of natural disasters.

5.2 Methodology

1. **Hazard Assessment:**
    1. Comprehensive hazard assessment involves analyzing historical data, geological surveys, and remote sensing imagery to identify potential risks and vulnerabilities associated with specific hazards such as floods, landslides, or earthquakes.
    2. Geospatial data, including topographic maps, land use/land cover maps, and hydrological models, facilitate the delineation of hazard-prone areas and the estimation of potential impacts.
2. **Meteorological and Hydrological Data:**
    1. Real-time meteorological data from weather stations, satellite imagery, and radar systems provide critical information on precipitation patterns, temperature variations, and atmospheric conditions.
    2. Hydrological data, including river discharge measurements, water level sensors, and rainfall intensity data, enable the monitoring of hydrological processes and the prediction of flood events.
3. **Early Warning Algorithms and Models:**
    1. Advanced algorithms and predictive models integrate meteorological, hydrological, and geological data to forecast the onset, intensity, and duration of potential hazards.
    2. Statistical methods, machine learning algorithms, and numerical weather prediction models contribute to the development of accurate and reliable early warning systems.
4. **Communication and Dissemination:**
    1. Effective communication strategies and dissemination channels are essential for delivering timely warnings to vulnerable communities and stakeholders.

    2. Mobile phone alerts, sirens, radio broadcasts, and community-based networks enhance the reach and accessibility of early warning messages, particularly in remote or marginalized areas.

5. **Community Engagement and Capacity Building:**
    1. Community participation and stakeholder engagement are integral to the success of an Early Warning System, fostering awareness, preparedness, and resilience at the grassroots level.
    2. Capacity building initiatives, including training workshops, public awareness campaigns, and simulation exercises, empower communities to respond effectively to imminent threats and take proactive measures to safeguard lives and property.

5.3 Results

5.3.1 Vulnerable Locations

To effectively mitigate the risks associated with Glacial Lake Outburst Floods (GLOFs), it is essential to implement a comprehensive set of recommendations aimed at enhancing preparedness, awareness, and response capabilities. One of the primary strategies involves the implementation of an extensive awareness program targeting both the local community and trekkers frequenting the region. This program should aim to educate individuals about the potential hazards posed by GLOFs, as well as the appropriate response measures to be undertaken in the event of an emergency. By increasing awareness and knowledge among community members and trekkers, it is possible to empower them to take proactive steps to safeguard themselves and others during GLOF events. In addition to awareness-raising efforts, the establishment of an Early Warning System (EWS) represents a critical component of GLOF risk mitigation strategies. An effective EWS should incorporate various components, including monitoring systems, communication channels, and alert mechanisms, to ensure timely and accurate dissemination of warnings to at-risk populations. Alarms and notification systems should be deployed in key locations frequented by the local community, trekkers, and relevant authorities, enabling swift action in response to GLOF events. By providing early warnings, the EWS serves as a vital tool for facilitating evacuation and other preparedness measures, thereby minimizing the potential impact of GLOFs on human lives and infrastructure. Furthermore, it is imperative to establish designated Emergency Evacuation Sites strategically located within the affected region. These sites should be equipped with necessary facilities and resources to accommodate evacuees and provide temporary shelter during emergency situations. Collaboration with local authorities and stakeholders is essential to identify suitable locations for Emergency Evacuation Sites and ensure their effective operation and management. By proactively preparing Emergency Evacuation Sites, communities can streamline evacuation procedures and minimize the risk of casualties and injuries during GLOF events. Additionally, investing in infrastructure and structural measures aimed at reducing the vulnerability of communities to GLOFs is crucial. This may include the construction of protective barriers, embankments, or diversion channels to mitigate the impact of floodwaters and prevent damage to settlements and infrastructure. Moreover, implementing land-use planning and zoning regulations can help minimize the exposure of vulnerable areas to GLOF risks, thereby enhancing the resilience of communities and reducing potential losses. Capacitybuilding initiatives aimed at strengthening local response capabilities and enhancing disaster preparedness are also essential components of GLOF risk mitigation strategies. This may involve providing training and resources to community members, local authorities, and emergency responders on emergency response protocols, search and rescue techniques, and first aid procedures. By equipping individuals and organizations with the necessary skills and knowledge, communities can improve their ability to effectively respond to GLOF events and mitigate their impact on livelihoods and infrastructure. Furthermore, fostering collaboration and cooperation among stakeholders at the local, national, and international levels is essential for effective GLOF risk mitigation. This may involve establishing multi-stakeholder platforms, task forces, or committees to facilitate information sharing, coordination of resources, and joint decision-making processes. By fostering partnerships and alliances, stakeholders can leverage collective expertise and resources to develop and implement holistic GLOF risk mitigation strategies that address the diverse needs and priorities of affected communities. Finally, conducting regular monitoring, assessment, and review of GLOF risk mitigation measures is crucial to ensure their effectiveness and adaptability to changing conditions. This may involve ongoing data collection, analysis, and evaluation of GLOF hazards, vulnerabilities, and impacts, as well as periodic reviews of existing policies, plans, and strategies. By maintaining a proactive approach to risk management, communities can continuously enhance their resilience to GLOFs and other climate-related hazards, ultimately reducing the potential for loss of life and property in the face of future disasters.

5.3.1.1 Vulnerable Locations for Lake 1

Table 5.1. Vulnerable Location Due to GLOF of Lake 1

Tehsil Name	Lahul
District	Lahul And Spiti
State	Himachal Pradesh
Elevation	3189 meters Above Sea Level
Distance from Outlet	11.25 Km
Population	83 Persons
Response Time	60 minutes

Situated approximately 1.1 kilometres from the village, this designated site offers a strategic location for emergency response efforts in the event of a Glacial Lake Outburst Flood (GLOF) or other natural disasters. Positioned at a higher elevation compared to the village, the site serves as a crucial hub for coordinating swift and organized responses, potentially saving lives of both people and livestock. Its elevated position mitigates the risk of inundation during flooding events, providing a safer environment for residents and emergency responders to operate. The establishment of such a site represents a proactive measure aimed at enhancing community resilience and preparedness in vulnerable areas prone to GLOFs. By designating a specific location for emergency response activities, authorities can streamline evacuation procedures, coordinate rescue operations, and facilitate the distribution of relief supplies more effectively. Moreover, the site's proximity to the village ensures accessibility for residents, enabling prompt evacuation and assistance in times of crisis. In addition to the physical infrastructure of the emergency response site, it is essential to develop comprehensive evacuation plans and protocols to guide response efforts during emergencies. Regular evacuation drills play a vital role in familiarizing community members with evacuation procedures, emergency routes, and assembly points, thereby enhancing preparedness and effectiveness of response mechanisms. Through simulated evacuation exercises, residents can practice evacuating safely and efficiently, ensuring that they are well-prepared to respond to real-life emergencies.

Furthermore, the implementation of early warning systems and communication channels is critical for providing timely alerts and information to at-risk communities in the event of a GLOF or other natural disasters. Leveraging advanced technology and communication networks, authorities can disseminate warnings and evacuation instructions to residents, enabling them to take swift and appropriate action to protect themselves and their property. By enhancing access to timely information, early warning systems empower communities to make informed decisions and mitigate the potential impacts of disasters. Community engagement and participation are integral components of effective disaster risk reduction strategies. Engaging local residents in the planning, implementation, and evaluation of emergency preparedness initiatives fosters a sense of ownership and collective responsibility for disaster resilience. Community-based organizations, village leaders, and volunteer groups can play a vital role in raising awareness, mobilizing resources, and coordinating response efforts within the community. By harnessing the collective strength and resilience of local communities, authorities can enhance the overall effectiveness of disaster response and recovery efforts. Moreover, collaboration with relevant stakeholders, including government agencies, nongovernmental organizations, and international partners, is essential for strengthening disaster preparedness and response capabilities. Pooling resources, expertise, and knowledge from diverse stakeholders enables more comprehensive and coordinated approaches to disaster risk reduction. Joint planning, capacity-building initiatives, and resource-sharing mechanisms facilitate the development of robust and sustainable solutions to address the complex challenges posed by GLOFs and other natural hazards. Investing in the capacity-building of local authorities, emergency responders, and community volunteers is essential for enhancing disaster preparedness and response capabilities. Providing training, workshops, and technical assistance on disaster management, first aid, search and rescue techniques, and emergency communication enables individuals and organizations to effectively respond to emergencies. By equipping frontline responders with the necessary skills and resources, communities can improve their ability to mitigate the impacts of disasters and save lives in times of crisis. Furthermore, ongoing monitoring, evaluation, and review of disaster preparedness initiatives are essential for ensuring their effectiveness and relevance over time. Regular assessments of evacuation drills, early warning systems, and emergency response protocols enable authorities to identify strengths, weaknesses, and areas for improvement. By incorporating lessons learned from past experiences and feedback from stakeholders, authorities can refine and enhance disaster preparedness measures, ultimately strengthening community resilience and reducing the risks associated with GLOFs and other natural disasters.

The establishment of emergency response sites, implementation of evacuation drills, deployment of early warning systems, community engagement, stakeholder collaboration, capacity-building initiatives, and continuous monitoring and evaluation are essential components of effective disaster risk reduction strategies. By adopting a holistic and proactive approach to disaster preparedness, communities and authorities can enhance their readiness and resilience in the face of potential GLOF events, ultimately safeguarding lives and livelihoods in vulnerable areas.

5.3.1.2 Vulnerable Locations for Lake 2

Table 5.2 Vulnerable Location Due to GLOF of Lake 2

Locality Name	Darcha Sumdo
Tehsil Name	Lahul
District	Lahul And Spiti
State	Himachal Pradesh
Elevation	4500 meters. Above Sea level
Distance from Outlet	68.50 Km.
Population	172
Response Time	4 Hours 15 minutes

Implementing comprehensive measures to enhance preparedness and resilience against Glacial Lake Outburst Floods (GLOFs) is essential for safeguarding lives and livelihoods in vulnerable areas. One key aspect of these efforts involves the implementation of an extensive awareness program targeting both the local community and trekkers frequenting the region. This program aims to educate individuals about the potential risks posed by GLOFs and provide them with the necessary knowledge and skills to respond effectively to early warnings. The awareness program will serve as a vital tool for empowering community members and trekkers to recognize the signs of an impending GLOF and take appropriate actions to protect themselves and others. By increasing awareness and understanding of GLOFs, individuals can better appreciate the importance of heeding early warnings and following established evacuation procedures. Through workshops, training sessions, and informational materials, participants will learn about the causes and impacts of GLOFs, as well as the specific measures they can take to mitigate their risks. In addition to raising awareness, the establishment of an Early Warning System (EWS) represents a crucial component of GLOF risk mitigation strategies. The EWS will comprise a network of monitoring stations equipped with sensors to detect changes in glacial lakes and other indicators of potential GLOF events. These monitoring stations will be linked to a centralized system capable of issuing timely alerts and warnings to at-risk populations. The Early Warning System will include alarm mechanisms specifically designed for local residents, trekkers, and relevant authorities. These alarms will be strategically positioned in key locations frequented by the community and trekkers, ensuring that everyone receives timely notification of an impending GLOF event. By providing early warnings, the EWS will enable individuals to evacuate to safety and take other necessary precautions before the floodwaters arrive. Furthermore, in collaboration with local authorities, a designated emergency evacuation site will be established at THOLONG Primary School, strategically located 1.9 kilometers from the village at a higher elevation. This site will serve as a swift-response center capable of accommodating evacuees and providing temporary shelter during GLOF events. By positioning the evacuation site at a higher elevation, it will be less susceptible to flooding, ensuring the safety of individuals seeking refuge. Regular evacuation drills will be conducted to reinforce evacuation procedures and ensure the preparedness and effectiveness of response mechanisms. These drills will simulate GLOF scenarios and provide participants with hands-on experience in evacuating to the designated safe zone. By practicing evacuation procedures regularly, community members and authorities will be better equipped to respond quickly and efficiently in the event of a real emergency. By implementing these comprehensive measures, communities and authorities can enhance their readiness and resilience in the face of potential GLOF events. The combination of awareness-raising efforts, an Early Warning System, designated evacuation sites, and regular drills will enable individuals to recognize and respond to GLOF threats effectively. Ultimately, these measures will contribute to safeguarding lives and livelihoods in vulnerable areas and reducing the overall impact of GLOFs on affected communities.

5.4 RECOMMENDED EARLY WARNING SYSTEMS FOR GLOF PREPAREDNESS

To bolster the monitoring and response capabilities for potential hazards linked to glacial lakes, a multifaceted strategy is proposed. Firstly, the deployment of a comprehensive geophysical monitoring system, incorporating instruments such as seismometers and ground-penetrating radar, is essential. These instruments enable the assessment of subsurface conditions and identification of geological instabilities that may contribute to glacial lake outburst floods (GLOFs). Secondly, leveraging advanced remote sensing techniques, such as synthetic aperture radar (SAR) and interferometry, is paramount for monitoring glacier dynamics and ice flow rates. These techniques allow for the detection of signs of glacier retreat or advance, providing valuable insights into potential changes in glacial lake behavior. Thirdly, the utilization of sophisticated hydrological modeling tools is crucial for simulating water flow and evaluating glacial melt patterns. By predicting changes in water levels and understanding the sensitivity of lakes to climatic variations, these models contribute significantly to hazard assessment and early warning efforts. Integration of high-resolution climate models further enhances the understanding of future climate scenarios and identifies potential long-term risks associated with glacial lake hazards. Machine learning algorithms play a pivotal role in analyzing multidimensional data sets, detecting subtle patterns indicative of impending hazards, and improving the accuracy of early warning systems. Real-time data fusion techniques play a vital role in integrating information from various sources, including remote sensing data, ground-based measurements, and climate models, to provide comprehensive situational awareness. This integrated approach ensures that decision-makers have access to timely and accurate information for informed decision-making. Designing an early warning decision support system is essential for facilitating timely and informed decision-making in response to potential hazards associated with glacial lakes. This system provides decision-makers with actionable insights and recommendations based on real-time data and hazard assessments. Establishing a redundant communication network is critical to ensuring continuous data transmission in remote terrains where glacial lakes are often located. This network ensures that critical information reaches relevant stakeholders promptly, even in challenging environmental conditions. Optimizing sensor arrays through spatial analysis techniques helps minimize blind spots in monitoring, ensuring comprehensive coverage of glacial lake environments. By strategically placing sensors and monitoring stations, gaps in data collection can be minimized, enhancing the effectiveness of early warning systems. Finally, developing adaptive evacuation strategies with dynamic risk assessments and local community involvement is essential for enhancing the effectiveness of evacuation procedures in the face of evolving hazards. By engaging with local communities and incorporating their knowledge and expertise, evacuation plans can be tailored to specific risks and vulnerabilities, improving overall resilience to glacial lake hazards.

CHAPTER 6

CONCLUSIONS AND MAJOR CONTRIBUTIONS

6.1 CONCLUSION

In the heart of the Himalayas lies the Chenab Basin, a region of unparalleled natural beauty and geological significance. Within this landscape of rugged terrain and pristine glaciers, two glacial lakes, Lake 1 and Lake 2, command attention not only for their scenic allure but also for the ominous threat they pose to surrounding communities. These lakes, while serene on the surface, harbor the potential for catastrophic Glacial Lake Outburst Floods (GLOFs), a sobering reminder of the delicate balance between nature's grandeur and its potential for devastation.

The meticulous documentation of Lake 1 and Lake 2's geographic coordinates and area measurements has been instrumental in understanding and mitigating the risks they present. Through comprehensive surveys and mapping efforts, researchers have laid the groundwork for effective risk assessment and mitigation strategies. Lake 1, with its precise coordinates and measured area, epitomizes the fusion of natural wonder and scientific inquiry. Yet beneath its tranquil facade lies the ever-present danger of a GLOF, necessitating urgent action to safeguard lives and infrastructure.

Similarly, Lake 2, nestled amidst the rugged Chenab Basin, serves as a focal point for scientific inquiry and risk management efforts. Its pristine waters belie the potential for devastation, underscoring the need for proactive measures to mitigate the risks posed by GLOFs. The repercussions of such events extend far beyond the immediate vicinity of the lakes, threatening downstream communities, infrastructure, and ecosystems throughout the region.

In response to this looming threat, scientists, policymakers, and local stakeholders have mobilized to develop and implement a range of mitigation strategies. Structural interventions, such as the reinforcement of moraine dams and the construction of spillways, aim to bolster the resilience of Lake 1 and Lake 2 against sudden outburst events. These engineering solutions draw upon cutting-edge technologies and best practices to enhance the natural defenses of these vulnerable water bodies.

In addition to structural interventions, early warning systems play a crucial role in mitigating the risks associated with Lake 1 and Lake 2. By harnessing remote sensing and real-time monitoring technologies, scientists can detect early warning signs of impending GLOFs and issue timely alerts to at-risk communities, enabling them to evacuate safely and mitigate potential damage.

Community preparedness measures form another vital component of the mitigation strategy. By empowering local communities with the knowledge and resources they need to respond effectively to GLOFs, authorities can enhance resilience and reduce vulnerability to disaster. This includes the development of emergency response plans, training programs, and awareness campaigns aimed at fostering a culture of preparedness at the grassroots level.

Sustainable land-use practices offer yet another avenue for mitigating the risks associated with Lake 1 and Lake 2. By promoting responsible land management practices, such as reforestation and erosion control, authorities can help minimize the risk of GLOFs and enhance the natural resilience of the landscape.

In conclusion, the Chenab Basin's glacial lakes, while breathtaking in their beauty, present a stark reminder of the unpredictable forces of nature. Through coordinated efforts and innovative strategies, we can mitigate the risks posed by Lake 1 and Lake 2, ensuring the safety and resilience of communities throughout the region for generations to come.

6.1.1 Identification of Vulnerable Lakes:

The Chenab Basin, nestled within the majestic Himalayan range, is home to numerous natural wonders, including its glacial lakes, which have long captivated scientists, environmentalists, and local communities alike. Among these crystalline bodies of water, two stand out for their unique significance and, unfortunately, their potential for catastrophic events – Lake 1 and Lake 2. Situated amidst the rugged terrain of the Chenab Basin, Lake 1 and Lake 2 have garnered attention not for their serene beauty alone but also for the looming threat they pose to the surrounding environment and human settlements. These lakes are particularly susceptible to Glacial Lake Outburst Floods (GLOFs), natural disasters triggered by the sudden release of water from glacial lakes, presenting a grave risk to nearby communities and infrastructure. The meticulous documentation of the geographic coordinates and area measurements of Lake 1 and Lake 2 has proven indispensable in understanding and addressing the potential hazards they entail. Through comprehensive surveys and mapping efforts, researchers have gathered crucial data that serves as the foundation for risk assessment and the formulation of effective mitigation strategies. Lake 1, with its precise coordinates and meticulously measured area, stands as a testament to the intricate relationship between nature and science. Its tranquil surface belies the latent danger lurking beneath, a danger that stems from the precarious balance between glacial meltwater accumulation and the structural integrity of the moraine dams that contain it. The vulnerability of Lake 1 to GLOFs underscores the urgent need for proactive measures to safeguard lives and livelihoods in the region. Similarly, Lake 2, nestled amidst the rugged terrain of the Chenab Basin, presents a stark reminder of the unpredictable forces of nature. Its pristine waters, reflecting the azure sky above, belie the potential for devastation that lies in wait. With its geographic coordinates meticulously documented and its area measurements carefully calculated, Lake 2 serves as a focal point for scientific inquiry and risk management efforts aimed at averting disaster. The risk posed by Lake 1 and Lake 2 extends far beyond their immediate surroundings, encompassing a vast expanse of the Chenab Basin and beyond. The potential for GLOFs to unleash torrents of water, debris, and sediment poses a significant threat to downstream communities, infrastructure, and ecosystems. The repercussions of such events can be far-reaching, causing widespread destruction and loss of life if adequate measures are not taken to mitigate the risks. In response to the looming threat posed by Lake 1 and Lake 2, scientists, policymakers, and local stakeholders have mobilized to develop and implement a range of mitigation strategies. These efforts encompass a multi-faceted approach that includes structural interventions, early warning systems, community preparedness measures, and sustainable land-use practices aimed at reducing the likelihood and impact of GLOFs. Structural interventions, such as the reinforcement of moraine dams and the construction of spillways, aim to enhance the stability and resilience of Lake 1 and Lake 2, reducing the risk of sudden outburst events. These engineering solutions draw upon cutting-edge technologies and best practices in dam engineering and hydrology to bolster the natural defenses of these vulnerable water bodies. In addition to structural interventions, early warning systems play a crucial role in mitigating the risks associated with Lake 1 and Lake 2. By harnessing the power of remote sensing, meteorological data, and real-time monitoring technologies, scientists can detect early warning signs of impending GLOFs and issue timely alerts to at-risk communities, enabling them to evacuate safety and mitigate potential damage. Community preparedness measures form another essential component of the mitigation strategy for Lake 1 and Lake 2. By empowering local communities with the knowledge, skills, and resources they need to respond effectively to GLOFs, authorities can enhance resilience and reduce vulnerability to disaster. This may include the development of emergency response plans, training programs, and awareness campaigns aimed at fostering a culture of preparedness and resilience at the grassroots level. Sustainable land-use practices offer yet another avenue for mitigating the risks associated with Lake 1 and Lake 2. By promoting responsible land management practices, such as reforestation, erosion control, and land zoning regulations, authorities can help minimize the risk of GLOFs and enhance the natural resilience of the landscape. These measures not only reduce the likelihood of catastrophic events but also contribute to the long-term sustainability of the Chenab Basin ecosystem.

6.1.2 GLOF Analysis and Flood Peak Assessment:

In the pursuit of understanding the potential ramifications of Glacial Lake Outburst Floods (GLOFs) emanating from Lake 1 and Lake 2, cutting-edge hydrological modelling techniques have been deployed, harnessing the power of advanced software such as HEC-RAS. This sophisticated tool has provided researchers with a means to delve into the intricacies of water flow dynamics, enabling the estimation of critical parameters essential for assessing flood risk and devising effective mitigation strategies. The utilization of HEC-RAS software has facilitated a comprehensive analysis of the hydrological processes governing GLOF events originating from Lake 1 and Lake 2. Through meticulous simulation and analysis, researchers have been able to ascertain key metrics such as peak discharge, time to peak flow, and various hydrological parameters critical for understanding the magnitude and timing of potential flood events. In the case of Lake 1, the hydrological modelling efforts have yielded insightful findings, revealing an estimated total flood peak of 10,917 cubic meters per second (m^3/s). This figure serves as a stark reminder of the immense volume of water that could be unleashed in the event of a GLOF, highlighting the substantial threat posed to downstream communities, infrastructure, and ecosystems. The urgency of implementing proactive measures to mitigate the potential impacts of GLOFs from Lake 1 becomes abundantly clear in the face of such significant discharge rates.

Similarly, the analysis of Lake 2's hydrological characteristics has unveiled even more daunting figures, with a calculated flood peak reaching as high as 17,971 m^3/s. This staggering volume underscores the heightened risk associated with Lake 2 and emphasizes the imperative nature of preemptive action to mitigate the potential devastation wrought by GLOFs originating from this glacial lake. The findings serve as a clarion call to policymakers, stakeholders, and local communities, urging them to prioritize the development and implementation of robust mitigation measures to safeguard lives and livelihoods in the face of such formidable threats. The implications of these findings extend far beyond the confines of scientific inquiry, resonating deeply with the communities inhabiting the downstream areas vulnerable to GLOFs. The stark reality of the potential consequences underscores the pressing need for collaborative efforts to address the looming threat posed by Lake 1 and Lake 2. By leveraging the insights gleaned from advanced hydrological modelling techniques, stakeholders can formulate targeted interventions aimed at reducing vulnerability and enhancing resilience in at-risk areas. The estimation of peak discharge and other hydrological parameters serves as a critical foundation upon which to build effective risk management strategies. Armed with this knowledge, authorities can make informed decisions regarding land-use planning, infrastructure development, and emergency preparedness, ensuring a proactive approach to GLOF mitigation. Furthermore, the findings underscore the importance of continued research and monitoring efforts to refine predictive models and improve our understanding of the complex interactions driving glacial lake dynamics. In addition to informing mitigation efforts, the insights gained from hydrological modelling also hold significant implications for disaster preparedness and response. By understanding the timing and magnitude of potential flood events, authorities can develop early warning systems capable of alerting at-risk communities in a timely manner, allowing for the implementation of evacuation procedures and other emergency measures. This proactive approach can help minimize the loss of life and property in the event of a GLOF, underscoring the crucial role of science in fostering resilience and adaptive capacity in the face of natural hazards. As we confront the escalating challenges posed by climate change and glacial retreat, the importance of proactive risk management strategies cannot be overstated. By harnessing the power of advanced hydrological modelling techniques, researchers and policymakers can gain valuable insights into the dynamics of glacial lakes and the potential hazards they pose. Armed with this knowledge, we can work towards building more resilient communities and mitigating the impacts of GLOFs, ensuring a safer and more sustainable future for generations to come.

6.1.3 Outlet Peaks and Travel Times:

Downstream outlet sites emerge as critical components in the intricate network of mitigation strategies aimed at minimizing the devastating impacts of Glacial Lake Outburst Floods (GLOFs). Positioned strategically, these outlets serve as conduits, directing the torrential flow of floodwaters away from vulnerable communities, infrastructure, and ecosystems downstream. Through meticulous analysis and simulation, the computed flood peaks at the outlet sites downstream from Lake 1 and Lake 2 have been revealed, shedding light on the magnitude of the potential flood events and the challenges posed by their swift and forceful progression. In the aftermath of a GLOF event originating from Lake 1, the downstream outlet site plays a pivotal role in redirecting floodwaters away from the path of destruction. With a computed flood peak of 9,717 cubic meters per second (m^3/s), the outlet site stands as a crucial buffer against the onslaught of water surging downstream. This figure underscores the formidable task facing authorities tasked with managing the aftermath of such an event, highlighting the urgent need for robust mitigation measures to protect downstream communities and infrastructure from the ravages of flooding. Similarly, in the case of Lake 2, the downstream outlet site assumes a paramount importance in mitigating the impacts of potential GLOF events. With a computed flood peak of 7,348 m^3/s, the outlet site serves as a vital lifeline for communities situated downstream, offering a means of escape from the deluge threatening to engulf their homes and livelihoods. Despite the somewhat lower flood peak compared to Lake 1, the challenges posed by the rapid and forceful flow of floodwaters remain significant, necessitating a coordinated and proactive response to safeguard lives and property. Beyond the mere magnitude of flood peaks, the determination of travel times to downstream outlet points holds profound implications for emergency response planning and evacuation strategies. In the case of Lake 1, the computed travel time to the outlet point stands at 1 hour and 10 minutes, underscoring the swift and relentless nature of the floodwaters' advance downstream. This abbreviated timeframe leaves little room for hesitation or delay, emphasizing the critical importance of early warning systems and rapid response protocols in ensuring the safety and well-being of at-risk populations. Conversely, Lake 2 presents a different set of challenges, with a longer travel time to the outlet point of 5 hours and 20 minutes. This extended timeframe necessitates a more comprehensive and proactive approach to emergency preparedness and response, allowing authorities ample opportunity to coordinate evacuation efforts and implement protective measures in advance of the floodwaters' arrival. While the longer travel time may afford some additional time for response and evacuation, it also underscores the need for robust early warning systems capable of providing timely alerts to downstream communities. The significance of these travel times extends beyond mere numerical values, serving as critical inputs for the development of effective emergency response plans and evacuation strategies. Armed with knowledge of the time it takes for floodwaters to reach downstream areas, authorities can make informed decisions regarding the allocation of resources, the coordination of evacuation routes, and the implementation of protective measures aimed at minimizing the loss of life and property in the event of a GLOF. Furthermore, the determination of travel times underscores the interconnectedness of upstream and downstream communities in the face of natural hazards such as GLOFs. While the immediate impacts may be felt most acutely in the vicinity of the glacial lakes themselves, the ripple effects of such events can reverberate far downstream, affecting communities and ecosystems along the entire length of the river basin. By recognizing and accounting for these interdependencies, authorities can develop more holistic and inclusive approaches to disaster risk reduction, fostering resilience and adaptive capacity at all levels of society.

6.1.4 Identification of Vulnerable Sites:

The meticulous analysis of flood peaks and travel times resulting from potential Glacial Lake Outburst Floods (GLOFs) originating from Lake 1 and Lake 2 has illuminated specific villages within the Chenab Basin that are particularly vulnerable to the onslaught of floodwaters. Through a comprehensive examination of the data, Village SHANSHA has emerged as a focal point of concern due to its close proximity to Lake 1, presenting a response time of merely 60 minutes in the event of a GLOF occurrence. Similarly, Village THOLONG finds itself in a precarious position, exposed to the looming threat of GLOFs from Lake 2, with a response time of 4 hours and 15 minutes. These vulnerable sites represent critical points of intervention, demanding immediate attention and preparedness measures to safeguard the lives and wellbeing of local residents in the face of potential disaster. The vulnerability of Village SHANSHA to GLOF events originating from Lake 1 underscores the urgent need for proactive measures to mitigate the risks posed by glacial lake outbursts. Situated in close proximity to the source of potential flooding, residents of SHANSHA face a narrow window of opportunity for evacuation and emergency response, heightening the stakes of preparedness efforts in the community. By implementing early warning systems, evacuation plans, and community preparedness initiatives, authorities can enhance the resilience of Village SHANSHA and minimize the potential impacts of GLOF events on local residents and infrastructure. Similarly, Village THOLONG's exposure to potential GLOFs from Lake 2 necessitates a comprehensive approach to disaster risk reduction and emergency preparedness. With a response time of over four hours, residents of THOLONG must be equipped with the knowledge, resources, and infrastructure necessary to respond effectively to the threat of flooding. By engaging in proactive measures such as land-use planning, infrastructure development, and community capacity-building initiatives, authorities can strengthen the resilience of Village THOLONG and reduce the vulnerability of local residents to the impacts of GLOF events. In addition to these specific vulnerable villages, the identification and analysis of vulnerable lakes, peak discharge rates, and travel times are essential components of effective GLOF risk assessment and mitigation strategies. By understanding the specific threats posed by glacial lake outbursts and their potential impacts on local communities, authorities can tailor interventions to address the unique challenges faced by vulnerable areas within the Chenab Basin. Furthermore, the implementation of proactive measures such as early warning systems, evacuation plans, and community preparedness initiatives can help minimize the potential impacts of GLOF events and enhance the resilience of vulnerable communities. Early warning systems, for example, can provide critical information to residents and authorities, allowing for timely evacuation and emergency response. Evacuation plans can help ensure the safe and orderly evacuation of residents from at-risk areas, while community preparedness initiatives can empower residents with the knowledge and resources necessary to respond effectively to GLOF events.

6.2 RESEARCH CONTRIBUTIONS

The comprehensive study conducted in the Chenab Basin represents a groundbreaking departure from traditional approaches to understanding and managing the risks associated with Glacial Lake Outburst Floods (GLOFs). Unlike previous studies that often focused on isolated aspects or subsets of GLOF phenomena, this integrated investigation adopts a holistic perspective, encompassing various dimensions of GLOF risk assessment and management. By synthesizing data from multiple sources and employing advanced analytical techniques, researchers have been able to gain a deeper understanding of the complex interactions driving GLOF events and develop more effective strategies for mitigating their impacts. At the heart of this comprehensive study lies a recognition of the interconnected nature of the factors contributing to GLOF risk. Rather than viewing GLOFs in isolation, researchers have sought to understand how a multitude of factors, including glacial dynamics, hydrological processes, geomorphological characteristics, and human activities, interact to shape the vulnerability of communities and ecosystems within the Chenab Basin. By taking a holistic approach, researchers have been able to uncover the underlying drivers of GLOF events and identify critical points of intervention to reduce their likelihood and impact. Central to the success of this comprehensive study is the integration of diverse datasets and analytical techniques from multiple disciplines. Researchers have drawn upon data from satellite imagery, aerial surveys, ground-based monitoring stations, hydrological models, and socio-economic surveys to create a comprehensive picture of GLOF risk in the Chenab Basin. By combining these disparate sources of information, researchers have been able to identify vulnerable areas, assess potential impacts, and develop targeted interventions to mitigate the risks posed by GLOFs. One of the key innovations of this integrated approach is the use of advanced hydrological modeling techniques to simulate GLOF events and assess their potential impacts. By utilizing sophisticated software such as HEC-RAS, researchers have been able to estimate peak discharge rates, travel times, and flood extents associated with GLOF events originating from specific glacial lakes within the basin. These simulations provide valuable insights into the dynamics of GLOF events and help researchers identify vulnerable areas downstream where the impacts are likely to be most severe. In addition to hydrological modeling, the comprehensive study also incorporates socio-economic analysis to understand the human dimensions of GLOF risk. By conducting surveys and interviews with local communities, researchers have been able to assess the vulnerability of different population groups and identify socio-economic factors that influence their ability to cope with GLOF events. This socio-economic analysis provides important context for understanding the broader implications of GLOFs on local livelihoods, infrastructure, and socio-cultural practices. The findings of the comprehensive study have important implications for GLOF risk management in the Chenab Basin and beyond. By identifying vulnerable areas, assessing potential impacts, and understanding the underlying drivers of GLOF risk, researchers have been able to develop targeted interventions to reduce the likelihood and impact of future events. These interventions may include structural measures such as the construction of flood defenses and early warning systems, as well as non-structural measures such as land-use planning, community preparedness, and capacity building. One of the key insights to emerge from the comprehensive study is the identification of specific villages within the Chenab Basin that are particularly vulnerable to GLOF events. Village SHANSHA, for example, is deemed vulnerable due to its proximity to Lake 1, with an estimated response time of just 60 minutes. Similarly, village THOLONG faces significant risk due to its exposure to potential GLOFs from Lake 2, with a response time of 4 hours and 15 minutes. These vulnerable sites require immediate attention and preparedness measures to ensure the safety and well-being of local residents in the event of a GLOF occurrence.

The major research contributions are summerised as follows: -

1. Instead of focusing on isolated aspects or subsets of GLOF phenomena, this integrated investigation provides a holistic perspective, encompassing various dimensions of GLOF risk assessment and management.
2. Study indicates that multitude of factors, including glacial dynamics, hydrological processes, geomorphological characteristics, and human activities interact to shape the vulnerability of lakes.
3. Use of advanced hydrological modelling techniques to simulate GLOF events and assess their potential impacts.
4. Estimation of peak discharge rates, travel times, and less frequently attempted flood extents associated with GLOF events originating from specific glacial lakes within the basin.

6.2.1 Comprehensive Study:

In the realm of glacial lake outburst floods (GLOFs), historical studies have often been characterized by a fragmented approach, with researchers focusing on isolated aspects or subsets of the phenomenon. However, a notable departure from this trend is evident in the present study, which adopts a comprehensive approach within the Chenab Basin. This shift in methodology marks a significant advancement in our understanding of GLOFs, as it allows for a more holistic examination of the complex interplay of factors driving these events. The foundation of the comprehensive study within the Chenab Basin was laid with a meticulous inventory of the diverse components of the glacial landscape. Researchers undertook an exhaustive survey to catalog glacial lakes, moraine dams, and other geomorphological features within the basin. This comprehensive inventory served as the bedrock for subsequent analyses, providing researchers with a comprehensive dataset to draw upon in their examination of GLOF risk. Central to the study was the identification of vulnerable lakes within the Chenab Basin. Leveraging data from the inventory and advanced hydrodynamic models, researchers meticulously pinpointed hazard locations where the potential for GLOF events was deemed to be highest. By combining information on the size, depth, and structural integrity of glacial lakes with data on surrounding topography and hydrological conditions, researchers were able to develop a nuanced understanding of GLOF dynamics in the region. The use of advanced hydrodynamic models played a crucial role in the identification and analysis of vulnerable lakes within the Chenab Basin. These models simulate the behavior of water flow in response to various inputs, allowing researchers to assess the likelihood and potential impacts of GLOF events under different scenarios. By incorporating factors such as glacier melt rates, precipitation patterns, and moraine dam stability into their models, researchers were able to generate detailed flood risk maps that highlighted areas of particular concern within the basin. One of the key findings of the study was the identification of specific lakes that posed a heightened risk of GLOF events. These lakes were characterized by factors such as large size, steep inflow channels, and unstable moraine dams, all of which increase the likelihood of a catastrophic outburst flood. By pinpointing these vulnerable lakes, researchers were able to prioritize monitoring efforts and develop targeted mitigation strategies to reduce the potential impacts of GLOF events in the region. In addition to identifying vulnerable lakes, the comprehensive study also assessed the potential impacts of GLOF events on downstream communities and infrastructure. By modeling the propagation of floodwaters through the river network, researchers were able to estimate flood depths, velocities, and inundation extents at various locations within the basin. This information provided valuable insights into the potential risks posed by GLOF events and helped to inform decision-making processes related to emergency preparedness and disaster response. One of the strengths of the comprehensive approach adopted in the present study is its interdisciplinary nature. By bringing together experts from diverse fields such as glaciology, hydrology, geomorphology, and risk assessment, researchers were able to gain a more holistic understanding of GLOF dynamics in the Chenab Basin. This interdisciplinary approach allowed for a more nuanced analysis of the complex interactions between glacial processes, hydrological conditions, and human activities that contribute to GLOF risk. Furthermore, the comprehensive study within the Chenab Basin serves as a valuable blueprint for future research and risk management efforts in other glaciallyfed regions around the world. By demonstrating the importance of taking a holistic approach to GLOF risk assessment and management, researchers have provided a framework for addressing similar challenges in other mountainous regions where glacial lakes pose a threat to downstream communities and infrastructure.

6.2.2 Early Warning Assessment:

The identification of vulnerable lakes within the Chenab Basin, notably Lake 1 and Lake 2, serves as a clarion call for tailored early warning systems and preparedness measures to safeguard at-risk communities. Among these, Village SHANSHA and THOLONG stand out as focal points of vulnerability, each facing distinct risks associated with their proximity to specific lakes. In response to these vulnerabilities, recommendations for appropriate warning systems and preparedness protocols have been meticulously outlined. Village SHANSHA, nestled in close proximity to Lake 1, presents a particularly urgent case requiring swift response measures. With a response time of just 60 minutes, the imperative for preparedness efforts cannot be overstated. The proximity of Village SHANSHA to Lake 1 underscores the need for robust early warning systems capable of detecting and alerting residents to impending GLOF events well in advance. Such systems may include a combination of monitoring technologies, such as satellite imagery, remote sensors, and real-time data analysis, to provide timely alerts and evacuation instructions to at-risk communities. Additionally, community-based preparedness initiatives, including training programs, emergency drills, and public awareness campaigns, are essential for ensuring that residents are equipped with the knowledge and resources needed to respond effectively to GLOF threats. Conversely, Village THOLONG faces potential risks emanating from Lake 2, necessitating a longer response time of 4 hours and 15 minutes. While the extended timeframe may afford some additional preparation and response opportunities, it also underscores the importance of proactive risk management measures. In light of the heightened risk posed by Lake 2, early warning systems tailored to the specific characteristics of the lake and its surrounding terrain are essential for mitigating potential impacts on Village THOLONG and other downstream communities. These warning systems may incorporate advanced modeling techniques, historical data analysis, and community feedback mechanisms to provide accurate and timely alerts to residents. Additionally, evacuation planning and preparedness efforts should be tailored to the unique needs and vulnerabilities of Village THOLONG, taking into account factors such as population density, infrastructure, and access to transportation. The integration of diverse methodologies and the holistic approach adopted in this study represent a paradigm shift in GLOF research and disaster management. By consolidating data from multiple sources and disciplines, researchers have been able to identify key vulnerabilities within the Chenab Basin and develop actionable insights and recommendations to enhance resilience and mitigate the impacts of potential GLOF events. This integrated approach not only advances our understanding of GLOF dynamics but also underscores the imperative of proactive risk management strategies in safeguarding vulnerable communities and ecosystems against the ravages of glacial lake outburst floods. Furthermore, the lessons learned from this study have far-reaching implications for future research endeavors and policy interventions aimed at building resilient communities in the face of evolving environmental challenges. By fostering collaborative efforts and embracing interdisciplinary approaches, researchers, policymakers, and local stakeholders can work together to develop innovative solutions to address the complex risks posed by GLOFs and other natural hazards. These solutions may include improved monitoring and early warning systems, enhanced infrastructure resilience, sustainable land-use planning, and community-based disaster preparedness initiatives. By integrating scientific knowledge with local expertise and community engagement, we can build more resilient societies capable of adapting to the impacts of climate change and other environmental threats. In conclusion, the comprehensive study conducted in the Chenab Basin represents a significant milestone in our efforts to understand and mitigate the risks associated with glacial lake outburst floods. By identifying vulnerable lakes, assessing potential impacts, and developing targeted recommendations for early warning systems and preparedness measures, researchers have provided valuable insights into the complex dynamics of GLOF events and the strategies needed to reduce their impacts on vulnerable communities. Through collaborative efforts and interdisciplinary approaches, we can translate these insights into concrete actions to build resilient communities and safeguard lives and livelihoods in the face of evolving environmental challenges.

6.3 Limitations:

Using a variety of GLOF situations, the GLOF Early Warning System installed in the Chenab basin creates maps of flood inundation. To warn those who live near the river the system is not connected with a siren system. The lake water level is measured using the ultrasonic sensor system which needs more resources to translate the level into discharge. Transportation of suspended sediment and debris flow are not computed in the current system. Because the lakes are situated in extremely restricted and remote regions, it was not possible to conduct a field verification of all the susceptible lakes. Installation of sensors was restricted to just two vulnerable lakes due to extremely high equipment and logistical costs. Satellite communication systems are the only means by which sensor data may be transmitted. The sensor system runs on solar energy and needs to periodically enter sleep mode to save battery life.

Multiple dangers, including but not limited to GLOFs, are faced by local communities near ice, suggesting that a more comprehensive social-environmental framework is necessary to fully understand GLOF risk. Communities that are subjected to GLOFs exhibit diversity in terms of factors such as ethnicity, class, gender, age, religion, education, language, geography, and other socioeconomic characteristics unique to certain locations and historical periods. Mountain villages are politically excluded and ignored when it comes to infrastructure, hazard mitigation, government aid, health care, education, and economic investments because they are frequently located far from cities and centers of power. These elements make mountain communities more susceptible to GLOFs. Therefore, in addition to the glaciers, additional geohazards such as earthquakes, floods, and landslides, as well as food shortages, misogyny, land loss, droughts, cold waves, and water contamination, must be acknowledged in GLOF studies that concentrate on the human components. Mountain people have traditionally faced several instances of outsider intrusions, ranging from tourists and national park officials to missionaries and mining enterprises who have the authority to limit local access to high-mountain areas and resources. However, it's equally critical to acknowledge that the communities that live downstream of glacial lakes are more than just victims; they actively combat persistent and pervasive hazards.

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APPENDIX - A

Details of Published Paper

S. No.	Title of Paper	Name of the Authors	Name of Journal	Indexation /Ranking of Journal (with proof)	Published/Accepted	Publisher	DOI
1	Identification of Vulnerable Lakes in Chenab River Basin of Western Himalayan Region	Anupam Srivastava, Dr. K.C. Tiwari	International Journal of COMADEM ISSN: 1363-7681 Publishe d on 202210-24	Scopus, Elsevier, UGC CARE	Published	COMADEM Inetrnational, U.K.	https://apscience.org/comadem/index.php/comadem/article/view/342
2	Simulation and Evolution of Glacier Lake Outburst Flood for Chenab River Basin	Anupam Srivastava, Dr. K.C. Tiwari	Solid State Technology, Vol. 64, No. 2, Year 2021 ISSN 0038-IIIX	Scopus, Elsevier	Published	Pennwell Corporation HIndex 27	Solid stated dchnology.us/index.php/JSST/article/view/10665

Conferences

S. No.	**Name of the Conference**	**Organizing Committee**	**Date of Conference**	**Title of the Paper**
1	Climate Change, GEO-Hazards and Sustainable Development	Karnataka, Science College, Dharwad, Karnataka	26th-27th November 2020	Unravelling Dynamics of Glacial Lake Outburst Floods (GLOFs) in the Chenab Basin: Causes, Consequences and Resilience Strategies
2	Climate change, Natural Hazards and Sustainable Livelihoods	Department of Geography, Kirori Mal College, University of Delhi	12th-13th March 2022	Temporal Analysis of Flood Disaster-2017: A Case Study of Kishanganj District, Bihar