सत्यमेव जयते

COMPENDIUM OF TASK FORCE REPORT ON NDMA GUIDELINES
MANAGEMENT OF GLACIAL LAKE OUTBURST FLOODS (GLOFs)



October 2020

NATIONAL DISASTER MANAGEMENT AUTHORITY
MINISTRY OF HOME AFFAIRS
GOVERNMENT OF INDIA

Schweizerische Eidgenossenschaft
Confédération suisse
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Compendium of Task Force Report on NDMA Guidelines
Management of Glacial Lake Outburst Floods (GLOFs)

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A publication of:

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Ministry of Home Affairs
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Abbreviations & Acronyms

APN	Asia-Pacific Network for Global Change Research
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
ATIs	Administrative Training Institutes
BIS	Bureau of Indian Standards
CD	Civil Defence
CBOs	Community Based Organisations
CWC	Central Water Commission
CAPF	Central Armed Paramilitary Forces
CPF	Central Police Force
DEM	Digital Elevation Model
DEOC	District Emergency Operating Centre
DoT	Department of Telecommunication
DPDC	District Planning and Development Council
EMS	Electromagnetic Spectrum
ESCAP	Economic and Social Commission for Asia and the Pacific
ENVI	Environment for Visualizing Images
EOC	Emergency Operations Centre
EOS	Earth Observation System
ETH	Swiss Federal Institute of Technology
EWS	Early Warning System
FCC	False Colour Composite
GAPHAZ	Glacier and Permafrost Hazards in Mountains
GCP	Ground Control Point
GIS	Geographic Information System
GLIMS	Global Land Ice Measurements from Space
GLOF	Glacial Lake Outburst Flood
GoI	Government of India

GoS	Government of Sikkim
GSI	Geological Survey of India
HKH	Hindu Kush Himalaya
IAHS	International Association of Hydrologists
ICIMOD	International Centre for Integrated Mountain Development
IDRN	India Disaster Resource Network
IHR	Indian Himalayan Region
IIRS	Indian Institute of Remote Sensing
IMCT	Inter-Ministerial Central Team
IRMSS	Infrared Multi-spectral Scanner
IRS	Indian Remote Sensing
ITBP	Indo Tibetan Border Police
RS-2	ResourceSat-2
ITC	International Institute for Geo-Information Science & Earth Observation
LLOF	Landslide Lake Outburst Flood
LISS	Linear Imaging and Self Scanning Sensor
MSL	Meter above Sea Level
MoD	Ministry of Defence
MoEFCC	Ministry of Environment, Forest and Climate Change
MSS	Multi Spectral Scanner
NASA	National Aeronautics and Space Administration
NCC	National Cadet Corps
NCPOR	National Centre for Polar and Ocean Research
NDRF	National Disaster Response Force
NGO	Non-Governmental Organisation
NDMA	National Disaster Management Authority
NDSI	Normalized Difference Snow Index
NDWI	Normalized Difference Water Index

NIDM	National Institute of Disaster Management
NIH	National Institute of Hydrology
NIM	National Institute of Mountaineering
NIR	Near Infra-Red
NMSHE	National Mission on Sustainable Himalayan Ecosystem
NRSC	National Remote Sensing Centre
NSS	National Service Scheme
NTRO	National Technical Research Organisation
NYKS	Nehru Yuva Kendra Snagathan
PAN	Panchromatic Mode Sensor System (SPOT)
RAMMS	Rapid Mass Movement Simulation
RMS	Root Mean Square
RS	Remote Sensing
SDMA	State Disaster Management Authority
SEOC	State Emergency Operating Centre
SRSAC	State Remote Sensing Application Centre
SMPDBK	Simplified Dam-Break
SPOT	Satellite Pour l'Observation de la Terre
SoI	Survey of India
SOPs	Standard Operating Procedures
SWIR	Short Wave InfraRed
TCPO	Town and Country Planning Organization
TIR	Thermal Infrared
TIN	Triangular Irregular Network
TM	Thematic Mapper
UAVs	Unmanned Aerial Vehicles
UT	Union Territory

UNESCO	United Nation Education Scientific Cultural Organization
UNDRR	United Nations office for Disaster Risk Reduction
UNISDR	United Nations International Strategy for Disaster Reduction
VCA	Vulnerability Capacity Assessment
VIS	Visible
VNIR	Visible and Near InfraRed
WIHG	Wadia Institute of Himalayan Geology
WWF	World Wildlife Fund

Executive Summary

Glacial retreat due to climate change occurring in most parts of the Hindu Kush Himalaya has given rise to the formation of numerous new glacial lakes, which are the major cause of Glacial Lake Outburst Floods (GLOFs). A GLOF is a type of flood occurring when water dammed by a glacier or a moraine is released suddenly. When glaciers melt, the water in these glacial lakes accumulates behind loose naturally formed 'glacial/moraine dams' made of ice, sand, pebbles and ice residue. Unlike earthen dams, the weak structure of the moraine dam leads to the abrupt failure of moraine dam on top of the glacial lake, which holds large volume of water. A catastrophic failure of the dam can release the water over periods of minutes to days causing extreme downstream flooding. Such outbursts known as GLOF have the potential of releasing millions of cubic metres of water in a short period causing catastrophic flooding downstream. Peak flows as high as 15,000 cubic metre per second have been recorded in such events. As a result, the threat of GLOFs is receiving increased attention and awareness for glacial lake monitoring and hazard mitigation has increased recently.

Since glaciers in the Himalayas are in a retreating phase, glacial lakes are growing and pose a potentially large risk to downstream infrastructure and life. As glaciers retreat, the formation of glacial lakes takes place behind moraine or ice 'dam'. Different types of lakes may have different levels of hazard potential. For instance, moraine-dammed lakes located at the snout of a glacier have a high probability of breaching with high hazard potential whereas erosion lakes have little chance of breaching. These floods pose severe geomorphological hazards and can wreak havoc on all manmade structures located along their path. Much of the damage caused during GLOF events are associated with large amounts of debris that accompany the flood waters. GLOF events have resulted in many deaths, as well as the destruction of houses, bridges, forests, and roads. Unrecoverable damage to settlements and farmland can take place at large distances from the outburst source with longer term disturbance to the livelihoods.

The potentially dangerous lakes can be identified based on the condition of lakes, dams, associated mother glaciers, and topographic features around the lakes and glaciers. The criteria used to identify these lakes are based on field observations, processes and records of past events, geomorphological and geotechnical characteristics of the lake/dam and surroundings, and other physical conditions.

Structure of the Compendium

In this compendium, **Chapter 1** provides a general outline of glaciers and glacial lakes in the IHR including factors contributing to glacial hazards. **Chapter 2** covers the Himalayan geo-environment, topographic and geomorpho-logical set up as well as hydrological setup. **Chapter 3** presents hazards and risk zonation mapping with details of the hazard and risk assessment. Risk reduction and mitigation measures which are an important part of the report are covered in **Chapter 4**. **Chapter 5** summarises the aspect of awareness and preparedness including community, medical preparedness. Capacity building has been described in brief in **Chapter 6**. Response such as emergency search and rescue, emergency relief, post-disaster damage, and need assessment, etc. have been given in **Chapter 7**. Research and development in the GLOF is described in **Chapter 8**. Regulation and enforcement covering planning, legal regime, and technical audits, etc. have been discussed in **Chapter 9**. Finally, **Chapter 10** enumerates the action plan and implementation of the Compendium.

CHAPTER 1: THE CONTEXT

1.1 GLACIAL LAKE OUTBURST FLOOD (GLOF) AND LANDSLIDE LAKE OUTBURST FLOOD (LLOF) HAZARDS— AN INTRODUCTION

Glacial lake outburst flood (GLOF) is a term used to describe a sudden release of (part of the) water retained in a glacial lake, irrespective of the cause (trigger), mechanism (dam failure or dam overtopping) and glacial lake subtype involved. The climate changes, which has set in after little Ice Age have regional challenges and local impact on the mountain eco-systems (Xu et al., 2007). The focus is now on GLOF hazard vis-à-vis impacts of climate change.

Outbursts of glacial lakes (GLOF) and of landslide-dammed lakes (LLOF) have caused severe catastrophes in mountain regions all over the world. Also, the Indian Himalayan Region (IHR) has experienced a series of disasters related to lake outbursts. The ongoing climate change is expected to alter and potentially increase the probability of lake outbursts in the future. To meet related disaster management challenges, the present document presents a framework for the management of glacial hazards and risks, especially focusing on risks of glacial lake outburst floods (GLOF) and landslide lake outburst floods (LLOF) in the IHR.

1.2 FACTORS CONTRIBUTING GLACIAL HAZARDS (GLOF & LLOF)

A Glacial Lake Outburst Flood (GLOF) is created when water dammed by a glacier or a moraine is released suddenly. Some of the glacial lakes are unstable and most of them are potentially susceptible to sudden discharge of large volumes of water and debris which causes floods downstream i.e. GLOF. Factors contributing to the hazard / risk of moraine-dammed glacial lakes include: (a) large lake volume; (b) narrow and high moraine dam; (c) stagnant glacier ice within the dam; and (d) limited freeboard between the lake level and the crest of the moraine ridge. Potential outburst flood triggers include avalanche displacement waves from (i) calving glaciers; (ii) hanging glaciers; (iii) rock falls; (iv) settlement and/or piping within the dam; (v) melting ice-core; and (vi) catastrophic glacial drainage into the lake from subglacial or englacial channels or supraglacial lakes. A schematic diagram of a moraine-dammed glacial lake is shown in Fig. 1.1.

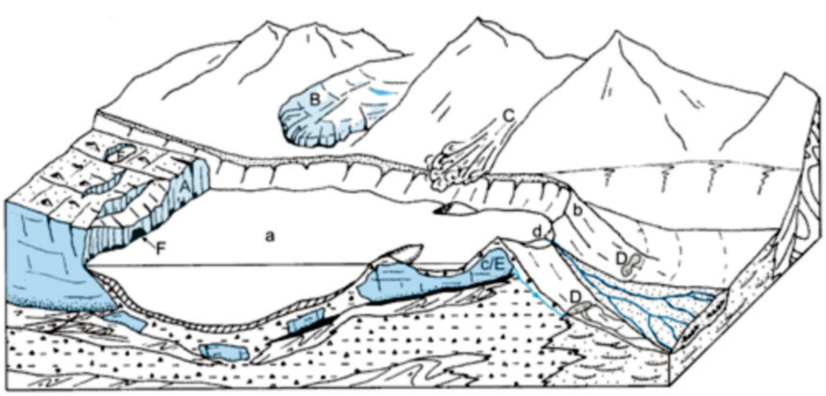


Fig. 1.1: Schematic diagram of a hazardous moraine-dammed glacial lake

[Source: Richardson, S.D. and J.M. Reynolds (2000)]

Triggering Mechanism

Different triggering mechanisms of GLOF events depend on the nature of the damming materials, the position of the lake, the volume of the water, the nature and position of the associated mother glacier, physical and topographical conditions, and other physical conditions of the surroundings. Interaction between the above-mentioned risk factors and triggering processes like ice avalanches, debris flows, rockfall, earthquake or landslides reaching a lake strongly affect the risk of a lake outburst.

Moraine dam formation process

End and lateral moraines are created from material pushed and piled from glacier movement till released when a glacier melts and recedes and act as an unstable dam to ice melting from the glacier. End moraines are formed at the farthest limit reached by a glacier. Lateral moraines are formed along the sides of a glacier. Both terminal and lateral moraines may act as dams.

Mechanism of moraine-dammed lake failure

In addition to, earthquakes being one of the causes for moraine dam failure (Clague 2003), the frequency and magnitude of moraine dam failures and GLOFs will continue to increase with the current and continued scenario of global warming (RGSL 2003) and present one of the greatest threats to people and property in mountainous regions. The unstable nature of moraine dams greatly increases the chances of dam failure. Large lake volume above the moraine dam increases pressure against the dam. Large wave caused from calving glaciers or ice or rock avalanches into the lake may overtop the moraine dam. Melting of stagnant glacier ice in the moraine dam may also reduce the freeboard or create passageways for piping to occur. Catastrophic glacial drainage may raise the lake level quickly and overtop the dam (RGSL 2003; Hambrey and Alean 2004).

Initiation of opening within or under the ice dam (glacier) occurs in six ways:

- Floatation of the ice dam (a lake can only be drained sub-glacially if it can lift the damming ice barrier sufficiently for the water to find its way underneath);
- Pressure deformation (plastic yielding of the ice dam due to a hydrostatic pressure difference between the lake water and the adjacent less dense ice of the dam; outward progression of cracks or crevasses under shear stress due to a combination of glacier flow and high hydrostatic pressure);
- Melting of a tunnel through or under the ice;
- Drainage associated with tectonic activity; and
- Water overflowing the ice dam generally along the lower margin.

The bursting mechanism for ice-dammed lakes can be highly complex and involve most or some of the above-stated processes. A landslide adjacent to the lake and subsequent partial abrasion on the ice can cause the draining of ice core-moraine-dammed lakes by overtopping as the water flows over, the glacier retreats, and the lake fills rapidly. A mechanical failure of the ice dam can result in extreme discharge and is the most critical outburst mechanism.

1.3 PRESENT MECHANISM FOR EARLY WARNING SYSTEM

The Early warning system (EWS) is an integral component of risk management for natural disaster. It has been listed as one of the five priorities under Hyogo Framework for Action (HFA) for building disaster resilient nations and communities and is one of the seven global targets of its succeeding document, the Sendai Framework for Disaster Risk Reduction (SFDRR). However, to put in place an operational and reliable technical GLOF EWS in the Himalaya, characterized by hostile terrain and climate, despite the urgency in view of the climate change is a challenge. It needs a robust and unique yet simple manageable and replicable system considering the number of potentially dangerous glacial lakes.

The traditional framework of early warning systems is composed of three phases: i) monitoring of precursors; ii) forecasting of a probable event; and iii) the notification of a warning or an alert before an event take place (see figure 1.2). Thereafter, the emergency response system becomes active. The purpose is to recognize the fact that there needs to be a response to the warning, where the initial responsibility relies on emergency response agencies. International standards set by the United Nations office for Disaster Risk Reduction (UNDRR) formerly United Nations International Strategy for Disaster Reduction (UNISDR) encompasses the four key components of EWS. Effective early warning systems require strong technical foundations and good knowledge of the risks. At the same time, they must be embedded in an understandable manner and relevant to the communities which they serve(Villagran de León et al., 2007) with clear messages, dissemination systems that reach those at risk, and practiced and knowledgeable responses by risk managers and the public. A detailed discussion on early warning systems is also covered in section 4.6.

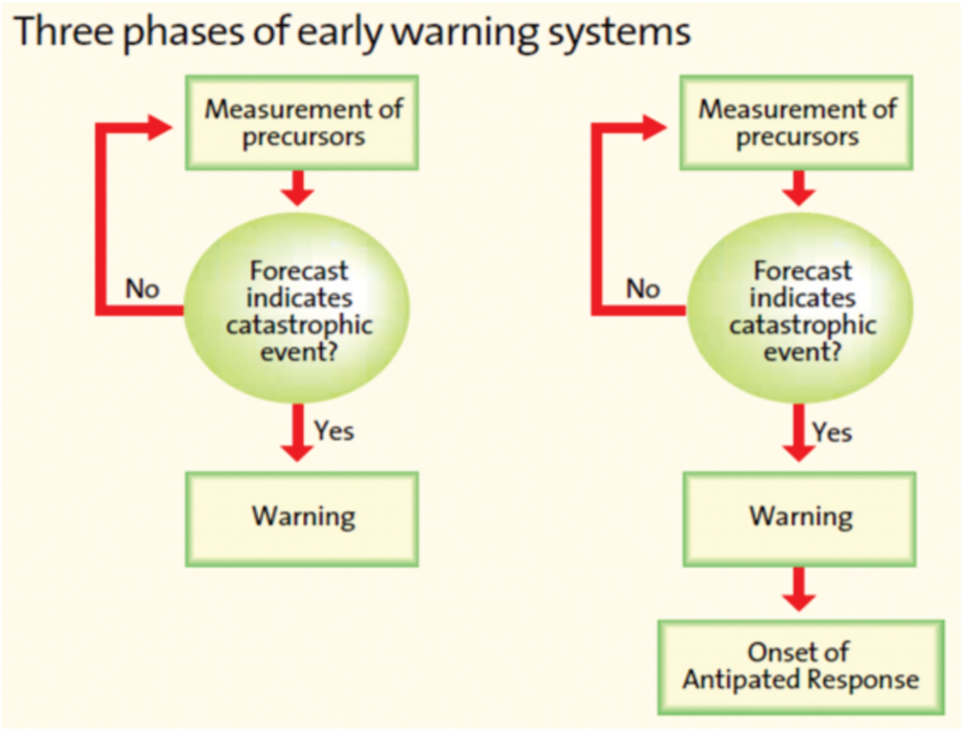


Fig. 1.2: Three phase early warning system

1.4 KEY RISK PARAMETERS

Risks are key if associated harmful consequences have a large magnitude, determined by a variety of metrics including human mortality and morbidity, economic loss, losses of cultural importance, and distributional consequences. Magnitude and frequency of the hazard as well as socio-economic factors that determine vulnerability and exposure contribute. Probability that significant risks will materialize and their timing. Risks are considered key when there is a high probability that the hazard will occur under circumstances where societies or social-ecological systems exposed are highly susceptible and havelimited capacities to cope or adapt and as a result potential consequence are severe. Both the timing of the hazard and the dynamics of vulnerability and exposure contribute to disaster impact. Risks that materialize in the near term may be evaluated differently than risks that materialize in the distant future, as the time available for building up adaptive capacities is different (Fig. 1.3).

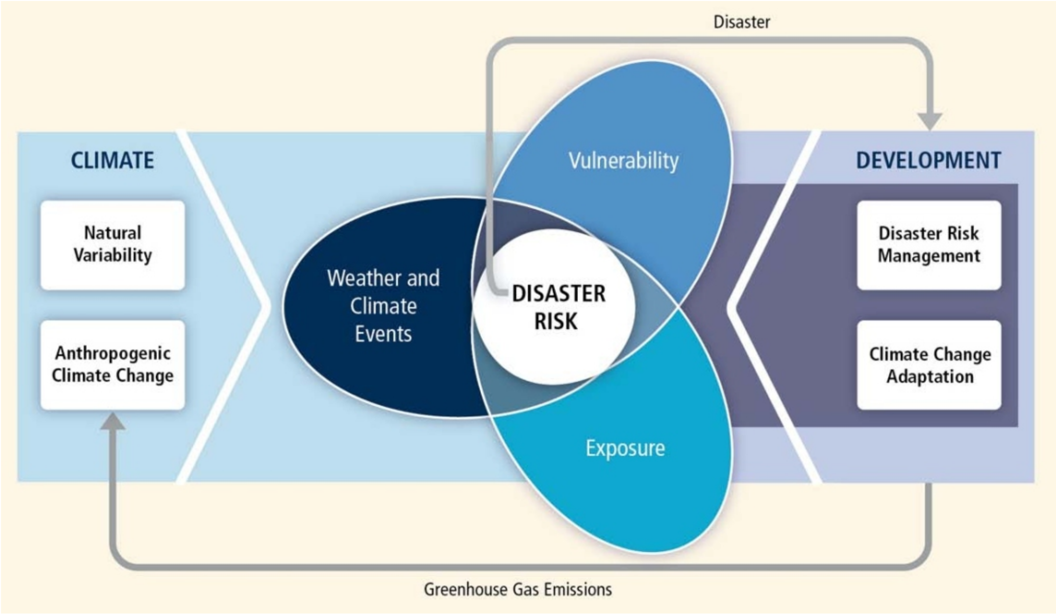


Fig. 1.3: Risk Concept of IPCC (IPCC, 2012)

1.5 GLOF MANAGEMENT STRATEGIES

Glacial lake outburst flood (GLOF) may cause a high magnitude flood at the downstream and a widespread flooding. The inundation of such a nature may cause an adverse effect on ecology and environment. In the event of GLOF, it is to be ascertained that losses to lives and properties could be kept at minimum by administering the feasible structural or non-structural measures. The important purpose of the GLOF study is to prepare an emergency action plan that will lessen or mitigate its impact upon human habitations and properties.

There are several possible methods for mitigating the impacts of GLOFs, for monitoring, and for early warning systems (cf. Chapter 5). The most important structural mitigation measure for reducing GLOF risk is to reduce the volume of water in the lake in order to reduce the peak surge discharge. In general, any one or combination of the following methods may be applied for reducing the volume of water in the lake: controlled breaching, construction of an outlet control structure, pumping or siphoning out the water from the lake, and making a tunnel through the moraine barrier or under an ice dam.

There should be monitoring systems prior to, during, and after construction of infrastructures and settlements in the downstream area. Careful evaluation by detailed studies of the lake, mother glaciers, damming materials, and the surrounding conditions are essential in choosing an appropriate method and in starting any mitigation measure. Any measure taken must be such that it should not create or increase the risk of a GLOF during and after the mitigation measures are in place. Physical monitoring systems of the dam, lake, mother glacier, and the surroundings are necessary at different stages during and after the mitigation process (Xu et al. 2007). Any existing and potential source of a larger snow and ice avalanche, slide, or rock fall around the lake area, which has a direct impact on the lake and dam has to be studied in detail. Preventative measures have to be taken such as removing masses of loose rocks to ensure there will be no avalanches into the lake. It will be necessary to build bridges with appropriate flow capacities and spans at elevations higher than those expected under GLOF events.

Planning for the anticipated situations :

The purpose of disaster management planning is to anticipate future situations and requirements and establish the frame work to meet them. The plan should include all disaster related activities in the pre disaster period, during a disaster and afterward events. But it never goes exactly as envisaged in a plan during an actual disaster. No disaster plan, even well thought out, will provide all the necessary answers to every problem to be faced. But the mental discipline entailed in preparing and practicing will enable a better grasp and help to cope much more effectively whenever it happens.

1.6 NATIONAL DISASTER MANAGEMENT POLICY AND GUIDELINES

As per Disaster Management (DM) Act 2005 and National Disaster Management Policy 2009; NDMA, as the apex body for disaster management headed by the Prime Minister, has the responsibility for laying down policies, plans and guidelines for the disaster management and coordinating their enforcement and implementation for ensuring timely and effective response to disasters in India.

The possibility of GLOF and LLOF in Indian Himalayan Region (IHR) are escalating very rapidly and pose a threat to the lives of millions of people living in this region. Preparation of these guidelines is an utmost need to mitigate the impact of glacial hazards and risks, to develop disaster resilient communities and significantly reduce the loss of life and assets.These guidelines will assist the Central Ministries, Departments and States to formulate their respective DM plansand extend necessary cooperation/assistance to NDMA for carrying out its mandate.

1.6.1 Approach to these Guidelines

The main objective of the guidelines on the management of GLOF and LLOF is to generate awareness of various aspect of dam failure hazards in India and to implement suitable actions to reduce both the risk and costs associated with these hazards. Accordingly, the Guidelines envision to administrative response, bringing together the relevant scientific capabilities of the nation to eliminate the losses from glacial and landslide hazards.

The main aims and objectives of the Guidelines is to develop a strategy that encourages the use of scientific information, maps, methodology, and guidance for early warning system and response management, development and implementation of initiatives to reduce losses from glacial hazards. This compendium also describes the awareness, preparedness, capacity development, research and development, regulations and enforcements and roles and responsibilities of the local, state and national Ministries/ Departments along with the various scientific organizations and institutions to reduce the potential risks.

CHAPTER 2: HIMALAYAN GEO-ENVIRONMENT AND CRYOSPHERE

2.1 INTRODUCTION

Geo-environmental studies focusing on the past, present and future attempt to predict system response to changes in geology, geomorphology, physical and cultural environments. These studies are essentially aimed to study interactions amongst various geo-factors and how these interactions affect mountainous landscapes leading to potential hazards. These investigations include the processes of erosion and deposition; mountain environments and cryosphere, hydrology, natural hazards like earthquakes, active faults, flash floods, mud flows, landslides and mass-wasting events etc. Anthropogenic activities and changing land use practices have accelerated the pace environmental degradation in rural and urban areas.

The Himalayan arc is young and tectonically active, formed as a result of massive collision between Eurasia and the northward-drifting Indian plate about 50 million years ago. It forms the northern limit of India. The mountain arc is ~2,400 km long, stretching from the peak of the Nanga Parbat (8,126 m asl) in the west to the Namcha Barwa peak (7,782 m asl) in the east. The mountain range is convex southwards with syntaxial, bends at the western and eastern ends (Wadia,1931; Valdiya, 1980). The Hindukush-Karakoram-Himalaya host the largest and most important glacier systems outsides poles and are commonly referred to as **the Third Pole on the Earth**. The changing climate associated with increased run-off and less infiltration coupled with removal of forest cover has resulted in the depletion of hill aquifer system in the region. Variability of monsoon rains and seasonal snow-glacier melt have often led to unpredictable flash floods, rock-fall, debris flow, avalanches, GLOFs, landslides, soil erosion resulting in the loss of human lives and property.

2.2 GEOLOGICAL SETUP

The Himalaya is a classic example of an orogenic system created by continent–continent collision (e.g., Dewey and Bird, 1970; Dewey and Burke, 1973). The Himalayan mountain range evolved as a result of the collision between the Indian and Eurasian continental plates about 50 Ma ago (Patriat and Achach,1984). The Himalayan mountain range is subdivided into four principal tectonic zones, from south to north these are: The Sub-Himalaya (Shiwalik Range), the Lesser Himalaya, the Higher Himalayan Crystalline, complex and the Tethyan Himalaya (Fig. 2.1).

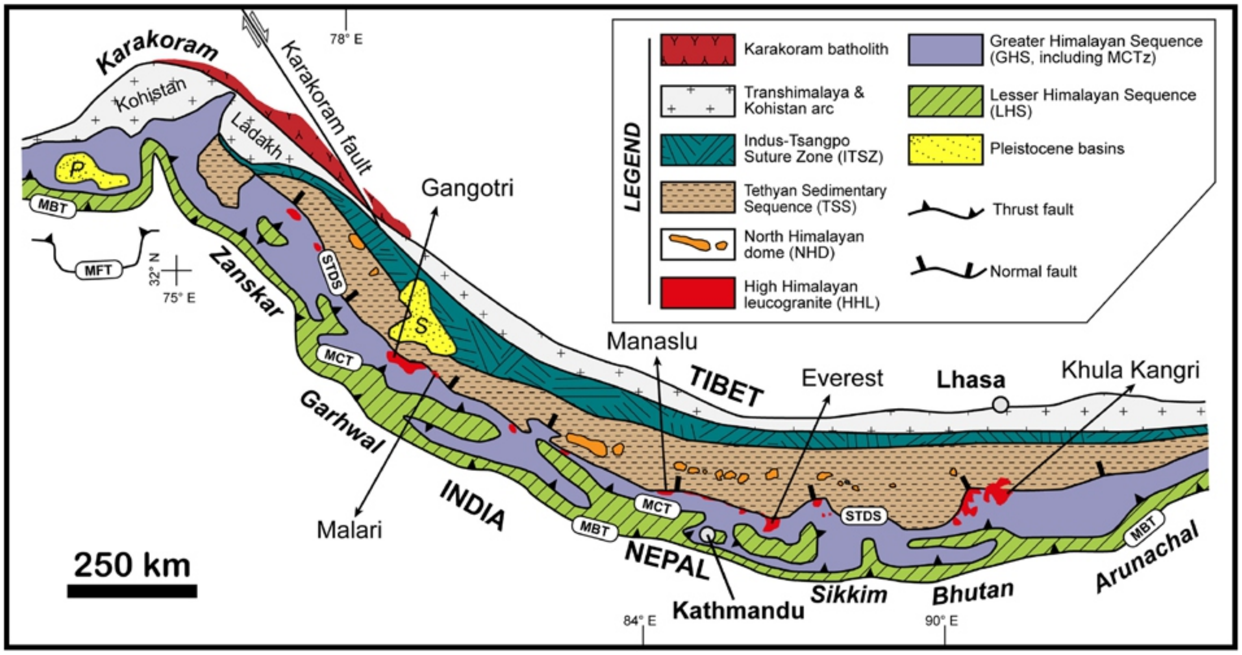


Fig. 2.1: Schematic geological map of the Himalayan belt showing the main units and tectonic boundaries (modified after Law et al., 2004 and Weinberg, 2016). MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STDS: South Tibetan Detachment System; P: Peshawar basin; S: Sutlej basin (*Source: Carosi et al., 2018).*

2.3 TOPOGRAPHIC AND GEOMORPHOLOGICAL SETUP

The most characteristic features of the Himalayas are their soaring height, steep-sided jagged peaks, valley and alpine glaciers often of astounding size, topography deeply cut by erosion, seemingly unfathomable river gorges, complex geologic structure, and series of elevation zones that display different ecological associations of flora, fauna, and climate. The regional geomorphology of the Himalaya reflects the interaction of mountain building and precipitation setup from the south.The Himalayas appear as a gigantic crescent with the main axis rising above the snow line, where snowfields, alpine glaciers, and avalanches all feed lower-valley glaciers that in turn constitute the sources of most of the Himalayan rivers. The greater part of the Himalayas, however, lies below the snow line. The mountain-building process that created the range is still active. As the bedrock is lifted, considerable stream erosion and gigantic landslides occur.

2.4 HYDROLOGICAL SETUP

The Himalaya are drained by 19 major rivers that form the Indus, the Ganges and the Brahmaputra river systems flowing throughout the Himalayan regions, each having a defined catchment area. These rivers rise north of the mountain ranges and flow through deep gorges that generally reflect some structural control, such as a fault line. All the major rivers like the Ganga, Indus, and Brahmaputra originate from the glacierized areas (Fig. 2.2).

Himalaya is the water tower of the Asia, characterized by high precipitation and little evaporation because of lower air temperatures and longer snow coverage, resulting in large contributions of snowmelt and ice melt to the runoff of lowland areas (Viviroli et al., 2007). This is especially true for the Greater Himalaya region, where the snow and ice stored in high-altitude glaciers and are a source of water for almost every major river system in the region. However, a complete understanding of the regional hydrology including the actual contribution of snow and glacial meltwater to surface waters and groundwater of the region is lacking because of diverse & fragile topography and large climatic fluctuations. Some studies suggest that glacial meltwater provides a large share of the water feeding discharge into major rivers such as the Ganges. (e.g., Kehrwald et al., 2008).

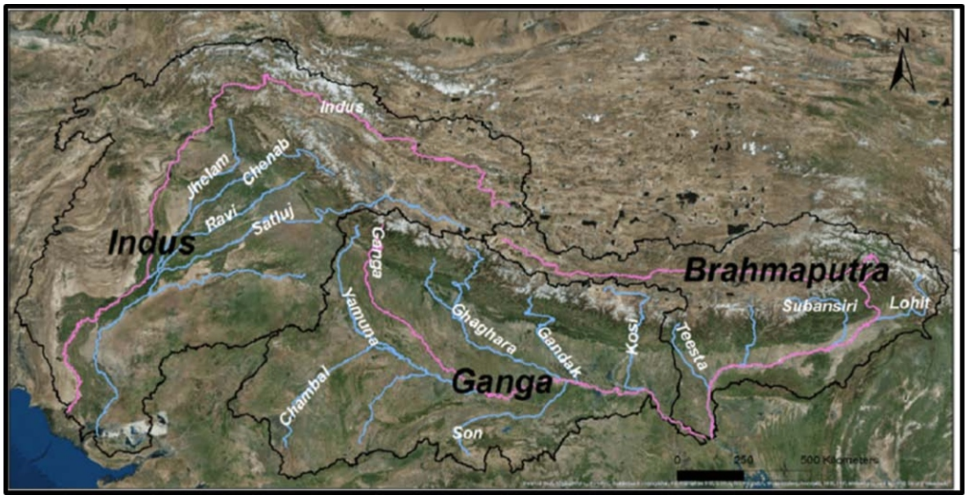


Fig. 2.2: Three major river system emerged from snow/glaciers bound area in the Himalaya.

2.5 CRYOSPHERE SYSTEM

The Himalayan snow and glaciers are apex natural water resource reservoirs and release large quantity of freshwater year-round. From west to east the Himalayan glaciers can be divided into three segments according to their latitudes and topographic features: Western Himalayas, the Central Himalayas and the Eastern Himalayas.

In India 35 percent of the geographical area is mountainous, of which 58 percent is covered under the Himalayas. This area covers about 20.3 percent of India's total geographical area. The Himalaya consist a large area of snow/ice and snow cover after the Polar Regions, hence, studies are largely focused on snow and glaciers due to its visible impact on the environment and resources. The water flowing in the Himalayan Rivers is the combined drainage from rainfall, snowmelt and glacier-melt runoff. In Himalayan region, several water resources projects are under operation and many more are coming up to harness these resources. These projects are of considerable national and local importance in terms of hydro-power generation, irrigation, flood control and subsequent socio-economic development of the region. Proper planning and management of these projects depends on correct assessment of stream flow generated from snow and glacier melt.

The Himalayas house one of the largest resources of snow and ice and its glaciers which form a source of fresh water for the perennial rivers such as the Indus, the Ganga, and the Brahmaputra.

Glacial melt may impact their long-term lean-season flows, with adverse impacts on the economy in terms of water availability and hydro-power generation. Recession of Himalayan glaciers will pose a major danger to the area.

The Himalaya, on the south of the Tibetan plateau contains one of the largest concentrations of glaciers and permanent snowfield outside of the polar region and influence hydrology and climate of the Indian sub-continent. The low latitude and high-altitude orographic characteristics of the Himalaya provide a unique snow/ ice and glacier gathering ground for three major river systems in the Indian part of the Himalaya. About 10 percent of the Himalaya is covered with glaciers and additional area of nearly 30 to 40 percent supports the snow cover. In total, there are about 9,575 glaciers (37,500 km^2) in the Indian Himalayan Region (IHR), spread across 6 states and union territories i.e., Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh (Raina and Srivastva,2008). These glaciers form the perennial source for three great rivers: viz, the Indus, the Ganga and the Brahmaputra. The three basins (India and Environs) put together have 71182.08 km^{2}of glaciated area with 32392 glaciers. The Indus basin (including Tibet, Karakoram, Great Himalaya) has 16049 glaciers occupying 32246.43 km^{2}of glaciated area. The 18 glaciated sub-basins in Indus basin are mapped. The Ganga basin (Including Nepal) has 6237 glaciers occupying 18392.90 km^{2}of glaciated area. There are 7 glaciated sub-basins in Ganga basin. The Brahmaputra basin (including Bhutan and south Kailash range in Tibet), has 10106 glaciers occupying 20542.75 km^{2}of glaciated area. The 27 glaciated sub-basins in Brahmaputra basin are mapped. Basin wise glacier summary for Indus, Ganga and Brahmaputra basin is provided in table 2.1 and Fig. 2.3.

The distribution of glaciers in the Himalaya is uneven, with higher concentration of glaciers in the North-Western part as compared to North-Eastern part. Such complexity is due to criss-cross mountains chain, altitude variation and different climatic conditions. Vohra (1996) stated that the glaciers are found in all those areas which attain or exceed the heights necessary for glacier generation. Most of the glaciers are situated on the main Himalayan range, but other ranges, such as the PirPanjal, the Dhauldhar and the Ladakh ranges also support glaciers.

It has been estimated by various researchers that about 17 percent of the Himalaya and 37 percent of the Karakoram are covered by glacier ice. The major clusters of glaciers occur in and around the following ten Himalayan peaks and massifs: the Nanga Parbat, the Nanda Devi group, the Dhaulagiri massif, the Everest-Makalu group, the Kanchenjunga, the Kula Kangri area, and the Namche Barwa. The principal glaciers of the Himalayas are Siachen (72 km^2), Gangotri (30 km^2), Zemu (26 km^2), Milam (19 km^2), and Bara Shigri (30.5 km^2).

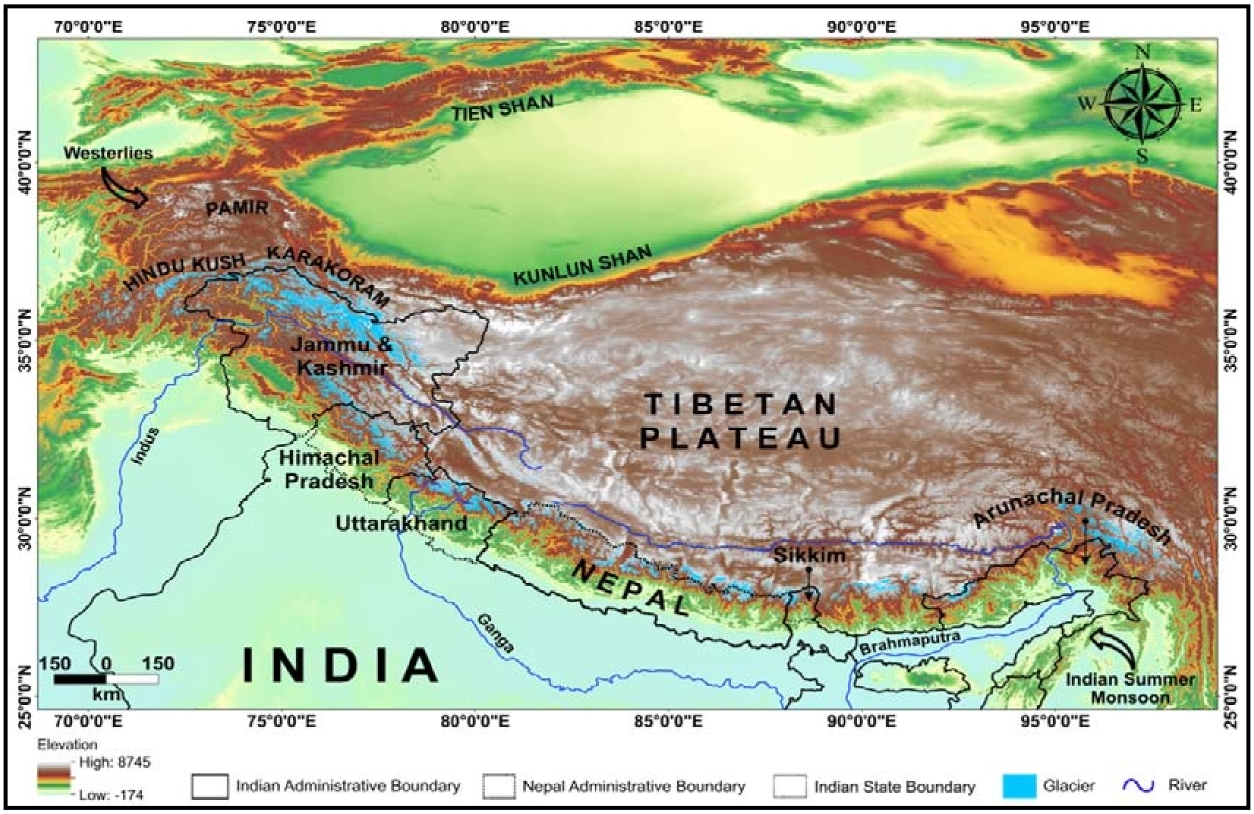


Fig. 2.3: Glaciers cover and the major river system (the Indus, the Ganga and the Brahmaputra) over the Indian Himalayan range.

Table 2.1: Summary of glacier and lake inventory of Indus, Ganga and Brahmaputra basins.

Sr. No.	Basin Characteristics	Indus Area (in km^2)	Ganga Area (in km^2)	Brahmaputra Area (in km^2)	Total basinArea all three (in km^2)
1	Sub-basins (Nos.)	18	7	27	52
2	Accumulation Area	19265.98	10884.6	12126.35	42276.94
3	Ablation Area Debris	6650.95	4844.7	5264.90	16760.55
4	Ablation Ice Exposed	6310.58	2663.5	3081.48	12055.56
5	Total no. of glaciers	16049	6237	10106	32392
6	Total glaciated area	32246.43	18392.9	20542.7	71182.08
7	No. of Permanent Snow fields and Glaciers	5117	641	3651	9409
8	Area under of Permanent Snow fields and Glaciers	991.68	198.70	1282.9	2474.3
9	No. of Supra-glacier lakes	411	87	474	972
10	Area of Supra-glacier lakes	18.92	15.20	70.0	104.13
11	No. of Moraine dam /Glacial lakes	469	194	226	889
12	Area of Moraine dam /Glacial lakes	33.82	64.10	70.2	168.07

*Source: ISRO, 2010. Snow and Glaciers of the Himalayas: Inventory and Monitoring, Discussion Paper II, Space Application Centre (SAC) Ahmedabad and Ministry of Environment and Forests, New Delhi. (*http://www.moef.nic.in/downloads/public-information/Discussion_Paper%20-%2013th%20June.pdf*)*

The Himalaya is essentially dominated by two moisture sources; the south-west monsoon which provides most of the precipitation in the eastern and central regions during the summer months and westerlies which predominate during the winter bring snow and rain in the winter such process act as natural regulators by storing in winter as snow and releasing it in summer in the form of melt water. Glaciers are dynamic and fragile ice mass, grow and shrink in response to changing climate.

Permafrost :

Permafrost and frozen grounds are key elements of the terrestrial cryosphere that will be strongly affected by a warming climate. Permafrost is defined as sub-surface earth materials that remain continuously at or below the freezing temperature of water for at least two consecutive years (Harriset al., 1988). Permafrost mainly occurs in the arctic and high mountain areas and impact around 25percent of the landmass of the northern hemisphere. Numbers of studies have shown permafrost thawing in the Northern Hemisphere during the past couple of decades. The permafrost evidences in the IHR was available from Tso Kar lake area way back in 1975-76 from a study conducted by the Geological Survey of India (GSI). Initial modelling assessment on a regional scale suggests that the permafrost area in the Hindu Kush Himalaya (HKH) region could extent up to 1 million km^2, which roughly translate into 14 times the area of glacier cover in the region. The permafrost covered glacial mountains in Sikkim are shown in Fig. 2.4.

Permafrost, perennially frozen ground, naturally occupying in areas where the mean annual air temperature becomes colder than 0 °C, some of the ground frozen in the winter will not be completely thawed in the summer; therefore, a layer of permafrost will form and continue to grow downward gradually each year from the seasonally frozen ground. Permafrost terrain consists of an active layer at the surface that freezes and thaws each year, underlain by perennially frozen ground (Fig. 10). Permafrost regions are divided into zones with varying spatial extent of perennially frozen ground by its subsurface extent in continuous (more than 90percent of the area underlain by permafrost), discontinuous (50–90percent of the area), sporadic (less than 50percent of the area) and isolated (only small patches) zones (Brown et al., 1997). Permafrost formation and degradation occur on timescales of decades up to millennia, so that the present permafrost distribution must be regarded as a mixed result of past and current climate conditions. In the last decade, a number of studies have gathered convincing observational and modeling evidence for a sustained warming in the Arctic and many mountain regions (e.g., Serrezeet al., 2000; Overland et al., 2008).

Fig. 2.4: The Permafrost coveredglacial mountains in Sikkim (Eastern Himalayas, Indian Himalayan Region)

Permafrost and ground ice result from the long-term energy and mass exchange between the atmosphere and the subsurface. The fundamental processes are the same for permafrost in lowlands and in mountains, whereas the configuration and relative importance of processes vary in differing environments. Regional climate, determined by global atmospheric and oceanic circulation as well as continentality and latitude, controls major patterns of air temperature and solar radiation, as well as the amount and seasonality of precipitation. Monitoring of permafrost and surface conditions is necessary to understand the permafrost distribution in a certain area and includes, i) compilation of information from detailed field soil surveys and mapping; ii) Historical data (maps and literature), photographs and, satellite imageries; iii) spatially explicit thermal modelling of ground temperatures. This information can be used for the design of a monitoring network, and assessment of regional ecosystems.

Permafrost thaw in the high mountain areas, especially in drier climatic zones such as the Upper Indus basin (UIB) could increase the probability of GLOF and LLOF occurrences. Most of the glacial lakes in this region are formed by melting of the ground ice left by the receding glacier and surrounded by ice cored moraine. Identification of shallow permafrost in the glacier elevations of cold-arid region of Ladakh in the Upper Indus basin recently (Schmidt et al., 2016, Wani et al.,2019, Thayyen, 2020) suggests serious implications of possible permafrost thaw on glacial lakes. As warming occurs in the region, the ice core within the moraine that holds the glacial lake water can lose its strength resulting in eventual collapse which will lead to GLOF. A number of GLOFs are reported from the region but no study has been conducted to assess the causative factors. Furthermore, thawing of permafrost in steep mountain slopes can increase the likelihood of rockfalls and large rock avalanches that can enter a lake and trigger GLOFs.

2.5.1 TYPES OF GLACIAL LAKES :

The salient aspects of different types of lakes are briefly enumerated as under:

Erosion lakes

Glacial Erosion lakes are the water bodies formed in a depression after the glacier has retreated. They may be Cirque type and trough-valley type lakes and are stable lakes. These Erosion lakes might be isolated and far away from the present glaciated area.

Supraglacial lakes

The Supraglacial lakes develop on the surface of the ice mass away from the moraine with dimensions of 50 to 100 meters. These lakes may develop in any position of the glacier. Shifting, merging, and draining of the lakes are the characteristics of the Supraglacial lakes. The merging of lakes results in expansion of the lake area and storage of a huge volume of water attributing it a high level of potential energy. The tendency of a glacial lake towards merging and expanding depends mainly from surface inclination and flow velocity of the glacier.

Moraine Dammed lakes

In the retreating process of a glacier, glacier ice tends to melt in the lowest part, surrounded by Lateral Moraine and End Moraines. A Moraine Dammed lake forms when melt water and rainwater accumulate behind the moraine dams after a retreating glacier recedes behind its former moraines. There are two kinds of moraines: an ice-cored moraine and an ice-free moraine. Before the ice body of the glacier completely melts away, glacier ice exists in the moraine and beneath the lake bottom. The ice bodies cored in the moraine and beneath the lake are sometimes called dead ice or fossil ice. As glacier ice continues to melt, the lake becomes deeper and wider. Finally, when ice contained in the moraines and beneath the lake completely melts away, the material causing containment of lake water consists of only the bedrock and the moraines.

Blocking lakes

Blocking lakes are formed through glacier and other factors, including the main glacier blocking the branch valley, the glacier branch blocking the main valley, and the lakes through snow avalanche, collapse and debris flow blockade. This kind of glacial lakes is typical for regions with surge-type glaciers.

Ice-dammed lakes

An Ice-dammed lake is produced on the side(s) of a glacier, when an advancing glacier happens to intercept a tributary/tributaries pouring into a main glacier valley. A glacial lake is formed and maintained only up to a certain stage of glacier fluctuation.

CHAPTER 3: HAZARD & RISK ZONATION MAPPING

3.1 INTRODUCTION

The Hazard and risk assessment provide the basis for prioritising, designing, and implementing risk management strategies, and is therefore considered as a cornerstone of disaster risk management (DRM). Given the complexity of interacting surface processes and landforms in high mountain environments, integrative, forward-looking and comprehensive system-wide approaches to hazard modelling are required, going beyond traditional modelling of single processes.

This chapter provides guidance on a systematic approach to the assessment of glacial and permafrost-related hazards and risk, and in particular Glacial Lake Outburst Floods (GLOFs), drawing upon latest international best practices (GAPHAZ, 2017). Following an introduction to the overarching hazard and risk assessment framework, the chapter focuses on two levels of assessment, firstly to identify potentially dangerous lakes, and then to undertake detailed hazard and risk assessment for such lakes, and downstream areas.

3.2 HAZARD AND RISK ASSESSMENT FRAMEWORK

The hazard and risk assessment framework follows the concept of climate risk, an integrative concept gaining increasing importance in international climate change policy (IPCC, 2014). Integrating the traditionally diverging perspectives from the disaster risk management and climate adaptation communities, climate risk is conceptualized by IPCC (Figs. 1.3 and 3.1). Figure 3.1 describes the first order risk assessment, to be applied to larger regions (e.g. national or state level) in order to identify hot-spots of risk and helps prioritising sites or regions where detailed risk assessments need to be focussed. Based on the detailed risk assessment various risk management options can be effective in reducing underlying vulnerabilities, exposure, or the hazard itself as a physical event intercepting with an exposed and vulnerable system (e.g., community, industry, or ecosystem). The assessment framework distinguishes between two primary levels of assessment; 1) First-order assessment at a national or regional scale to provide a preliminary overview of risk hot-spots where further investigation and prioritization can be focused; and 2) the detailed hazard and risk assessment for a specific location or community that then provides the basis for decision-making, design, and implementation of risk management strategies (see section 5).

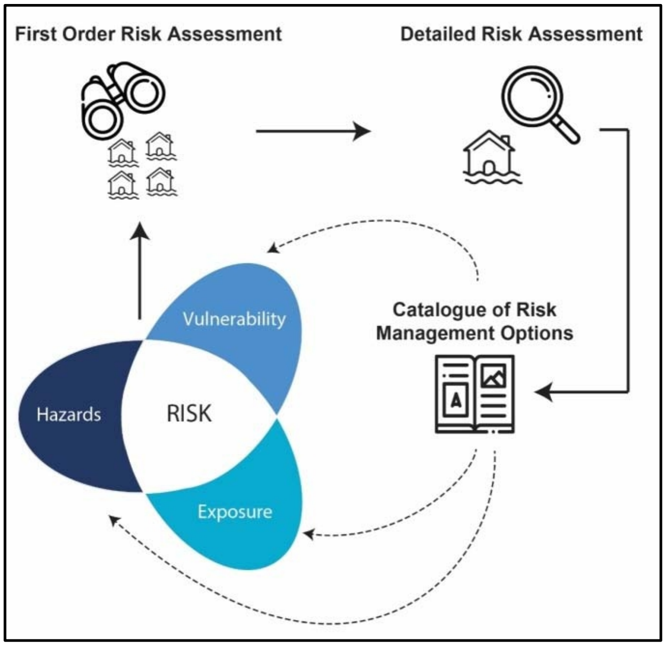


Figure 3.1: Glacial and Permafrost-related Risk Management within the broader Climate Risk framework of IPCC (2014).

3.2.1 Hazard

Hazard in the context of these guidelines refers to the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. The component of the assessment of GLOF builds on from internationally accepted best practices in hazard assessment recently published by the International Association of Cryospheric Sciences and International Permafrost Association (IACS/IPA) Standing Group on Glacier and Permafrost Hazards(GAPHAZ, 2017).

Two core components (or outcomes) of the hazard assessment process include :

1. *Susceptibility and stability assessment:* Identifying where from and how likely hazard processes are to initiate, based on an assessment of wide-ranging triggering and conditioning factors.
2. *Hazard mapping:* Identifying the potential threat from the hazard for downslope and downstream areas, and providing the scientific basis for decision making and planning.

Typically, hazard is then quantified and communicated in the form of classified hazard maps, defined on the basis of the probability (or likelihood) that an event will occur, and the expected intensity (or magnitude) of the given event.

3.2.2 Exposure

Exposure is defined as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by hazard. For glacial and permafrost-related risks, exposure is therefore typically assessed based on an inventory of anthropogenic elements (villages, habitations, roads, bridges, critical lifelines, hydropower stations, heritage sites, sacred places, schools, hospitals, military infrastructure etc.) located within the runout path of potential flood and mass movement events.

3.2.3 Vulnerability

Vulnerability is defined as the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Vulnerability is therefore highly context specific, and can vary significantly as physical vulnerability (housing-infrastructure), social vulnerability (age, gender, caste, education, etc.) and economic vulnerability.

3.3 DISASTER CATALOGUING AND LAKE INVENTORIES

Cataloguing of past GLOFs or other disasters is to be distinguished from a glacial lake inventory that literally maps all glacial lakes in a given region.

The cataloguing of past catastrophic mass movements is a fundamental prerequisite for the assessment of hazard and risks. Through investigation of the distribution, type, and pattern of past hazard events, understanding of triggering and conditioning processes can be improved. When physical access or remotely sensed imagery allows detailed investigation of an outburst event, main physical parameters to be considered are:

- Lake name
- coordinates (longitude, latitude, altitude)
- location (mountain range, valley)
- lake type (supra-, pro-, peri-, subglacial, etc.)
- lake size (pre and post event)
- dam type (bedrock-dammed, moraine-dammed, ice-dammed, combined dam, landslide dammed)
- permafrost conditions (ice-cored moraine, rock glaciers, surrounding rock slopes)
- best estimate of date of lake formation (particularly for landslide-dammed lakes)
- date of outburst event
- probable trigger
- outburst mechanism(s)
- flood volume
- peak discharge at lake site
- downstream reach - the water levels and discharges along the reach at certain intervals
- flow type/ sediment load
- downstream impacts

Glacial lake inventories provide information on the distribution of mapped lakes, their size (area), type, dam characteristics and other factors that may be relevant for a hazard assessment. As a minimum requirement, information on the location and area of the lakes should be recorded. Glacial lake inventories are widely developed for nearly all the mountain regions of the world but methodologies are typically inconsistent. Instead of using spectral indices, manual digitizing of lake boundaries from high resolution satellite imagery provides greater accuracy, and can be used to validate semi-automated approaches. The spatial scale of glacier lake mapping should be at 1:25000 or better. For example, the Resourcesat-1/2/2A Linear Imaging Self Scanner (LISS-IV) multi spectral remote sensing data with spatial resolution of 5.8 m and cartosat-1/2 with 2.5/1 m resolution can be used for glacier lake mapping and hazard assessment exercise in the IHR.

Key considerations for a glacial lake inventory concern the definition of what will be included as glacial lake, and the temporal and spatial scale at which the inventory will be undertaken. On these aspects the following factors may be considered:

- Lakes that remain in direct contact with a glacier
- Lakes which are formed within and/or dammed by glacial ice or debris (moraine)
- Lakes that are in contact with, or formed within creeping permafrost features.
- Bedrock dammed lakes occupying glaciated or former glaciated cirques.
- Other lakes that are in close proximity, and therefore directly threatened by unstable glaciers or permafrost zones.
- Have a minimum size of 1 hectare (0.01 km2)
- Mapping all lakes within the catchment area of the district or state under consideration, including the ones whose catchment areas may extend beyond administrative boundaries.
- Undertake mapping in the post-monsoon window, when lakes will be at their largest, and conditions are most favorable for remote-sensing based analyses.

In terms of the temporal scale, the need will vary depending on rate of environmental change occurring in a given region. In a best case, annual updating of lake inventories is encouraged, particularly in monsoon affected areas, while the length of time between comprehensive mapping efforts should not exceed 5 years. Indian Remote Sensing (IRS) satellites Resourcesat-1/2/2A aboard has Advanced Wide Field Sensor (AWiFS) suitable for inventorying of glacial lakes of size greater than 10 ha which can be updated annually. In addition, Resourcesat-1/2/2A LISS-IV satellite data is best suited for inventorying of glacial lakes of size even less than 1 ha and also for updating comprehensively for once in 5 years. Data from foreign satellites like Landsat, Sentinel, etc, (free of cost) can also be very useful in preparing inventory and regular updating of the lakes. It is also possible, and recommended, for inventories to consider the extent to which lakes will expand, or newly form, over future decades. Such forward-looking approaches are possible, through consideration of glacial geometry and bed topography (see section 3.5.1.1).

Landslide dammed lakes cannot be systematically mapped in the same manner, as they occur more spontaneously, and their duration may be limited. Nevertheless, large-scale detection of landslide lakes should be undertaken in the aftermath of any significant triggering event, namely, earthquakes or extreme rainfall events. Annual updating of glacial lake inventories could be coupled with detection of landslide dammed lakes in monsoon affected areas of the IHR.

3.4 FIRST-ORDER HAZARD AND RISK ASSESSMENT

First order hazard and/or risk assessments are typically implemented at large-scale (e.g., National to State level), in order to establish an overview of potential risk hotspots and as a basis for prioritising further actions. Such assessments can extend across administrative boundaries, to consider far-reaching transboundary hazards and risks. For GLOFs, the starting point for any assessment is establishing a comprehensive and up-to-date lake inventory for the region of interest (Section 3.3), including existing information from studies that have assessed hazard and/or risk associated with the mapped lakes.

3.4.1 Large-Scale Assessment Methods

Large-scale assessment methods include a range of approaches that provide a first indication of the extent and threat of hazard and risk, but where hazard intensities and impacts are not physically modelled, and field studies not undertaken. Such approaches have been widely applied in glacier and permafrost hazard research over the past decade, and serve multiple purposes:

1. As an intermediary step to identify potential hazard or risk hotspots where further studies, field investigations and process-based hazard and risk mapping is to be focused
2. As an alternative to process-based modelling, where field access and/or the quality and resolution of data prevents a more sophisticated approach.
3. Identification of potential cascading processes and chain reaction events.
4. For early anticipation of future threats.

GIS-based flow-routing models often used for large-scale assessment require minimal computing requirements even for large-scale applications (e.g. entire mountain range), and can be implemented using freely available digital elevation data with a grid resolution of 30 – 90m (e.g, ASTER GDEM or SRTMor ALOS). The key limitation of these approaches is their inability to capture the actual physical behavior of mass movements, such as overtopping of barriers in the flow path or flow transformations, and physical parameters such as flow heights, impact pressures, velocities, etc. are not modeled. Rather, these models provide only a coarse estimation of the possible downslope or downstream area that may be affected by a given event. Where modeled paths intersect with other potential hazard source areas (e.g., lakes, or steep unstable debris accumulations), the likelihood of secondary events or flow transformations can be anticipated.

At large scales, key factors that are considered in a remote-sensing based assessment of lake stability in the Himalayan context typically include as a minimum:

- The potential for ice and rock avalanche triggering of an outburst event (including role of glacial de-buttressing and permafrost degradation)
- Climatological conditions (rainfall, snowfall, temperature)
- Lake area (as a proxy for lake volume)
- Lake watershed characteristics (e.g., favouring rainfall and snowmelt into the lake)
- Dam type (ice, rock, or debris)
- Steepness of the downstream slope of the dam

While other factors sometimes considered, depending on the availability of data and scale of the assessment include:

- Dam freeboard
- Dam width to height ratio
- Permafrost conditions – presence of an ice cored moraine

Note that a full explanation of the various predisposing and triggering factors that would be considered in a more detailed local assessment are outlined (see Section 3.5).

Homogeneity of methods and underlying datasets is crucial to ensure that results can be reasonably compared across blocks, districts, and states, to support decision-making. This can be most difficult for *exposure*, as official GIS layers defining village boundaries, or infrastructure such as roads, bridges, hydropower installations etc. are not always uniformly and freely available, and opensource datasets such as Open Street Map are comprehensive in some areas, but incomplete in others. Available large-scale data for some or all states of the IHR that can be used to characterise exposure to GLOFs and other hazards includes:

- Population (population density grids or census data)
- Village locations (as points or outlines)
- Transport infrastructure, including strategically important roads
- Agricultural land area
- Forest areas
- Wetland areas
- Cultural heritage sites
- Tourism sites and hotels
- Hydropower stations.

Societal vulnerability can be characterised using well-established proxy indicators from census data that capture societal capacities to anticipate, respond to, and recover from a flood disaster (Table 3.1). For example, the ability to read and having access to communication systems (e.g, mobile phone, radio, and internet) enhances a household's ability to heed warnings, prepare accordingly, and follow through with an emergency response plan. Information on population demographics is also important, with differences in the capacity to respond to a disaster based on age, gender, religion, health, and other socio-cultural factors.

Table 3.1 : Indicators used in the flood vulnerability assessment for Himachal Pradesh, India. The main components of vulnerability represented by each indicator are listed, and the dependency of the relationship with vulnerability is given.

Indicator	Components represented	Dependency(1)
Female population	Sensitivity, capacity to prepare, respond and recover	+
Population <6 years of age	Sensitivity, capacity to prepare, respond and recover	+
Population >60 years of age	Sensitivity, capacity to prepare, respond and recover	+
Literacy rate	Capacity to prepare, respond and recover	-
Unemployment	Capacity to prepare, respond and recover	+
Employment in farming	Sensitivity, capacity to recover	+
Disabled population	Sensitivity, capacity to prepare, respond and recover	+
Home renters	Capacity to recover	+
Derelict houses	Sensitivity, capacity to respond and recover	+
Water availability	Capacity to prepare and respond	-
Medical facilities	Capacity to prepare and respond	-
Education facilities	Capacity to prepare, respond and recover	-
Banking services	Capacity to prepare and recover	-
Access to radio	Capacity to prepare and respond	-
Access to TV	Capacity to prepare and respond	-
Access to internet	Capacity to prepare and respond	-
Access to mobile	Capacity to prepare and respond	-
Access to vehicle	Capacity to prepare, respond and recover	-

(1) A positive (+) dependency means that an increase in the measured variable indicates an increase in vulnerability. A negative (-) dependency means that an increase in the measured variable indicates a decrease in vulnerability.

3.4.2 Potentially critical Lakes in the IHR

To identify potentially dangerous lakes, one should ideally draw upon multiple sources of information, combining large-scale first order assessment results (including transboundary threats), with knowledge available from previous state level investigations and studies. Such an approach is favoured because it emphasises those lakes that have been identified as critical in one or more studies, and therefore provides the most robust basis for prioritising where further local investigations, and potentially risk reduction strategies should be targeted. Importantly, the selection criteria should be based on mutually agreed and scientifically accepted criteria. A first-order assessment and prioritised listing of potentially dangerous lakes in support of this guidance document has been provided in Annex 1. It must be stressed however, that such prioritised listings of potentially dangerous lakes are merely a static snapshot, and first order hazard and risk assessments should be updated at regular intervals to keep pace with rapidly changing environmental and social landscapes.

Various decision-trees have been proposed to help identify potentially dangerous lakes (as was done by Worni et al. 2013 for the IHR). Alternatively, index-based approaches can be used by

Annex -1: *Synthesis Report on current GLOF hazard and risk across IHR by University of Zurich. Available at: https://eclim-research.ch/synthesis-report-on-current-glof-hazard-and-risk-across-ihr-5/*

combining standardised indices (see Annex 1) for hazard, exposure, and vulnerability. Indices have the advantage that they remain objective, whereas decision-trees require a higher level of expert judgement.

Typically, first-order approaches focus on the threat to people and property, however, sector-based assessments are also recommended, as lakes that may pose a critical threat to one sector, e.g., the farming or transportation sector, may be different from those lakes that threaten populated areas, or another sector. Hence, prioritised listings of potentially dangerous lakes should always be explicit about who or what is threatened. Annex 1 provides state level listings of potentially dangerous lakes considering exposure of hydropower stations, cropland, and roads. For lakes that threaten densely populated areas, an assessment of social vulnerability is included (after IHCAP 2019), to determine risk levels associated with each lake. General conclusions from the first order assessment and synthesis provided in Annex 1 include (Figures 3.2 and 3.3):

- Major roads and bridges across all states are threatened by potentially dangerous lakes.
- The threat to cropland is greatest in the union territory of Jammu and Kashmir & Leh - Ladakh, Sikkim, and Arunachal Pradesh.
- The threat to hydropower is the highest in Sikkim.
- GLOF risk to the population is the highest in Sikkim and Jammu and Kashmir, but a danger exists across all Himalayan states (note this does not consider seasonal variations in population as related to, e.g., tourism).

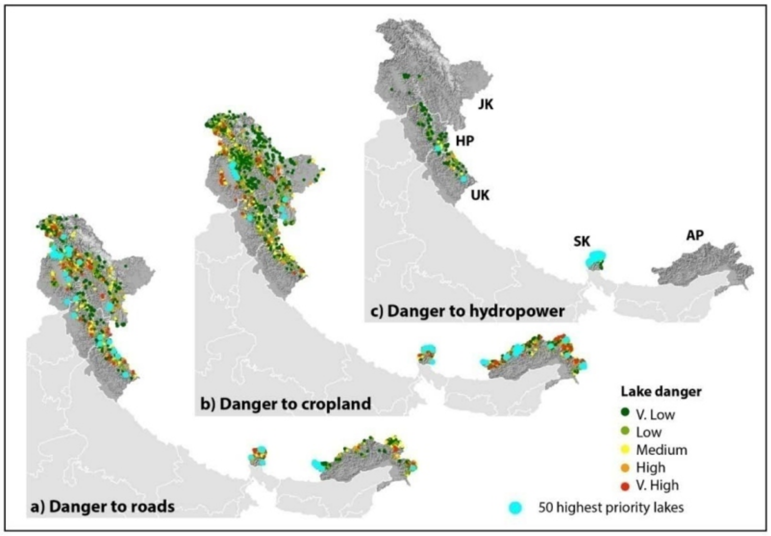


Figure 3.2: Lake danger levels assessed with a large-scale first-order approach, considering exposure of roads, cropland, and hydropower stations.

(*For full results & final listing based on comparison with other studies, see Appendix 1)*

Annex -1: *Synthesis Report on current GLOF hazard and risk across IHR by University of Zurich. Available at: https://eclim-research.ch/synthesis-report-on-current-glof-hazard-and-risk-across-ihr-5/*

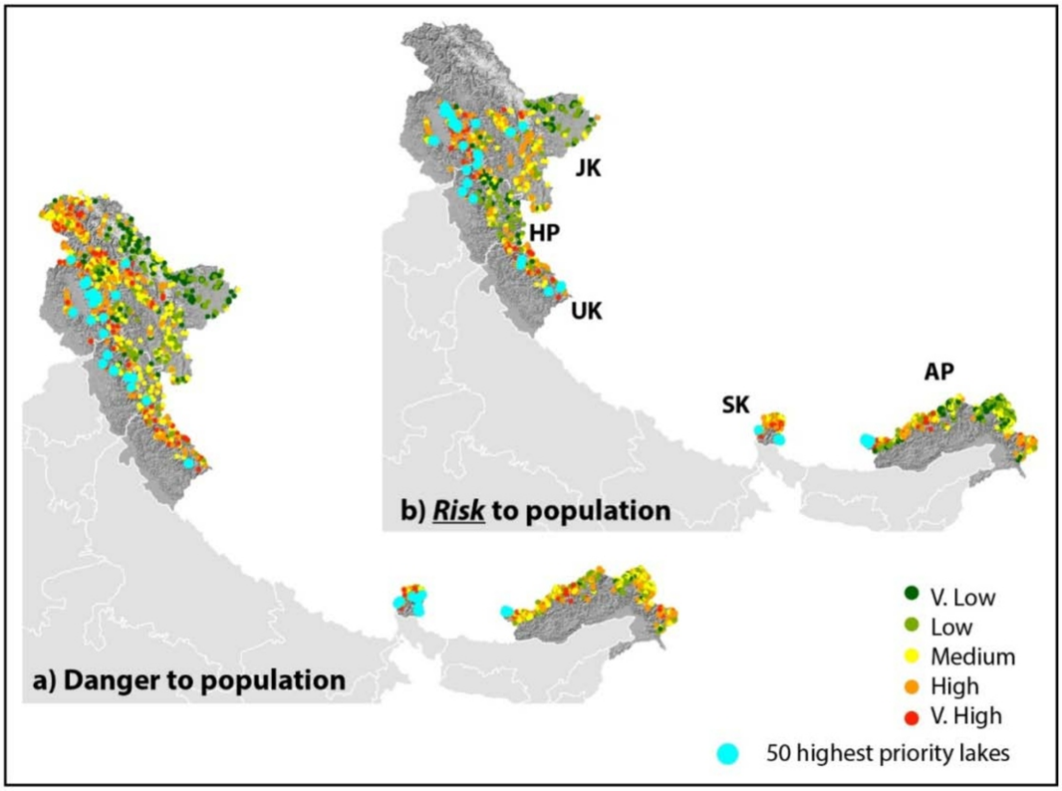


Figure 3.3: Lake danger and risk levels assessed with a large-scale first-order approach. Danger considers lake hazard levels and population density. Lake risk includes social vulnerability (from IHCAP 2019), which as not available for all of JK.

(For full results & final listing based on comparison with other studies, see Appendix 1)

Special awareness needs to be given to lakes that present a transboundary threat to the IHR. In fact, the threat of landslide-dammed or glacier lakes located upstream in Tibet, and to a lesser extent in Nepal, represent a potential threat to much of the IHR. Early identification of such threats is important, to enable timely communication and exchange of information with authorities in neighbouring countries.

3.5 DETAILED HAZARD AND RISK ASSESSMENT

Where critical situations are identified (e.g., where the large-scale assessment has revealed hot-spots of risk), detailed hazard and risk assessments should be undertaken, combining sophisticated hazard modelling and mapping with on-ground assessment of vulnerability and exposure to generate local risk maps. A detailed risk assessment aligns to section 5.1.2 of the 2009 National Policy on Disaster Management, and institutional responsibilities for undertaking GLOF hazard and risk mapping are outlined under section 7.11.1 of the 2019 National Disaster Management Plan (NDMP). A prominent example of this level of assessment is at South Lhonak glacier lake in Sikkim, where major work was carried out by Geological Survey of India (GSI) and Defence Research & Development Organization (DRDO), including remote sensing and field observations to assess

3.5.1 Assessing susceptibility/stability

Wide-ranging atmospheric, cryospheric, and geotechnical factors can condition and trigger GLOFs and other glacial or permafrost-related hazards (see Appendices 1-3). The relevance of certain factors for susceptibility or stability will vary from one region to another, and expert judgement is needed to determine whether or not more emphasis (weight) should be applied to some factors. For example, in monsoon affected parts of the IHR, more emphasis might be given to the role of heavy precipitation in triggering GLOF events, while in drier permafrost-rich zones, degradation of buried ice in the moraine dam could be the most critical factor. Conditioning and triggering factors inform not only about the location and likelihood of an event, but also provide insights on the possible magnitude of the event.

Table 3.2 below outlines the main factors to be considered, corresponding methodological approaches and assessment scale to be applied to assess the susceptibility and stability of a glacial lake. The factors are broadly grouped as those relating to the cryosphere or to the geotechnical and geomorphological setting, while recognizing that there are strong interlinkages between the various factors. The final susceptibility rating for any given lake has often been based on a simplified decision-tree and classification scheme, which requires a large amount of subjective expert judgement and understanding gained from past events. Alternatively, a more objective approach that is recommended under these guidelines is to establish a susceptibility index, that is an unweighted average across all factors outlined in table 3.2 to arrive at a final susceptibility score. In this way, the expert systematically considers as many factors as possible (some may not be relevant in all cases), standardizes the measurements (e.g., values from 1 – 10), and then averages these values to give a final susceptibility score. Weighting of different factors is not recommended, given the scientific evidence for doing this is generally lacking, and the relative importance of different factors will vary significantly from one region to another (GAPHAZ 2017). For sub- or glacial drainage of ice-dammed lakes, process understanding remains rather limited and robust assessment criteria are lacking.

Table 3.2: Factors to be considered under an assessment of GLOF susceptibility (from GAPHAZ 2017). Factors may be relevant for conditioning (Con.), triggering (Trig.), and/or the magnitude (Mag.) of any GLOF. For many factors, relationships with susceptibility or stability are not straightforward, and the expert must apply judgement across a range of attributes to determine whether conditions are favourable (low susceptibility) or unfavourable (high susceptibility)

Susceptibility factors forGLOFS	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment Scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature				Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses (e.g. IMD)	Basin
				Intensity and frequency of extreme temperatures	Low	High		
Precipitation				Intensity and frequency of extreme precipitation events (inc. snowfall).	Low	High	Station-based or gridded climate analyses (e.g. IMD or GPM-IMERG)	Basin
Cryospheric								
Permafrost conditions				State of permafrost, distribution and persistence within lake dam area and bedrock surrounding slopes	No permafrost or cold permafrost	Warm (melting) permafrost in dam area and/or surrounding debris or bedrock slopes	Model-based (indirect) Geophysical (semi-direct)	Regional to basin. Site specific.
Glacier retreat and downwasting				Enlargement of proglacial lakes, enhanced supraglacial lake formation, dam removal or subsidence	No retreat, lake expansion, or dam subsidence	Significant retreat, lake expansion, or dam subsidence	Remote sensing	Regional to basin
Advancing glacier(incl. surging)				Formation of ice-dammed lakes	No change evident	Advance and damming evident	Remote sensing	Regional to basin
Iceavalanche potential				SEE ICE AVALANCHE SUSCEPTIBILITY ASSESSMENT (Appendix 1)	Lower	Higher	SEE ICE AVALANCHE SUSCEPTIBILITY ASSESSMENT	Basin to site specific
Calving potential				Width of glacier calving front, activity, crevasse density	Not evident	Large and frequent	Remote sensing and field studies.	Basin to site specific

Lake size		+	+	Area or volume	Smaller	Larger	Remote sensing, modelling of bed topography, field studies	Regional to site specific
Lake bathymetry		+	+	Influence on dam hydraulics, influence on displacement wave propagation and run-up	Favorable	Unfavorable	field studies (sonar measurements)	Site specific
Sub- Supra- or englacial drainage		+	-	Connectivity of the lake to the glacial hydrological system	Not connected	Well connected	Field studies and modelling	Site specific
Geotechnical and geomorphic								
a) Dam characteristics								
Type		+	+	Bedrock, moraine, ice	Bedrock	Ice, (ice-cored moraine)	Remote sensing	Regional to basin
Ice-cored moraine		+		Thickness, persistence, and condition (linked to permafrost)	Absent	Large and thawing	Geophysical field studies	Site specific
Dam width to height ratio		+	+	Width across the dam crest relative to the dam height	Larger	Smaller	DTM analysis, field studies	Basin to site specific
Freeboard to dam height ratio		+	+	Elevation difference between lake surface and lowest point of moraine.	Larger	Smaller	Remote sensing, DTM analysis, field studies	Basin to site specific
Lithology		+	+	Coarseness of moraine material, presence of fine-grained material, volcanic material etc.	Coarse material predominant	Fine-grained or volcanic material predominant	Field studies	Site specific
Downstream slope		+		Mean slope on downstream side of lake dam.	More gentle	Steeper	DTM analysis, field studies	Basin to site specific
Vegetation and anthropogenic disturbance		+		Density and type of vegetation (grass, shrubs, trees). Destabilizing effects of anthropogenic activities.	Widespread	Absent	Remote sensing, field studies	Basin to site specific
b) Catchment topography and hydrology								
Catchment area		+		Total size of drainage area upstream of catchment, proportion glaciated/non-glaciated	Smaller	Larger	DTM analysis	Regional to basin
Mean slope		+		Steepness of catchment area	More gentle	Steeper	DTM analysis	Regional to basin
Drainage density		+		Density of the stream network in catchment area	Lower	Higher	DTM analysis	Regional to basin
Stream order		+		Presence of large fluvial streams, facilitating	No or low order only	Large high order	Remote sensing, DTM	Regional to basin

				rapid drainage into lake		streams evident	analysis	
Upstream lakes				Presence and susceptibility of upstream lakes.	Absent	Several lakes	Remote sensing	Regional to basin
c) Geotechnical stability								
Rock avalanche potential				SEE ROCK AVALANCHE SUSCEPTIBILITY ASSESSMENT (Appendix 2)	Lower	Higher	SEE ROCK AVALANCHE SUSCEPTIBILITY ASSESSMENT	Basin to site specific
Moraine instabilities				Potential for landslides from moraine slopes into the lake	No steep moraine slopes adjacent to lake	Steep, unstable moraine slopes adjacent to lake.	DTM analysis, remote sensing, field work, geophysical investigations	Basin to site specific
Seismicity				Potential magnitude & frequency, ground acceleration	Lower	Higher	Geological mapping & modelling (e.g. GSHAP)	Regional

3.5.1.1 Cryospheric Factors

Key overarching determinants of GLOF susceptibility and the resulting event magnitude are the size of the glacier lake, the outburst mechanism (and related hydrograph), and the characteristics of the downstream torrent (determined by channel inclination and debris availability). Large lakes can produce potentially greater flood magnitudes, and larger lakes are also more susceptible to impacts from rock and ice. Lake area is easily quantified from remotely sensed imagery. On the other hand, direct measurements of lake volumes are rare owing to the difficulties and danger involved in surveying lake bathymetries in remote regions. Approaches using small unmanned boats with sonar instrumentation provide a safe and cost-effective option for surveying critical lakes, providing detailed bathymetries. Hence, it is recommended that glacier lake depth surveillance of critical lakes be planned in all Indian Himalayan states for better information on volume of water in these lakes.

For regional to basin scale studies, a first-order estimate of lake volume can be derived from empirical equations that link mean lake depths with lake area. For lakes in the Himalaya the relationship from Fujita et al.(2013) has proven most promising:

$$D_m = 55A^{0.25}$$

where A and D_m are the lake area (km^2) and mean depth of the lake (m), respectively. Ideally such empirical models should be calibrated and improved using data measured from accessible lakes in the IHR.

Another further possibility to improve the estimation of lake volumes is based on modeled glacier parameters (e.g., surface velocity, slope and flow patterns) to determine bed topography. Studies on South Lhonak lake, Sikkim, have shown this method was able to estimate volume within 9percent of the sonar-measured volume (Remya et al. 2019. Future threats can be anticipated in a similar way, where lakes expand or newly develop within depressions in the glacier bed. Possible locations of large overdeepening can be established from morphological criteria (Figure 3.4) or derived from modelled bed topography (e.g., Linsbauer et al., 2016, Remya et al. 2019). A combination of these approaches is rather favored, allowing confidence levels to be established (e.g., Magnin et al., 2020). While there can be relatively high confidence in the location at which future lakes will develop, future volumes can only be estimated to within an approximate order of magnitude.

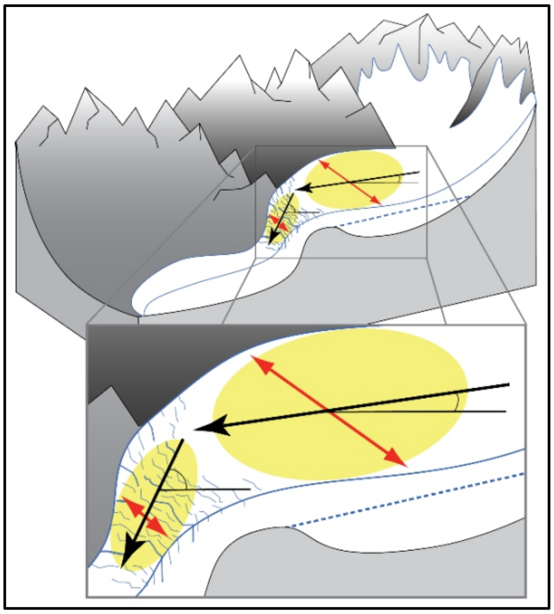


Figure 3.4: Simplified schematic sketch showing three surface morphological criteria indicating potential over-deepening in the bed topography (blue dashed line) where new lakes may develop in the future (*Source: after Frey et al., 2010).*

(The black arrows indicate a sudden steepening of the slope, the red arrows show a narrowing of the glacier width, and the yellow areas indicate a flat and crevasse free region above a heavily crevassed area)

Government of India under Impacting Research Innovation and Technology (IMPRINT) initiative has launched a major program to estimate volume of existing and potential lakes. The project has produced new techniques to estimate volume of glacier lakes, which can significantly improve accuracy.Sattar et.al. (2019) developed a methodology to quantify glacier volume and retreat in the Central Himalaya. They proposed a volume-area power law, wherein the raster-based modelling technique enabled determination of spatially distributed glacier-ice thickness and expansion of the study over a broader geographical area. The study also incorporates investigation of the glacier bed topography for discrete identification of the over-deepening sites in the glacier valley which are potential lake formation sites in the future. Remya et.al., (2019) also developed a technique to estimate the depth and volume of glacial lakes using parameters such as glacier surface velocity, slope and laminar flow of ice. They have also developed a semi-automated tool for potential future expansion of lakes. The above-mentioned techniques can provide accurate information on volume of existing and potential glacier lakes.

Permafrost conditions need to be characterized for both the surrounding steep bedrock slopes (see rock avalanche susceptibility assessment), but also for the dam area of the lake to infer the presence and likely condition of any ground ice in the dam structure (ice-cored moraine or rock glacier) that may be highly susceptible to further warming and melting. Furthermore, expansion of periglacial lakes can be directly linked to thawing of permafrost. At present, mapped information on permafrost distribution across all Indian Himalayan states is too coarse, at 1km resolution, but local inspections with google earth imagery can identify typical landforms indicative of permafrost, such as rock glaciers (Figure 3.5). For critical dam structures, geophysical techniques can then be employed to more precisely determine the subsurface thermal conditions. The snow avalanches can also trigger the GLOF event, as happened during the Kedarnath GLOF event on the morning of 17th June 2013 (Bhambari et al., 2016) and shown in Figure 3.6. This kind of geomorphic setting which lead to formation of end moraine or lateral moraine glacier lakes, a high relief mountain side, which favors a snow avalanche is also found in many glaciated areas of India. Therefore, in addition to ice and rock avalanches, which gets triggered during a seismic event, the snow avalanche should also be considered as one of the trigger factors. The winter time snow avalanche may not that sever for a GLOF as compared to a late spring or late monsoon event, during which the glacier lakes are full, as compared to winter, when most of these lakes are frozen.

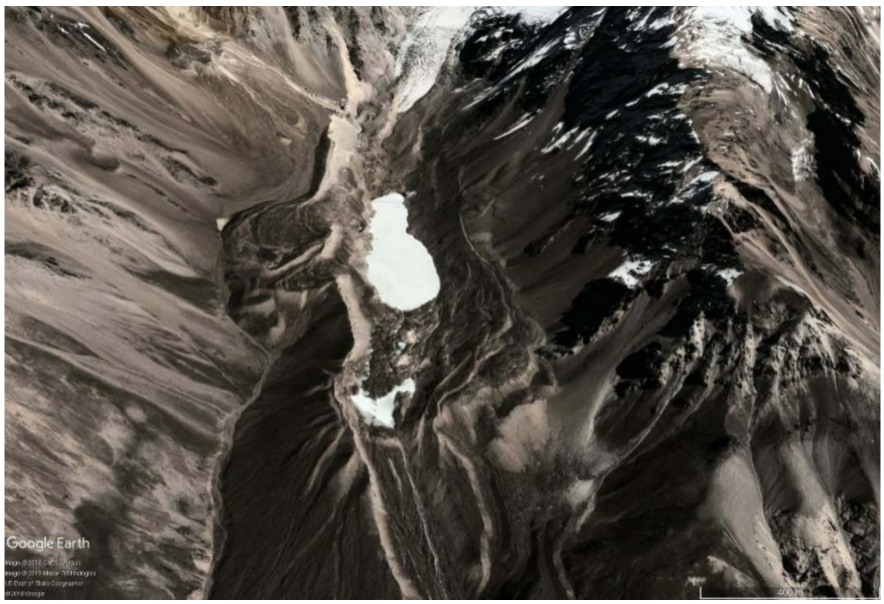
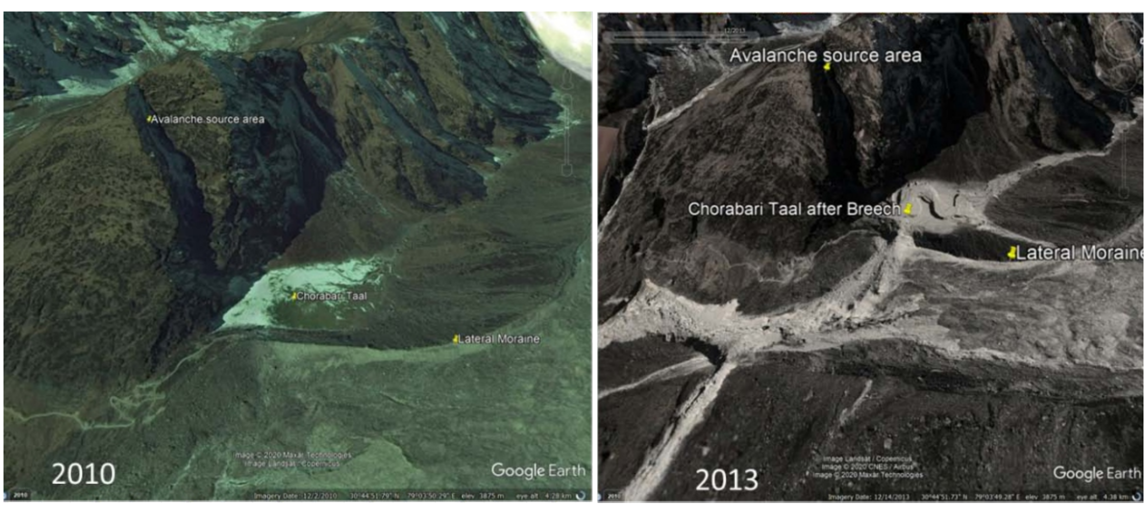


Figure 3.5: Lake in Uttarakhand, showing distinctive lobe-like, creeping flow structures around the lake, indicative of permafrost.



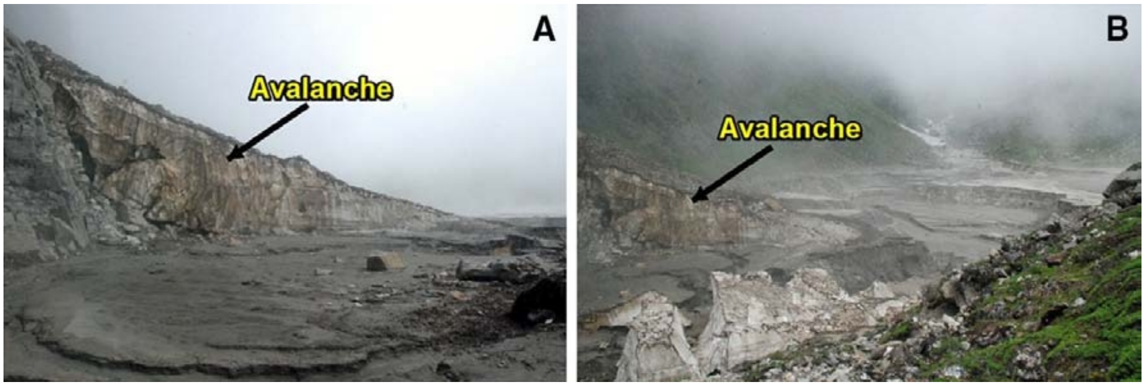


Figure 3.6: The high-resolution images showing the Chorabari Lake before(A) and after (B) GLOF disaster of 2013.
The lake, snow avalanche path and lateral moraine are clearly visible in the images. Avalanche material in Chorabari Lake after outburst (20.06.2013). *Photographs source: Uttarakhand police (Ref paper, Bhambari et al., 2016)*

3.5.1.2 Geotechnical and geomorphic factors

A distinction is made between those factors that are critical to the stability of the lake dam and those that determine the hydrological response of the lake catchment area, and thereby influence the susceptibility to precipitation or melt-triggered outburst events.

With high resolution optical and RADAR imagery (such as available World view, Cartosat-2, SPOT, ALOS-PRISM, TANDEM-X etc.) and corresponding high quality digital terrain models (e.g., ALOS DEM with 12.5 m; ALOS PRISM 5, 30 m DSM, Copernicus 12, 30, and 90 m DEM), it has become possible to quantify various physical characteristics of the dam and catchment area remotely over large spatial scales. However, precise geometric measurements (e.g. dam freeboard or dam height) and in situ characteristics (e.g., ice-core, lithology) can only be obtained through local site investigations. Some of the critical glacier lakes can also be mapped using UAVs with stereo imaging sensors, which can provide very high resolution (cm level) accurate DEM and as well as downstream river profiles for some critical and vulnerable river stretches. The required permission for use of UAV can be facilitated by state and central disaster management agencies.

GIS tools and remote sensing can be used to determine the upstream catchment area of each glacial lake, and quantify key characteristics of the mother glacier (topographic setting, debris cover etc) and hydrological characteristics therein. While empirical evidence linking catchment characteristics with GLOF susceptibility remains limited, it can be assumed that lakes fed by a steep, fast-draining catchment area are more susceptible to rapid inflow from precipitation or snowmelt. The same tools may be used to assess the topographic and geomorphological characteristics of the downstream flood path below the lake.

In the steep and tectonically active Indian Himalayan environment, GLOF triggering is closely linked to the stability of the surrounding mountain slopes and an integrated approach to glacier and permafrost-related hazard assessment is encouraged. Hence, Appendices 1 and 2 provide further consideration for the assessment of ice avalanches and rock.

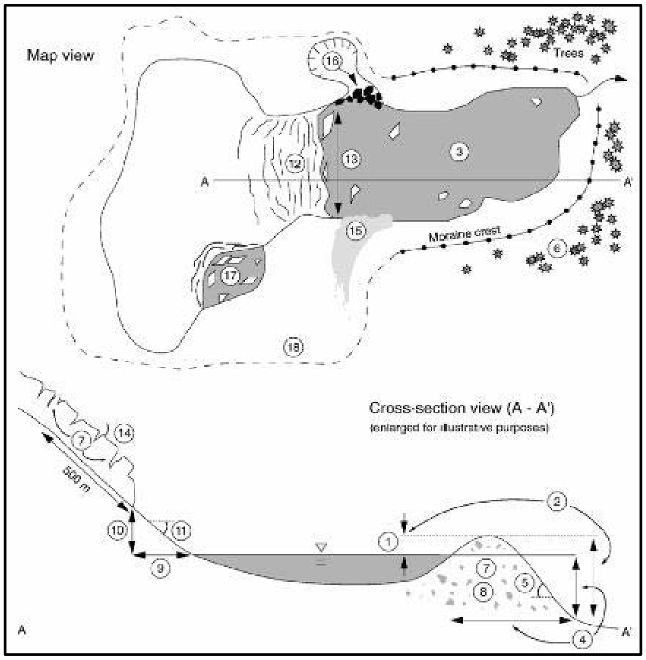


Figure 3.7: Summary of factors relevant to the stability of moraine dammed glacial lakes.
(*Source: McKillop and Clague)*

The figure above consists of: (1) lake freeboard, (2) lake freeboard-to-moraine crest height ratio, (3) lake area, (4) moraine height-to-width ratio, (5) moraine downstream slope steepness, (6) moraine vegetation coverage, (7) ice-cored moraine, (8) moraine lithology, (9) lake–glacier proximity (horizontal distance), (10) lake–glacier relief (vertical distance), (11) slope between lake and glacier, (12) crevassed glacier snout, (13) glacier calving front width, (14) glacier snout steepness, (15) snow avalanches, (16) landslides, (17) unstable lake upstream, and (18) watershed area.

3.5.2 Hazard mapping and zonation

Hazard mapping and zonation typically draws upon historical records to establish frequency – magnitude relationships that can then be used as a basis for scenario development and hazard modelling, e.g., hazard mapping for a given river floodplain might be conducted for a 20-year flood event with an established peak discharge of 1000 $m^3 s^{-1}$. For hazards such as GLOFs that originate in high mountain environments, the ability to establish reliable frequency – magnitude relationships are limited by three factors:

- Hazards originate often in remote, inaccessible locations, meaning even large events may have passed unnoticed and dates of previous events are missing or highly uncertain for the historical record.
- The cryosphere is changing rapidly and, in some cases, conditions are already beyond any historical precedence, meaning frequency – magnitude relationships are of decreasing significance.
- Many events can occur only once (e.g. complete incision of a moraine dam), and hence, frequency – magnitude relationships may not apply at all.

Given these limitations, a semi-qualitative approach to scenario development is recommended whereby scenarios of three different magnitudes (small, medium, and large) are linked to corresponding best estimates of the likely probability of occurrence (e.g., low, medium, high). The fundamental basis for the scenario development is the information gathered during the susceptibility and stability assessment, augmented where possible with best understanding of past events occurring in the region or other areas (Figure 3.8).

3.5.2.1 Scenario development

The goal is to establish three feasible scenarios based on the underlying lakes susceptibility assessment, where the potential mass or volume initiated in a small, medium, or large event is estimated, and a corresponding best estimate of the probability of such an event occurring is assigned. These scenarios then serve as input for hazard modelling and mapping (Section 3.5.2.2). The expert will ideally draw primarily upon the quantitative information coming out of the susceptibility and stability assessment, supported with field studies, available historical information, international evidence and process understanding to assign probability levels to the three scenarios. In view of rapidly changing environmental conditions, scenarios should be revised at regular intervals, to consider changing event frequencies and magnitudes.

For GLOFs, the following general approaches for scenario development are foreseen:

- Probabilities are specifically assigned based on careful consideration of the underlying lake susceptibility and stability assessment. All probability – magnitude combinations are possible.
- A simple inverse frequency-magnitude relationship is applied, with the large scenario assigned the lowest probability outburst event, and the small scenario the highest probability outburst event.
- Where there is an insufficient basis or reasoning to distinguish probabilities, it may be feasible to maintain the same probability level across all 3 scenarios, i.e., all three outburst scenarios are considered equally likely.

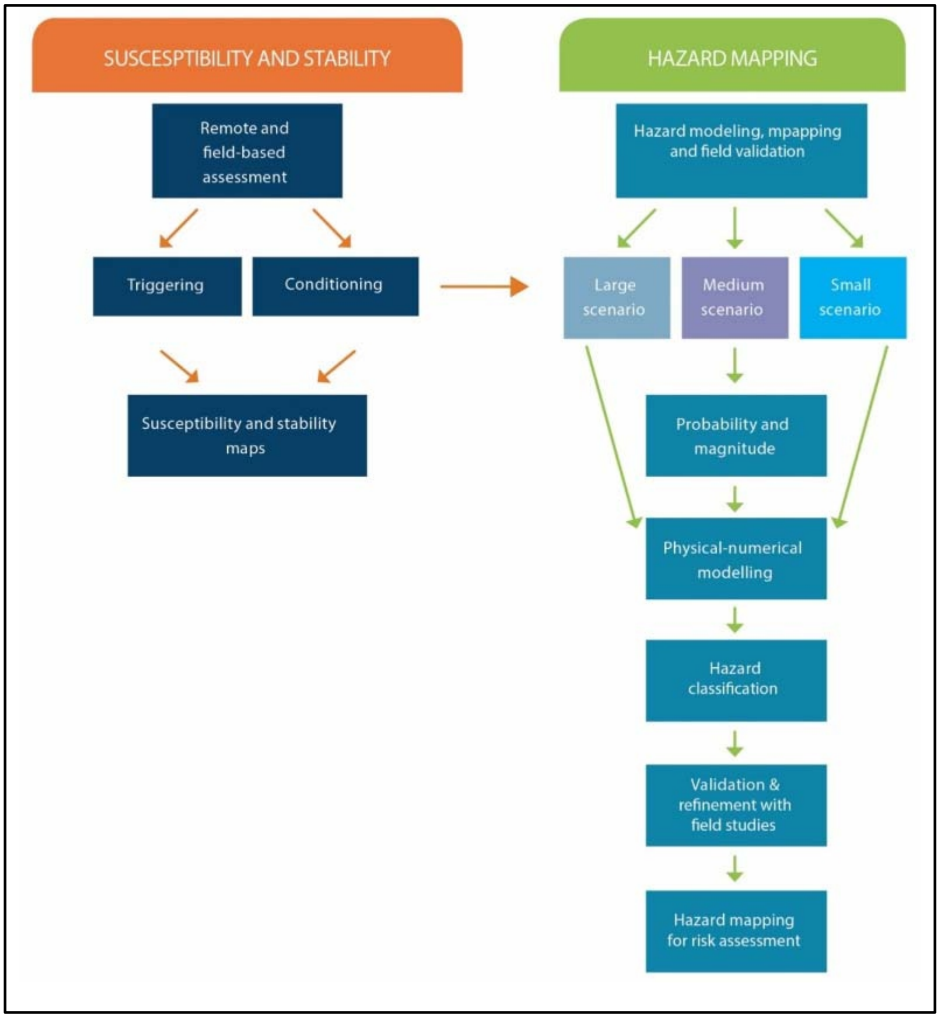


Figure 3.8: Framework for the assessment and mapping of glacial and permafrost-related hazards using a scenario-based approach (GAPHAZ 2017)

Scenarios for GLOFs are complex, owing to the various trigger mechanisms, lake types, and dam compositions. For bedrock-dammed lakes, where the only likely outburst mechanism is a mass movement triggered impact wave, a first approximation of the likely displaced water volume will be equal to the potential incoming mass. In this case, the associated probabilities will be linked to the ice and bedrock stability assessment for the surrounding slopes (see Appendices 1 and 2). For moraine-dammed lakes, the large scenario will involve complete incision of the dam and removal of the downstream slope of the dam, with steep, narrow dams most susceptible to irreversible erosion. Where the breach depth is greater than the mean depth of the lake, full release of the lake volume is possible. Due to the self-enhancing nature of dam incision, a large scenario may be considered equally probable as a small scenario for critical dam structures. For more favorable dam geometries, a reduction in outflow and cessation of erosion can occur well before the full lake volume has been emptied, making smaller scenarios more probable for impact-triggered events, and also events triggered by seepage and piping.

Based on empirical evidence, maximum (worst-case) flood discharge at the source can be correlated with lake volume (Huggel et al., 2002). The type of triggering process has a strong influence on the initial discharge, while process chains occurring downstream will influence the degree to which the flood attenuates, or even intensifies. For moraine dammed lakes, the determining factor is the rate and extent of breach development which can be simulated with modeling approaches (e.g. BASEMENT) where high resolution topography and bathymetric data are available. Typically, ice-dammed lakes draining sub- or englacial produce small floods relative to similar sized moraine-dammed lakes. However, for scenarios involving mechanical fracturing of the ice, peak discharge may be comparable as for moraine dammed lakes, while large lakes trapped behind surging glaciers may produce exceptionally large magnitude and high probability events.

In view of possible extreme outburst events characterized by very low probabilities but very large dimensions and potential societal impacts, a single “worst-case” scenario can be proposed. This could be appropriate, for example, for a very large volume lake that is deemed to have very-low probability of an outburst. Included under this category could also be scenarios relating to anticipated new lakes, threated by avalanches of ice or rock from surrounding degrading and destabilized slopes. According to the hazard modelling results (see section 3.5.2.2) the potential land area affected by such a worst-case event could be marked as an area of residual danger.

It is not possible to be prescriptive about how scenarios should be established, and considerable expert judgement is required. For instance, whether and how a “worst-case” scenario is modeled should be part of a discussion with local authorities and responsible institutions because it involves a political, economic and social dimensions. Most importantly, lake breach and subsequent GLOF scenarios should be developed in consensus with local stakeholders and the scientific community.

3.5.2.2 Hazard modelling and mapping

To link the results of scenario modelling with a corresponding hazard level, a matrix-based approach to hazard classification is typically used, as for instance employed within the Swiss codes of practice. For each scenario, the 3-by-3 matrix links the modelled flood or mass movement intensities with the assigned probability level for that scenario, to establish a danger or hazard level (Figure 3.9). Multiple scenarios (e.g., small, medium, large scenarios) can then be overlaid and fine-tuned through field mapping to arrive at a final hazard map. This common framework can be applied for various processes occurring in glacial environments (GLOFs/debris flows, landslides, avalanches etc.).

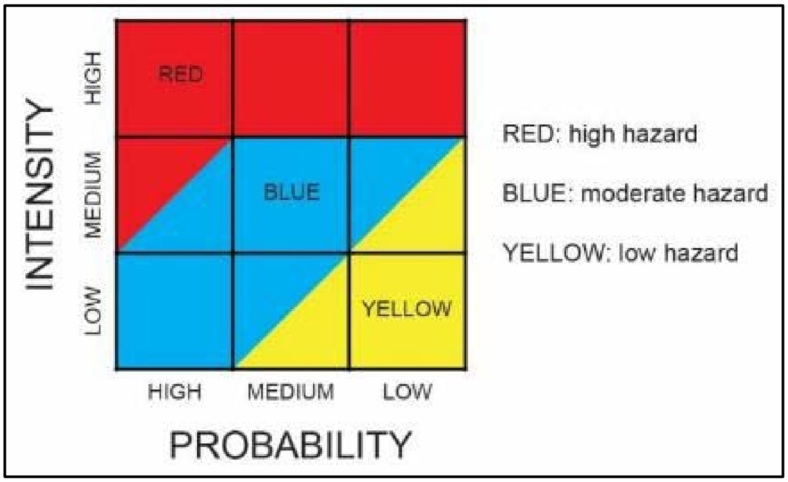


Figure 3.9: Matrix based approach for linking the susceptibility assessment (probability) with the scenario-based intensity modelling to arrive at a hazard classification. *(Colors are usually subject to nationally defined standards*)

Various numerical modelling tools are available for simulating GLOFs and other mass movements as a basis for hazard mapping and land zoning (Appendix 3). There is no best-approach, and selected models should align to local requirements, capacities, resources, and data availability. For example, in the case of South Lhonak lake, Sattar et al. (2019) have undertaken hydrodynamic GLOF modelling and downstream hazard assessment using the freely available HEC-RAS (Figure 3.9).

According to the Swiss practice, qualitative intensity relates to potential damage the event could cause to people and property (if they were present).

High intensity : people and animals would face threat of injury inside buildings; heavy damage to buildings or even destruction of buildings would be possible.

Medium intensity : people and animals would face threat of injury outside buildings, but would face low threat levels inside buildings; lighter damage to buildings should be expected.

Low intensity : people and animals would be slightly threatened, even outside buildings (except in the case of stone and block avalanches, which could harm or kill people and animals); superficial damage to buildings could be expected.

Various quantitative criteria can be used to define these intensity classes using one or more outputs from the model simulations. Indicative values proposed in Switzerland for defining the hazard intensity classes for different high mountain processes are given in Table 3.3. These definitions should serve as general guidance only, and other definitions may need to be identified based on the local context and physical characteristics of the built environment (e.g., house construction material).

Note that for some processes not all three intensity classes are valid, e.g., in the impact zone of a rock avalanche the intensity is always considered *high*. Likewise, for debris flows, *low* intensities are not considered, according to the Swiss guidelines.

Table 3.3 : Indicative values for the intensity classification for various high mountain hazards as used in Swiss practice (after, Hürlimann et al., 2006; Raetzo et al., 2002).

Kinetic energy (E); Velocity (v); flow depth or height of the deposit (h).

Phenomena	Low intensity	Medium intensity	High intensity
Rockfall	E < 30 kJ	30 < E < 300 kJ	E > 300 kJ
Rock avalanche			E > 300 kJ
Landslide	v≤ 2cm/year	v:dm/year (>2cm/year)	v > 0.1 m/day for shallow landslides; displacement > 1m per event
GLOF/ Debris flow (single parameter)		h < 1 m	h > 1 m
GLOF/ Debris flow (multiple parameter)		h < 1 m or v < 1m/s	h > 1 m and v > 1m/s

As outlined under the scenario development, extremely rare and potentially large "worst-case" events are not included within the matrix classification approach. Such very low probability events are typically classified within a zone of residual danger where modeled intensity levels are high (in Switzerland, for instance, this zone extends to include events with a return period of >300 years). The implications of the final classified hazard zones and appropriate management responses will vary based on the local societal, governance, and legal context.

Figure 3.10 shows the GLOF hazard modeling and mapping approach adopted for South Lhonak Lake in Sikkim state.

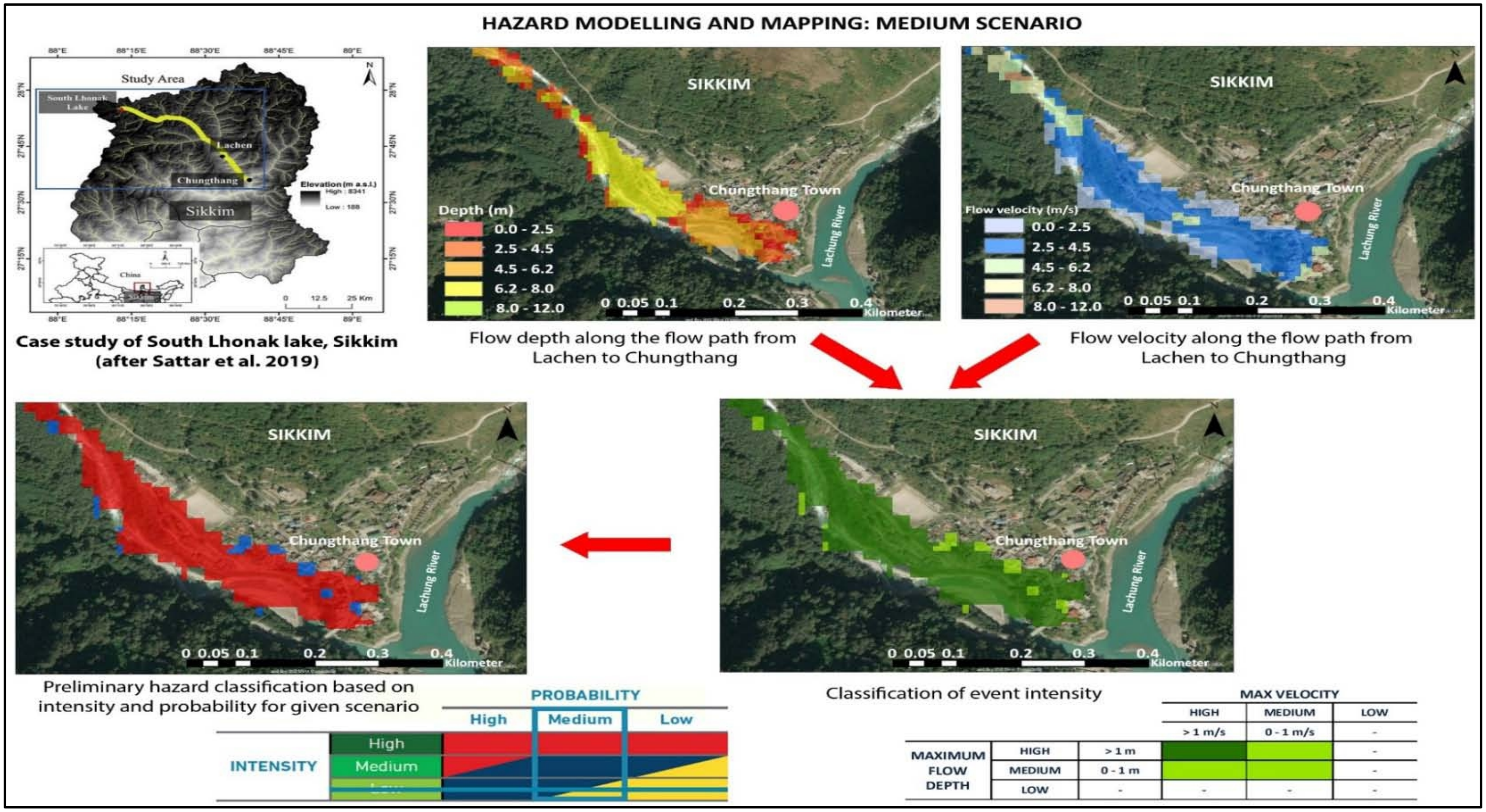


Figure 3.10: Illustrative example of GLOF hazard modelling and mapping for South Lhonak lake, Sikkim *(based on Sattar et al. 2019).*

3.5.3 Risk Assessment

In order to advance from a hazard assessment to a risk assessment, results from the hazard mapping need to be combined with information on exposure (of people, assets, infrastructure and ecosystems), with information on vulnerability.

3.5.3.1 Exposure

The most challenging aspect is to quantify exposure of livelihoods, environmental services, and also to determine temporal dimensions of exposure. In high tourism areas, for example, many buildings located in a flood path may be unoccupied for much of the year, and in agricultural areas, families may migrate up or down valley to different land holdings depending on the season. Given such challenges, exposure mapping should also be supported with information collected at the ground level through community surveys and focus group meetings (see also vulnerability capacity assessment VCA below). This should also integrate information on grazing areas and multi-locality of households.

Where possible, it is also important to consider how exposure might evolve in the future, in response to changing population dynamics, expansion of tourism, and foreseen infrastructural development. Some of this information likely exists within government department plans and could be integrated within a forward-looking risk assessment.

3.5.3.2 Vulnerability

A detailed risk assessment requires that patterns of vulnerability are characterised at the ground-level, within potentially affected communities, using participatory surveys and focus group discussions. Community-level surveys and focus group meetings could bring together community leaders, farmer organizations, self-help groups, and other grass-roots organizations to explore local drivers of vulnerability, and undertake a qualitative Vulnerability Capacity Assessment (VCA). In particular, we highlight the importance of ensuring good representation of marginalized and disadvantaged groups in such participatory studies, including nomadic/seasonal populations, woman, children, and people with disabilities. The 2009 National Policy on Disaster Management also underlines the importance of including these groups when undertaking a comprehensive assessment of vulnerability.

Important components that can be included in a VCA include:

- **Historical time line:** Analysis of the historical climate-related impacts (not only glacier related) from a community point of view. The participants will list major climate-related impacts of the past 30–40 years, including enumeration of major political, socio-economic and environmental/climatic changes and development interventions that may have played a role.

- **Seasonal calendar:** Identification of the temporal periods of stress, hazards, vulnerability and other issues in the community including livelihoods and coping strategies, to reveal seasonal trends.

- **Patterns of vulnerability:** Analysis and ranking of vulnerabilities across different social groups and sectors including identification of the most vulnerable people and sectors, and the driving factors.

- **Stakeholder mapping:** Participants identify the institutions that are crucial for building adaptive capacity, adaptation planning, and disaster management in their community.

- **Coping mechanisms:** Listing of the various mechanisms and networks that communities utilise to cope with climate change and natural disasters, both community-led and with support of authorities and other external agencies (e.g. financial assistance, insurances).

The results of participatory VCA's can be used to validate and refine large scale indicator-based assessments (see 3.4.1), ensuring that the selected indicators adequately capture the perceived drivers and patterns of vulnerability in a community. Participatory VCA's are best led by institutions and agencies that have long-standing experience and established relationships within the communities.

3.5.3.2 Integrated Risk Mapping

Final risk maps can then be created by combining hazard mapping/zones, with vulnerability and exposure maps. Figure 3.11 provides an illustrative example of a GLOF risk assessment undertaken for the state of Himachal Pradesh, where standardised indices were multiplied to establish GLOF risk at the administration unit of a Tehsil. Under this approach, GLOF risk (R) is calculated as the consequence of the physical hazard (H), intersecting with vulnerable (V) and exposed people (E):

$$R = H \cdot V \cdot E$$

Comparable GLOF risk assessments at local-scale (e.g. for a village or community) are rare, but should follow the same approach of combing standardised values of hazard, exposure and vulnerability. As seen with the example of a local debris flow/flood risk assessment in Colombia, South America (Figure 3.12), risk assessment at this scale provides information on risk levels for specific dwellings and properties, providing a robust basis for the implementation of risk reduction strategies that aim to address those most affected by a potential event.

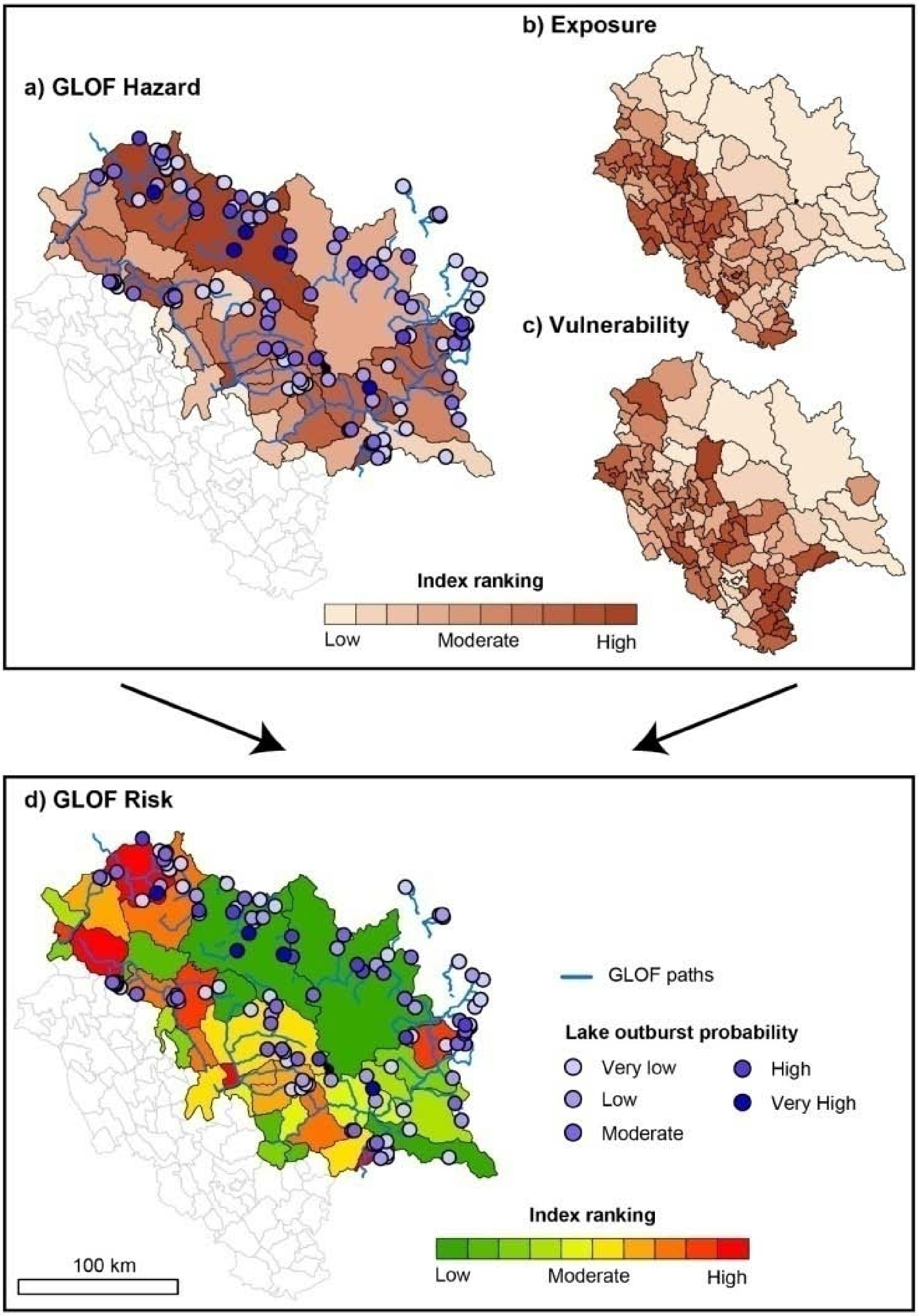


Figure 3.11: Large-scale GIS based assessment of GLOF risk, integrating mapped indices of GLOF hazard, exposure and vulnerability (Source : Allen et al., 2016)

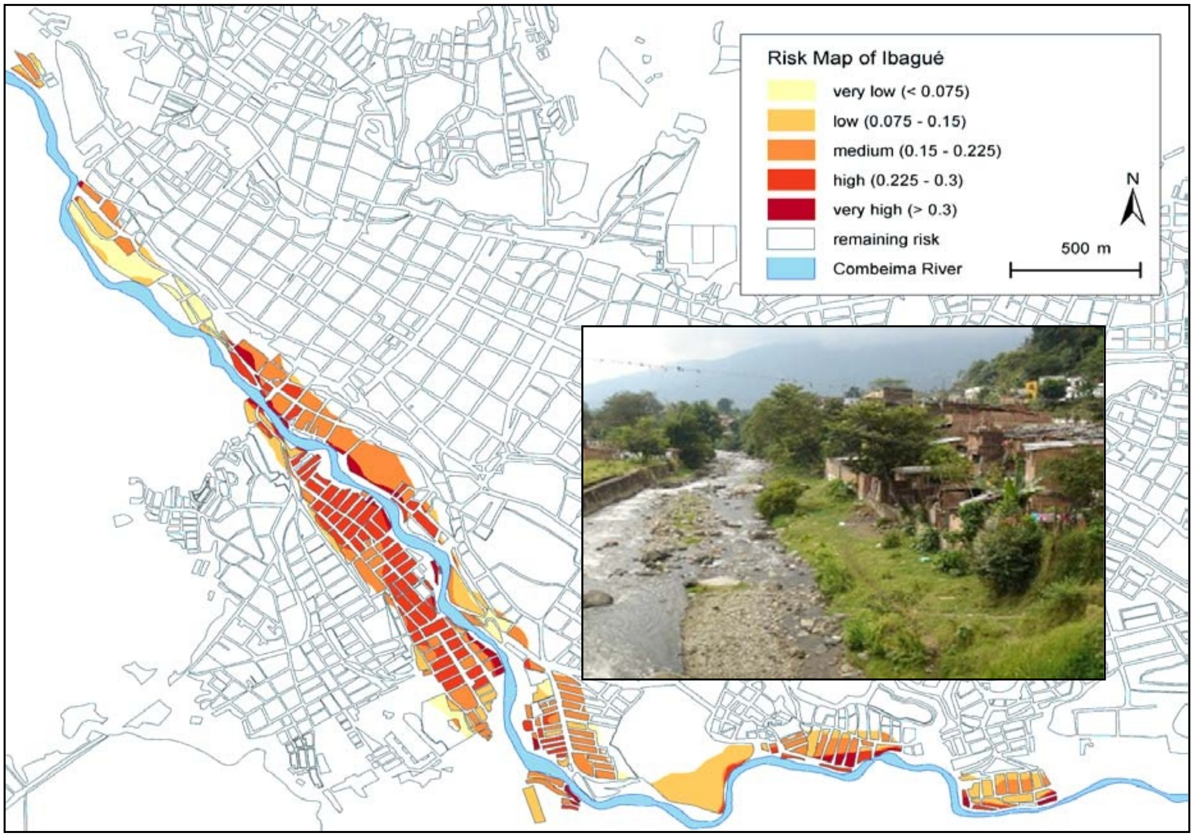


Figure 3.12: Flood and Lahar risk map for the Colombian city of Ibague, combining information on hazard, exposure and vulnerability *(Source : Künzler et al., 2012)* .

Chapter 4: Monitoring, Risk Reduction & Mitigation Measures

4.1 INTRODUCTION

A prerequisite for successful, effective and sustainable risk management and risk reduction is a comprehensive and detailed site-specific risk assessment (cf. Chapter 3). Only the information provided by such an assessment allows the relevant authorities to take informed decisions on the most suitable measure or measures for effective and sustainable reduction of risks in a given situation. For the identification of suitable risk management options, thus, a comprehensive, multi-risk approach should be followed. This is also important in order to avoid any unintended negative effects.

Involvement of the local stakeholders in the planning of risk reduction measures is essential to guarantee an effective risk reduction strategy that is also supported by the local population. Ownership of risk reduction measures by the local population furthermore is important in view of maintenance and sustainability.

Risk reduction and mitigation measures may incur huge costs and may not be feasible to implement, therefore Central/State Governments should apply a cost-benefit analysis and focus on implementing the strategy part that covers up for the major percent of the risk.

A treatment plan for each option may be used to delineate how the option will be implemented. The plan also needs to identify the responsibilities of each stakeholder during and after implementation, the extent of work required, cost estimates, the implementation programme, performance evaluation of the measures, the expected outcome, and a maintenance strategy. It is essential to reconsider all the stages of analysis, assessment, and prioritisation as the treatment plan evolves and is implemented.

4.2 CASE STUDIES IN HIMALAYAN REGION

India has a remarkable history of successful warnings in relation with LLOFs, dating back to the 19th century. In 1894, a landslide in Gohna, Uttarakhand (UK), dammed the main river. On 5 July that year, the engineer in charge estimated the lake to overflow the dam in mid-August, which eventually happened. Despite the devastating impact of the flood, including washing away most of the buildings along the river and severe destruction in the town of Srinagar, no victims were reported, thanks to the precise prediction of the event and related efficient dissemination of the early warning to the population (Nature, 1894). This was made possible by the installation of a telephone line between the lake and the towns of Chamoli, Srinagar, etc., located downstream (Dimri, 2013). This can be considered as the first Early Warning System (EWS) for lake outburst floods in the Himalayas.

At global scale, a number of GLOF risk reduction measures have been implemented at glacial lakes or in the downstream communities, threatened by these lakes. The most prominent mountain range in the world in terms technical risk mitigation measures at glacial lakes, is the

Cordillera Blanca Peru. In this mountain range in the tropical Andes, the national glaciological office implemented structural remediation measures at more than 35 glacial lakes. Tunneling, culverts and spillways, siphoning, artificial and reinforced dams and artificial drainage systems and combinations thereof are the most commonly used techniques. Details on Peruvian lake mitigation experiences can be found in Portocarreo (2014).

One of the most promising options for efficient and effective disaster risk management, is the implementation of EWS. EWS are promoted by the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) and the number of EWS for all kinds of natural hazards has been increasing over the past years. Nevertheless, the number of implemented and operational GLOF EWS is still very small, even at the global scale. In the Himalayan region, three cases are reported, where sensor and monitoring based technical systems for GLOF early warning have been implemented (Table 4.1). In two of the three cases, at TshoRolpa and Imja Lake, these EWS were complemented by structural measures for lake level lowering.

Table 4.1: Selected Cases of GLOF EWS implementations in the Himalayan region.

Lake	Region	Year	Reference
TshoRolpa	Rolwaling Valley, Nepal	1998	Rana et al. (2000)
Imja lake	Everest region, Nepal	2008	Fukui et al. (2008)
Kyagar glacial lake	Shaksgam Valley, PR China	2013	Haemmig et al. (2014)

However, today none of these systems is operational, mainly due to a lack of identification and ownership by the local population (c.f. Watanabe et al., 2016, for the Imja case). This emphasizes the importance of the involvement of the local population for a successful and sustainable implementation of EWS.Another example for a GLOF EWS from the Peruvian Andes is described in more detail below (Section 5.5.5)

4.2.1 The Operation Phuktal (2015)

In cases where the dammed obstruction needs to be removed like river blockage due to landslide, explosives are sometimes used to clear the way for effective drainage.One such landslide occurred along the Phuktal River (tributary to Zanskar River) on December 31, 2014 about 90 km from Padum in Kargil district of Ladakh which led to blockage of the river and eventually led to a potential flood situation (Fig. 4.1).

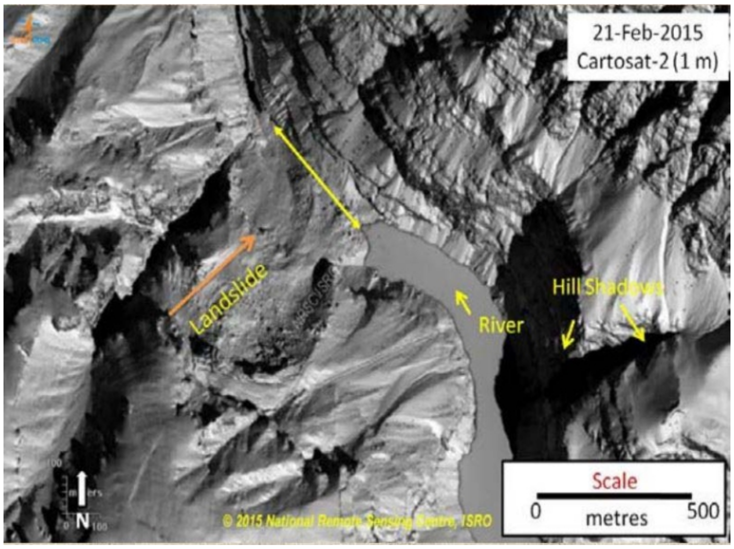


Figure 4.1: Blockage of Phuktal River due to landslide as can be seen from the image obtained through CARTOSAT- 2 *(Source: NRSC).*

It posed a major threat to life, property and infrastructure especially the Nimmo Bazgo dam.The NDMA created an Expert Task Force from various organisations. The Task force along with Indian Army devised explosives for channelization of water from landslide dammed river through control blasting and manual excavation by clearing out the landslide debris (Fig. 4.2).

Figure 4.2: Indian Army installing a safety rope from camp base to the landslide location.

4.3 RISK REDUCTION TECHNIQUES AND MODELS

Risk reduction can be effective on each of the three components of risk (hazard, exposure, vulnerability). The selection of an adequate action depends on the urgency of the situation, the available resources as well as the specific characteristics of the site. In many cases, a combination of different measures will result in a more robust and effective reduction of disaster risk. A detailed hazard and risk assessment, according to the procedure described (Section 3.5), provides the information for a decision on (a) robust risk management option(s). Figure 4.3 gives an overview of such actions, which are further described below.

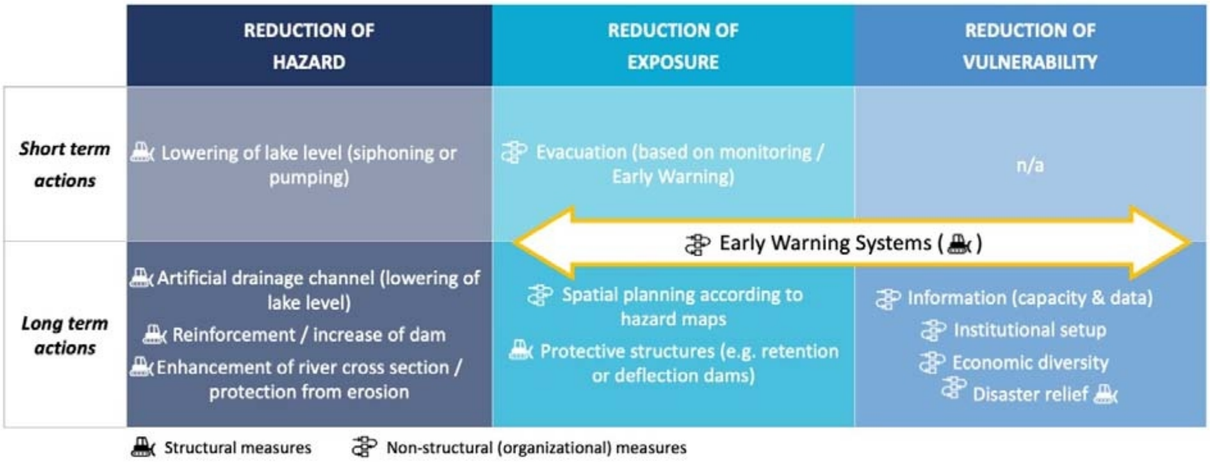


Figure 4.3: Overview of options for the risk management of glacial lakes.

These options can be discriminated by the risk element the actions are effective on (i.e. reduction of hazard, reduction of exposure or reduction of vulnerability). Also, these options can be distinguished into structural and non-structural (i.e. organizational). Structural measures (c.f. digger symbols in Figure 4.3) typically involve the construction of remediation structures, either at the lake itself, or at the settlements or infrastructure potentially affected. Such structural measures have the potential to be very effective for risk reduction, in particular when achieving a substantial reduction of the hazard. However, such actions are expensive, especially when implemented in remote regions, such as the IHR. Limited access for heavy machinery can be an impeding factor for such actions. Organizational, non-structural measures, on the other hand, in many cases can be cheaper and faster to implement. As they often aim at a reduction of exposure and/or vulnerability, they can be effective not only for GLOF and LLOF related risks, but for the reduction of multiple risks.

For decision making on risk reduction measures, cost-benefit evaluations need to be applied. In such analyses, the estimated costs of a measure, including its maintenance costs during the planned lifetime of the measure, are contrasted to the costs of the prevented damages to evaluate whether the investment is justified or not.

4.4 MANAGEMENT OPTIONS FOR GLOF &LLOF INDUCED HAZARDS AND RISKS

4.4.1 Hazard Reduction Options (Artificial Drainage System i.e., Siphoning Techniques, Control Blasting, etc.)

Actions aiming at a reduction of the hazard typically involve structural measures at the glacial lake itself and thus aiming at a reduction of the outburst susceptibility or a reduction of the magnitude of a potential event. Such measures have parallels with structural measures for floods outlined in the Section 3.3.3 of the National Disaster Management Plan (NDMA 2019), focussing on enhancing the safety of reservoirs and construction of embankments and levees.

Lowering the lake level directly influences the hazard potential of a lake, as it reduces the volume of the lake (and thus the potential flood volume and peak discharge) on the one hand, and on the other hand increases the freeboard of the dam, which is another important factor of the lake outburst susceptibility. In the short term and in emergency situations, the level of a lake can be lowered by siphoning or pumping. The effectiveness of such efforts depends on the characteristics of the site, as well as on the access to the lake, the availability of equipment for siphoning and/or pumping and the experience of the personnel involved in such actions. Grabs and Hanisch (1993) present experiences from the Himalayas, where lake level were lowered by about 5m.

At moraine dammed and landslide dammed lakes with a low freeboard and thus in a critical situation, highly susceptible for an outburst, it is in some cases possible to lower the lake level by lowering artificially the outlet point. However, such an action is extremely risky, as it might initiate the formation of a breach, by starting a self-reinforcing process of increased discharge and increased erosion, eventually causing a GLOF or LLOF. Such measures should only be undertaken with utmost care, and have to be accompanied by measures to prevent erosion in the artificially created outlet channel.

Figure 4.4: Artificial Channel Enlargement of Imja Lake, Nepal, 26 September 2016 *(Source: UNDP). (Artificial channel enlargement for lake level lowering is a very critical moment, as it can lead to the formation of a breach and a GLOF / LLOF)*

Culverts and open spillways are introduced in the moraine crests generally at the lowest point to keep excavation volumes to a minimum. The construction is usually carried away in a cofferdam as to isolate the site from the lake. Culverts are generally reinforced with concrete or are made up of cast sheet metal. Geotextile liners may also be used to line channels and protect the floor from erosion. Spillways are generally left opten, but it is recommended to install gateways which can control downstream erosion during the initial phase of draw down e.g. Tsho Rolpa, Nepal (Rana et. al., 2000). Strong implementation and safety measures are required when dealing with critical lakes.

Reinforcing and/or increasing the dam is a suitable option for the hazard reduction of lakes dammed by moraine and other unconsolidated material. Raising the dam crest increases the dam freeboard and decreases the potential for overtopping of a large volume of water in case of a large displacement wave in the lake. Reinforcing the dam with a stone facade provides protection against erosion and the initiation of a breach formation.

Such measures have been successfully applied to more than 35 lakes in the Cordillera Blanca, Peru over the past seven decades. Portocarreo (2014) gives an overview of the typical steps involved in such works:

1. Establish logistical access to the site.
2. Lowering of lake level by pumping or siphoning. Successful applications of siphoning have been made at lakes at altitudes up to 4,500 m a.s.l. (Reynolds GS Ltd, 2003). Applications at higher lakes remain to be tested.
3. Permanent reduction of lake level
    a. For moraine dammed lakes:
        i. Cutting the downstream face of the moraine into a V shape
        ii. Installing a reinforced concrete pipe* of appropriate diameter
        iii. Building an earth dam with a stone facade over the pipes, restoring much of the original V- shaped cut in the moraine (protection against the hydrodynamic effects of big waves). Cf. Fig. 4.5, left)
        iv. Open cuts* are also an option (Fig. 4.5, right), c.f. remediation measures at Tsho Rolpa and Imja Lake. In these cases, the floor and the sides of the drainage channel need to be protected by concrete or geotextile liners (Reynolds GS Ltd, 2003).
    b. For bedrock dammed lakes:
        i. Drilling of one or several drainage channels/tunnels* through the bedrock dam.
        ii. Tunnels in moraine dams have only been drilled above water .level in order to limit any rise in water level (e.g. Safuna Alta Lake, Peru) (Reynolds GS Ltd, 2003).

* for pipes, cuts, channels and tunnels, measures have to be taken to prevent objects (blocks of ice or snow; driftwood; etc.) from entering the structure and cause a blockage of the drainage.

Figure 4.5: (a) Outlet channel with reinforced dam reconstruction at the moraine dammed lake Laguna Cuchillacocha, Peru *(Photo: C. Portocarrero)*, **(b) Open channel at Imja Lake, Nepal, inaugurated in October 2016** *(Source: UNDP).*

The major disadvantages of such structural measures are the related high costs. In particular, in remote regions of the IHR, with glacial lakes often located in rough and inaccessible terrain, such works are not feasible. An alternative to this is structural works implemented at locations between the lake and the settlements/ infrastructure at risk. This can include retention basins, retention and/or deflection dams.

4.4.2 Exposure Reduction Options

Exposure can be reduced either (i.) on the short term in the form of an evacuation in case of an event or (ii.) on the long term, by considering hazard maps of all relevant processes for spatial planning. Restricting constructions and development in GLOF/LLOF prone areas is a very efficient mean to reduce risks at no cost. Roles and responsibilities concerning the regulation and enforcement around flood plain zoning and flood inundation management are outlined in Section 7.2.4 of the National Disaster Management Plan (NDMP 2019).

For (i.), information on imminent or ongoing events is needed, such as, for instance, provided by an Early Warning System (Section 5.5). Since GLOFs are very fast processes, an evacuation must be executed within very short time, this requires an alarming infrastructure, clear protocols for all involved actors, and capacitation of the involved population and responsible authorities. Besides classical alarming infrastructure consisting of acoustic alarms by sirens, modern communication technology using cell and smart phones can complement or even replace traditional alarming infrastructure.

(ii.) In contrast to other countries, there are no uniform codes for excavation, construction and grading codes in India. Nevertheless, a hazard map provides a solid basis for the consideration of hazards in the spatial planning:

In the high hazard zone, the construction of any habitation should be prohibited. Existing buildings are to be relocated to a safer nearby region and all the resources for the relocation have to be managed by Central/State governments. New infrastructure in the medium hazard zone have to be accompanied by specific protection measures. Retrofitting techniques to strengthen the weak structures should be implemented in order to protect existing infrastructure.

Land use planning is the most effective and economical ways of reducing losses due to landslides by avoiding the hazard and minimizing the risk. There are no widely accepted procedures or regulation in India for land use planning in the GLOF/LLOF prone areas. Such regulations need to be developed concerning the increased risk of future GLOF/LLOF events.

Figure 4.6 shows a hazard map with five levels of GLOF hazard, along with indicated evacuation routes (arrows) and safety zones (green rectangles with a white S). Such a hazard map with evacuation routes included, in combination with a spatial planning and building law, is a very effective tool for the reduction of exposure.

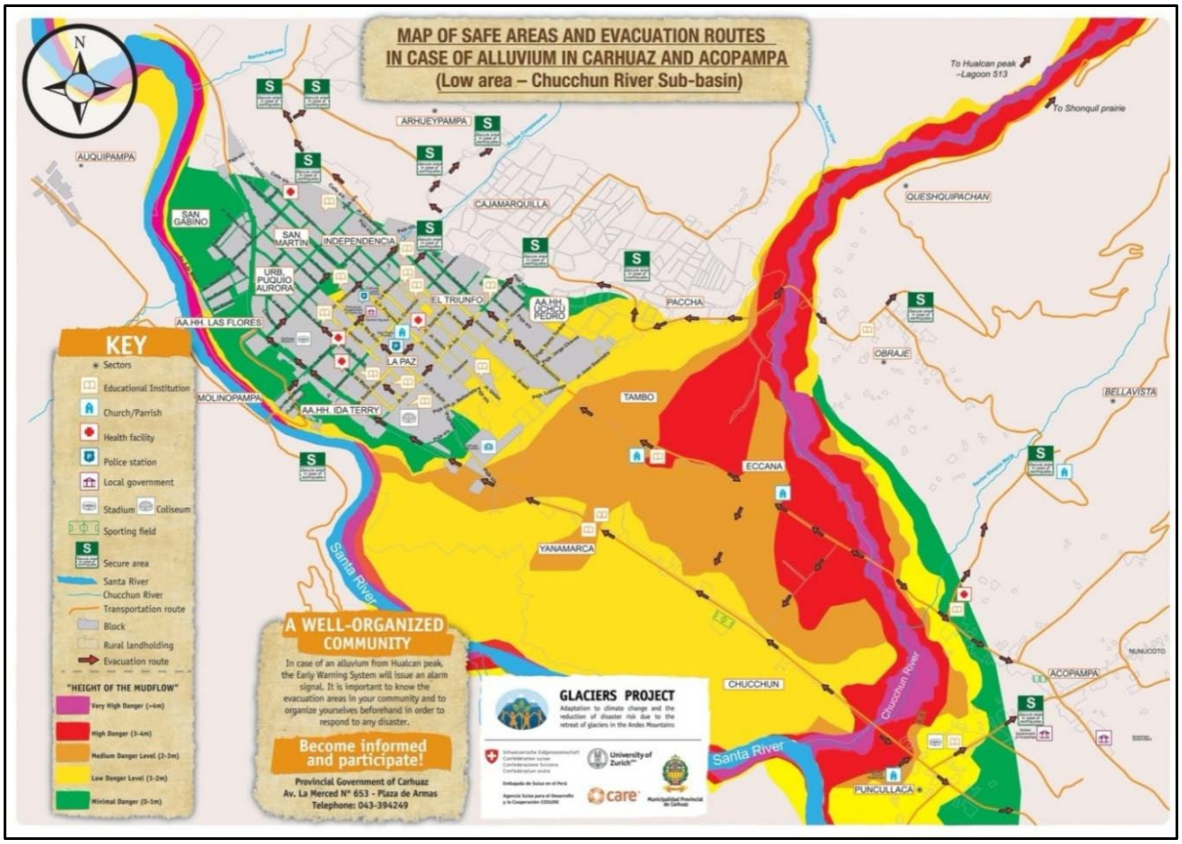


Figure 4.6:GLOF hazard map for the city of Carhuaz, Peru *(Source: CARE Peru)*

[Used as a tool for risk communication and reduction: Besides the hazard zones, evacuation routes(arrows) and safety zones (green rectangles with a white S) are indicated]

Locally and for particularly vulnerable infrastructures such as schools, hospitals, hydropower installations, pilgrim sites, major bridges, communication and energy lines, etc., protective structures like retention or deflection dams can significantly reduce the exposure of selected entities.

4.4.3 Vulnerability Reduction Options

Vulnerability can only be reduced in the long term. Based on the vulnerability assessment, weaknesses should be extenuated or eliminated. Capacity building with the population at risk is a crucial activity to reduce vulnerability on climate change, which also has a positive effect on most other risk management actions. Such capacity building should provide the relevant understanding of climate change and related impacts at both a regional and the local scale. Also, it should take into account cultural and traditions as well as local knowledge on experienced changes of the physical environment. Knowledge on the perception and prioritization of the different risks provides valuable information for the selection of site-specific and adequate risk management actions, which will be accepted be the local communities.

Insurances and compensation for losses are a further, efficient mean to reduce vulnerability. GLOF/LLOF insurance would be a logical means to provide compensation, and at the same time an incentive to avoid or mitigate the hazard. GLOF/LLOF insurance coverage could be made a requirement for mortgage loans. Controls on building, development, and property maintenance would need to accompany the mandatory insurance. Insurance and appropriate government intervention can work together, each complementing the other in reducing losses and compensating the victims.

Figure 4.7: Representation of a school where children were taking part in mock drill.

4.4.4 Immediate mitigation measures in urgent and critical situations

In situations, like for instance directly after landslide depositions are blocking a river or when a glacial lake cannot be drained artificially, i.e. in cases where immediate dam failure is likely, the following immediate measures should be taken:

I) In case a report of landslide dam formation after heavy rainfall/strong earthquake/ rapid snowmelt in hilly areas is received, the vulnerable areas will be reconnoitred immediately, if required by helicopter, to see whether more such landslide dams have been formed or not. For inaccessible areas and trans-boundary rivers, the vulnerable areas will be monitored by the NRSC through satellites on a real-time basis. If such an occurrence is noticed, the situation will be monitored continuously and information about the developments will be communicated immediately to the designated authorities such as the MHA, NDMA and the concerned SDMAs.

ii) The SDMAs will establish and activate the warning and communications systems immediately so that information reaches the last post on a real-time basis and proper action is taken by all players involved in an effort to save lives and minimise the loss to property and infrastructural elements.

iii) Satellite data will be consulted for understanding the nature of damming. The pre- and post-occurrence satellite data would be useful in understanding the cause of impounding, extent and the areas affected. This becomes an important tool in inaccessible areas. Periodic monitoring will be done using satellite data to understand the breaching, etc.

iv) A team of experts will reach the affected site as soon as possible to monitor the situation, assess the stability status of the structure and landslide activity, and changes in water level in the impounded lake. The teams will implement the required initial measures to the extent possible immediately. One of the immediate tasks will be to establish a communications link between the site and the designated authorities. This would help the authorities to take appropriate decisions related to preparedness and response whenever required. If, however, overflow from the dammed lake has already begun, or the dammed body is collapsing, then urgent preventive measures to prevent losses in downstream areas will have to be adopted on an emergency basis. Attempts will be made to release the impounded water in a controlled way by creating an outlet.

v) If the landslide/glacial/moraine dam is found to exist without any immediate threat of failure, then actions involving preparedness in the eventuality of an outburst of the landslide dam, or dam stabilisation, depending upon site conditions, will be formulated.

vi) Removal measures: If there is negligible risk of outburst then the dam formed can be excavated or blown out with explosives after assessing the probable impact on downstream areas, or the dam can be left as it is without taking any immediate measures. The partial removal of the blockage will be in a phased manner to the extent that the threat to downstream areas is minimal.

vii) Monitoring the stability status of the landslide dam, even if it is apparently found to be stabilised, and the water level behaviour, will be continued for longer periods. This can be done through earth observation systems and by installing automatic telemetric water level recorders at site. Similarly, hydrological observations will be continued by installing automatic telemetric rain and discharge gauges for both the upstream and downstream areas of the site.

viii) Assessing the stability of the dam and the possibility of its failure due to overtopping, piping, heaving, floods, impact of new landslides, impact of earthquake, etc., through detailed field investigations and testing of the materials forming the dam.

ix) Evolving remedial measures on the basis of the probable causes and mechanism of the collapse of the dammed body in advance. These should be checked for their efficiency and implemented as soon as site conditions are permissible.

x) For assessing the flood hazard posed by the dam in the event of its breaching by a landslide/glacial ice/moraine, Dam Break Analysis will be conducted for identifying vulnerable areas. Communities living in such areas will be kept in a state of alert as long as the threat of flash floods exists.

4.5 MONITORING TECHNIQUES

4.5.1 Introduction

Torrential rain or earthquakes may cause large-scale flank collapse damming the river channel. The collapse of such a landslide dam causes catastrophic downstream flooding. The biggest difference of such landslide-dammed lakes to glacial lakes is that glacial lakes can be identified and the risk assessed in a planned way, as the glaciers and moraines have a fixed position, unlike landslide dams which are unpredictable. Thus, more time is available to plan and implement measures to reduce the likelihood of GLOF. This can be ensured through continuous monitoring. The various means and methods which can be adopted for monitoring are discussed below.

4.5.2 Monitoring Glacial Lakes

Between early warning (hours to minutes), and long-term monitoring of dangerous lakes (annual to biannual), there is a challenge to detect new threats that may emerge over the course of days, weeks, and months. This can include rapidly expanding glacial lakes in response to prolonged heavy rainfall, new glacial lakes as a result of blockages in the glacial hydrological system or associated with surging glaciers, and newly formed landslide lakes. Asmany of these processes are more likely to occur during the monsoon months, cloud cover can prevent the use of optical remote sensing. There are therefore opportunities to exploit Synthetic-Aperture Radar (SAR) imagery to automatically detect changes in water bodies, including new lake formations, during the monsoon months. Methods and protocols could be developed to allow year-round remote monitoring of lake bodies from space, as a compliment and precursor to ground-based early warning systems at critical lakes.

National Remote Sensing Centre (NRSC) had completed a project during 2011-15 on "Inventory and Monitoring of Glacial Lakes / Water Bodies in the Himalayan Region of Indian River Basins", sponsored by Climate Change Directorate, Central Water Commission (CWC), New Delhi, Govt. of India. Under this project, glacial lakes and water bodies located in all three major river basins viz., Indus, Ganga, and Brahmaputra including transboundary region were mapped with a water spread area of size greater than 10 ha using IRS-AWiFS sensor data of 56 m spatial resolution. A total of 2,028 features were mapped consisting of both glacial lakes (503) and water bodies (1,525). It was observed that there are 352, 283 and 1,393 glacial lakes and water bodies in Indus, Ganga and Brahmaputra river basins respectively. Glacial lake extent change monitoring for lakes of size greater than 50 ha (477 glacial lakes and water bodies) has been carried out by NRSC from 2011 to 2015 during monsoon period of June to October on monthly basis. The continuation of glacial lake monitoring is being carried out by CWC for 477 lakes from 2016 onwards (every year) on monthly basis during monsoon months using IRS-AWiFS satellite data. The entire GIS database on glacial lakes and water bodies over Himalayas mentioned above is available with CWC.

In addition to or instead of remote sensing approaches, a combination of precipitation thresholds and river stage monitoring can be considered for the monitoring of landslide dammed lakes, as described below:

4.5.2.1 Use of Remote Sensing Technique

Majority of glacial lakes around the world are located in remote and hardly accessible regions. The use of remote sensing data is therefore of high importance to identify and assess their potential hazards. Besides National satellites, nowadays, a series earth observation satellites provide freely available data, both optical imagery and SAR data. Prominent examples, for instance, are the Landsat series or the Sentinel satellites of the European Space Agency (ESA). Combinations of different data sources is encouraged; this can significantly increase temporal and spatial coverage.

Cloud cover poses a major limitation to the use of optical satellite imagery. In particular monsoon dominated regions of the IHR, such as Sikkim, a state with a large number of glacial lakes, this implies, that during summer months, mostly no useful imagery is available. Remote sensing data and methods of Synthetic Aperture Radar (SAR) provide promising alternatives to optical remote sensing techniques, due to the ability of the radar signal to penetrate clouds and its independence of daylight. SAR data from different satellites is freely available, such as Sentinel-1 from ESA. Strozzi et al. (2012) proved the feasibility of glacial lake detection and monitoring using SAR data and techniques.

Monitoring through GIS - The glacial lakes & water bodies are delineated based on the visual interpretation of satellite images of Resourcesat-2 AWiFS sensor or other suitable imagery, preferably multispectral optical data. Identification of features is done through panchromatic mode and/or different colour combinations of the multi-spectral bands namely Green, Red, Near InfraRed (NIR) and Short-WaveInfra-Red (SWIR). Given the location of glacial lakes at high altitudes and the spatial resolution, LISS IV and III imagery might be a more suitable alternative to AWiFS. Identification of features is done through panchromatic mode and/or different colour combinations of the multi-spectral bands namely green, red, near infrared and shortwave infrared. To identify the glacial lakes & water bodies, different image enhancement techniques are used to improve the visual interpretation. With different spectral band combinations in false colour composite (FCC) and in individual spectral bands, glacial lakes and water bodies can be identified. The knowledge of image interpretation keys: colour, tone, texture, pattern, association, shape, shadow, etc. will also enhance the capability of identifying these features. The water spread area of the lakes in false colour composite images ranges in appearance from light blue to blue to black. The frozen lakes appear white in colour, similar to clean-ice glacier surfaces. Sizes of water bodies are generally small, having circular, semi-circular, or irregular shapes with very fine texture. The boundary of glacial lakes and water bodies are digitized as polygon feature using on-screen digitisation techniques. The polygons are geo-processed and the water spread area of glacial lakes & water bodies computed digitally. These steps may be repeated for each date of satellite data and water spread area computed.

4.5.2.2. Object-Based Image Analysis (OBIA) technique

Traditionally supraglacial lakes SGLs (as small as 100 sqm) were mapped through field surveys which are laborious, risky and time consuming. The location of these glacial lakes in rugged and remote terrain makes it difficult to monitor them manually. Remote sensing plays a vital role in creating inventories and monitoring of the glacial lakes quickly and accurately due to wider coverage and repetition. The satellite images provide greater details for the evaluation of physical conditions of the area. There are alternative approaches to manual mapping of SGLs, for instance by using automated or semi-automated mapping approaches. Also, there are ways of processing remote sensing data using a technique called Object-Based Image Analysis (OBIA) technique.

4.5.2.3. Field investigation of critical lakes

Field investigations including topographical and bathymetric mapping, hydro-meteorological observations, and geological, geophysical and glaciological surveys may be carried out for high priority/vulnerable lakes. Reconnaissance by field survey may include investigation of the stability of the moraine by topographical survey of the moraine, the outlet, and the surrounding area, including changes in the lake shoreline and the position of the glacier terminus. Drones and other unmanned aerial vehicles (UAVs) provide powerful tools for efficiently combining on-site field work and remote sensing techniques.

The selection of critical lakes should be done based on a first-order, regional assessment of hazards and risks of glacial lakes, based on remote sensing analyses.

4.5.2.4 Monitoring by trekking guides

The guides and porters employed by private/ semi-government agencies are regular visitors to the glacial lakes. This resource can be amalgamated into the monitoring grid after suitable training and registration, for effective surveillance and reporting of the glacial lakes.

4.5.3 Precipitation threshold for landslides

Rainfall is widely recognized as an important trigger for landslides, posing an increased threat to people and economies worldwide under climate change conditions. Rainfall thresholds, defined as the best separators for triggering and non-triggering known rainfall conditions, are the most used instrument in landslide hazard assessment and early warning tools. The most common parameters used to define empirical thresholds are the combinations of rainfall intensity duration, rainfall event-duration, and antecedent rainfall conditions.

The relationship between the amount of rainfall associated with landslide occurrences is generally studied using either an empirical or physical based approach. Physical process models are based on numerical models which study the relationship between rainfall, pore water pressure, soil type, and volumetric water content that can lead to slope instability. Such a study is usually site specific due to variation in soil properties. It is a challenge to extend this approach to large areas, as the extensive data that is required are usually not available, and their use for an early warning system is either experimental or prototype based. On the other hand, empirical methods study the landslides that are caused by rainfall events—both massive downpour that triggers instantaneous landslides and the low but continuous antecedent rain that destabilizes the slope and triggers the landslide. Although, there are many factors like rainfall, earthquake, geology, soil type etc. involved for landslide triggering, in the present study, precipitation rates have been considered as this is the primary cause of several changes in soil properties, pressure variations, etc. The minimum quantity of precipitation requisite for landslide occurrences known as thresholds can be determined using empirical models. The limit is defined by lower-bound lines to the precipitation conditions causing landslides and plotted in Cartesian, semi-logarithmic, or logarithmic coordinates.

Contingent upon the kind of available rainfall data, empirical thresholds can be summarized as follows:

(1) thresholds which combine rainfall data obtained from specific rainfall events,

(2) thresholds involving antecedent parameters, and

(3) alternating thresholds, like hydrological thresholds

For setting up an early warning system using empirical rainfall thresholds, various factors need to be taken care of:

- collection of reliable and large rainfall and landslide datasets.
- selecting threshold parameters depending on landslide characteristics and precipitation data.
- defining the events and using an objective and standardized methodology.
- validation of the thresholds determined.

4.5.4 Measurement of River and Lake Water Level

River stage is an important concept when analysing how much water is moving in a stream at any given moment. Stage is the water level above some arbitrary point, usually with the zero height being near the river bed, in the river. It is important to be able to remotely monitor how fast water is rising "in real time" in order to warn people that might be affected by a dangerous flood. At the same time, unusual low water levels, e.g. almost no flow during a rainfall period, might indicate a temporary blockage of the river upstream the measurement station.

Water level or stage of the River is measured as its elevation above the GTS datum. Water level measurement was conducted by reading non-recording gauges. A series of vertical staff gauges as per the specifications laid down in IS 4080-1977 have to be fixed at three sections at each site i.e. upstream, station gauge and downstream. The gauge posts are generally of RCC/wooden/ metallic with cut and edge waters and are fixed securely in position by installing them in concrete blocks of suitable size. Enameled gauge plate with marking in metric unit is fixed on the gauge posts with least count 0.005 m. Out of the three-gauge lines the central line is used as station gauge line and readings of the other two lines are used for calculating the surface slope.

There exist also water level recorders for continuous or distinct, automated measurements of water levels. Two types of water level recorders exist, (i) pressure sensors, which determine changes of the water level based on changes of water pressure, and (ii) contact-less sensors, using sonic waves to determine water level. Such automated devices for water level measurements and recording as well have the potential to be incorporated into an automated monitoring or early warning system.

Water levels are usually monitored by means of gauging stations. However, water level gauges are characterized by some drawbacks as for instance their point wise measurements and their limited use in uneasy-to-access environments. Moreover, their accuracy can be affected by several issues such as severe storm events and systematic errors.

Water level sensors installed along the banks of the river channel, immediately downstream of the lake outlet can be used in an Early Warning System (EWS) for GLOFs to detect the onset of a breach, cf. Section 5.7.

In addition to the traditional methods of WLs, the satellite altimeter and LIDAR can also be used for basin level WL monitoring of glacier lakes and downstream rivers (Thakur et al., 2020; Yuan et al., 2020).

4.6 EARLY WARNING SYSTEMS

Increasing the availability of EWS for disaster risk reduction is one of the seven targets of the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015). EWS range from very simple approaches, including a watchman, equipped with a communication device, observing a critical situation and a simple alarming procedure, up to complex technical multi-hazard warning systems, comprising high-tech monitoring devices and sensors, data transfer, storage and access protocols, as well as warning, alarming and response procedures, involving stakeholders and actors at various scales. The selection of an adequate system depends on the situation and site characteristics, the urgency of a situation, time horizon/duration of the critical situation, available resources and available infrastructure.

Monitoring, Early Warning and Alarming are key elements for an effective reduction of disaster risk, and the National Policy on Disaster Management (2009) emphasises the need to establish, upgrade and modernise forecasting and early-warning systems for all types of disasters. As indicated in Fig. 4.3, Early Warning Systems (EWS) are able to reduce both the exposure as well as the vulnerability of the potentially affected population. EWS are complex systems, involving not only technical, but also social, political and even juristic aspects. As defined by the United Nations International Strategy for Disaster Reduction (UNISDR, 2006), EWS consist of four key elements (Figure 4.8):

- Risk Knowledge
- Monitoring and Warning Systems
- Dissemination and Communication
- Response Capability

Figure 4.8: Key elements of Early Warning Systems *(source : UNDP 2018)*.

Till date, there area very limited number of GLOF EWS operational globally. This is due to the extremely challenging conditions, with short warning times, limited pre-event indicators, often combined with the necessity to evacuate a large number of persons. In the following, the four EWS elements are outlined in more detail.

4.6.1 Risk Knowledge

A detailed, site-specific risk assessment is a prerequisite for an effective design and successful implementation of an EWS. This includes a detailed assessment and mapping of hazard and a detailed evaluation of the vulnerabilities. Hazard maps allow the identification of sites for stations and installations of the EWS. Knowledge of the different types of vulnerabilities of the potentially affected population is needed for the development of a suitable communication and warning strategy (Element 3).

Risk is undergoing constant changes. The hazard situation is altered by retreating glaciers, changes in the stress fields and thermal conditions of steep slopes, varying and changing hydrometeorological conditions, and other changes related to global warming. At the same time, the other components of risk, exposure and vulnerability, are continuously changing as well. Population and infrastructure are in flux, reflecting the socio-economic developments and resulting in constant changes of vulnerability and exposure. For these reasons, EWS continuously need to adapt to changing natural and socio-economic conditions, related emergency plans and procedures have to be updated periodically. Eventually also the underlying risk assessments need to be updated in a frequent manner, to reflect and consider ongoing changes.

4.6.2 Monitoring and Warning Services

The monitoring and warning services constitute the technical core component of an EWS. This element comprises the installation of adequate measurement devices to constantly observe the critical parameters. This potentially includes sensors at the lake, in the lake surrounding, at the dam/outlet, in the stream and at other sites potentially at risk. Also, remote information from other sources can be part of the monitoring strategy of an EWS, such as satellite observations, meteorological and hydrological prediction models etc.

For the monitoring strategy it is important to incorporate redundancy into the system, to guarantee a potential event will be predicted or registered, even if one of the monitoring components or observing stations fails. Continuous operability needs to be guaranteed, even under the extreme conditions typical for high-mountain regions (extreme temperatures, wind, snow cover, harsh meteorological conditions with limited visibility, etc.). In particular the energy supply for the monitoring devices can be a challenge. Electricity is normally needs to be provided by solar panels and batteries, also under conditions of continues cloud cover over several weeks to moths and low temperatures.

Figure 4.9: EWS station equipped with an infrared camera, a solar panel, data logger and communication cable monitoring a lake on Plaine Morte glacier, Switzerland *(Photo: L. Meier).*

Data transmission, storage, and access is another component of the monitoring and warning element of EWS. This comprises the transmission lines (cable, radio, satellite), which should as well have redundancy to prevent the failure of the system in case of a failure of a transmission line; a data storage infrastructure as well as protocols and interfaces for data access by the different users of the system. The data storage infrastructure must guarantee a long-term storage of the obtained information, and at the same time secure the constant access to this information, even in moments of black outs and when the data centre potentially is affected by an event. A decentralized storage infrastructure is therefore recommended. Finally, the obtained data needs to be processed and converted into readily available formats, such as graphics. Eventually the data component of an EWS has to manage the access of the different users (authorities, population, scientist, etc.) to the different kind of data and information stored.

Based on the risk assessment and understanding (Element 1), preliminary warning, alerting and alarming thresholds need to be defined for the different observed parameters. These thresholds have to be evident and comprehensible for the authorities and personnel in charge of issuing warnings and have to be defined in a standardized warning protocol.

4.6.3 Dissemination and Communication

The dissemination and communication element comprises the distribution of understandable alerts, warnings and alarms, including also preparedness information to the population at risk. In their recommendations for building functional EWS, UNDP notes that *"Historically, most failures in EWS occurred due to miscommunication – not equipment or infrastructure failure – further underscoring the gravity of this element"* (UNDP, 2018).

A critical component of this EWS element is the establishment of an institutionalized decision-making protocol. In such a protocol, it needs to be specified which institution or person has to do what based on which information (Figure 4.10). For the elaboration of such a protocol, it is important to include all relevant stakeholders and authorities at different levels.

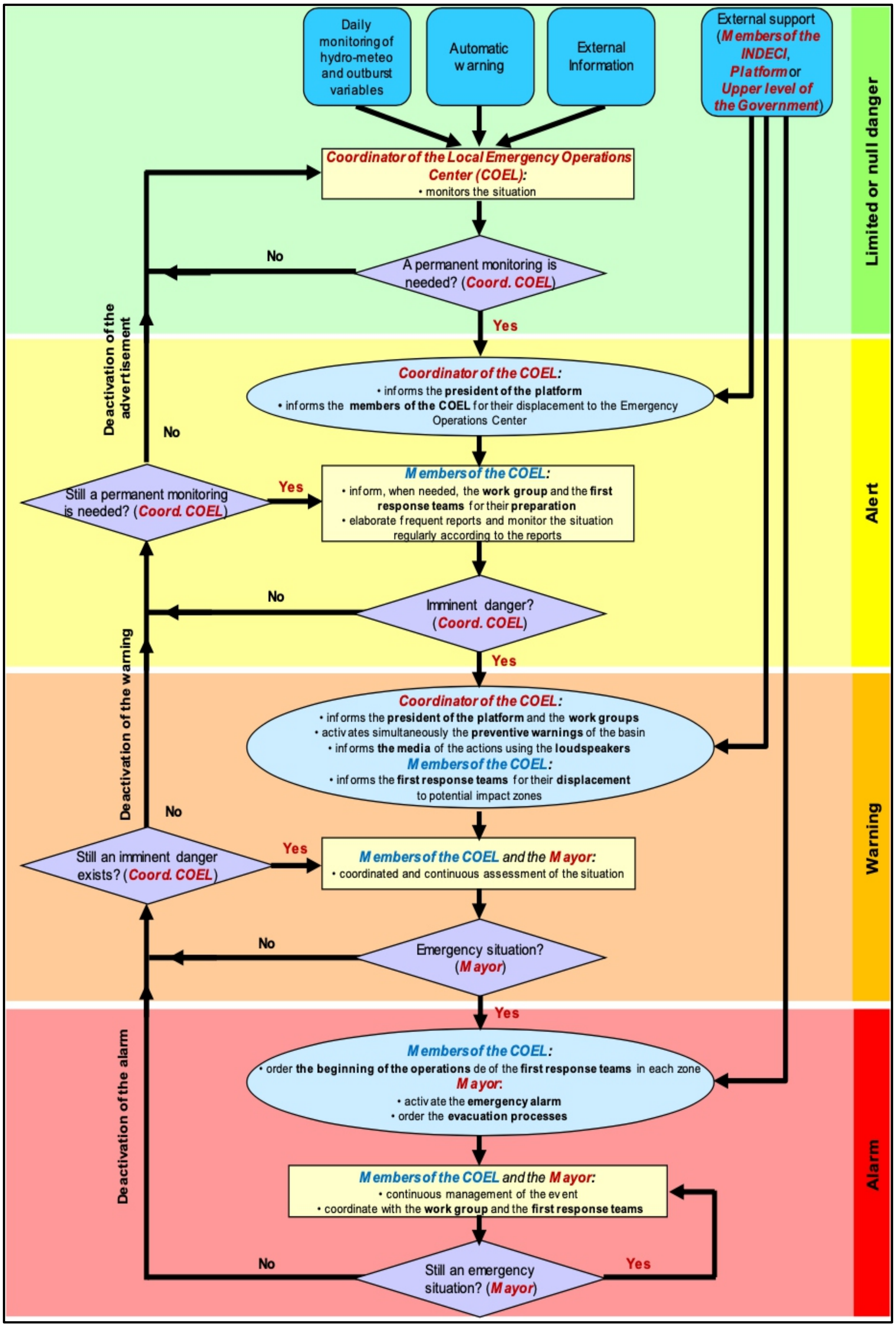


Figure 4.10: Flow chart type protocol of a GLOF Early Warning System in Peru.

It is essential that the decision-making protocol is simple and clear. In many situations involved stakeholder will have very limited time for decision making and might be under stress. At the same time, constant availability of the involved stakeholders has to be guaranteed, also at night and public holidays. A deputy system is indispensable in most cases.

Whatever risk communication infrastructure is chosen, it is important the system is reliable and consists of disaster-resistant hardware. Similar to the monitoring element, also the dissemination and communication element should include redundancy in the alerting and alarming infrastructure, in particular during black outs which will affect both acoustic sirens as well as mobile communication antennas and networks.

The warnings issued by the EWS should not only warn about a specific, imminent disaster risk, but also empower people at risk to take effective countermeasures to reduce and mitigate their individual risk. Therefore, detailed knowledge of the habits and vulnerabilities of the different groups of population, including marginalized groups and minorities, is needed to find the right linguistic and technological tools to issue effective warnings. Language, dialects, linguistic limitations and literacy have to be considered for this. Positive experiences have been made with short, simple and clear messages, using a traffic light colour scale for the different alert and alarm levels (e.g. green = save, yellow = alertlevel 1, orange = alert level 2, red = alarm and evacuation, cf. Fig. 4.10). Such streamlined communication is valuable in situations where the receiver of information may be under pressure or in extremis.

4.6.4 Response Capability

Response capability, the last element of EWS, consists of the centralised knowledge, plans, protocols and other inputs needed for timely and appropriate action by affected population and involved other stakeholders and authorities. Prerequisites for a successful response to EWS warnings are that the endangered population is aware of the looming risks and perceives them as relevant, and also that they have trust in the Early Warning System.

Preparedness and response capacity can be significantly improved through drills and trainings (Figure 4.11). Such simulation events not only allow the population to familiarize with the warning and alarming procedures and related risk reduction measures, but at the same time also train the authorities operating the EWS. Direct campaigns to raise risk awareness and perception, as well as checklists of actions to undertake in certain situations are further activities to improve the response capacity within the different groups of the population.

Figure 4.11: Evacuation simulation with school kids in a rural settlement in the Andes
(Photo: CARE Peru).

4.6.5 General Remarks

Due to the technical complexity of some systems, it is essential to have a calibration phase after the installation of an EWS. This time is needed to refine the warning thresholds, and for the personnel operating the EWS to familiarize with the system. This calibrations phase should be used for simulations and drills.

In order to guarantee a constant availability and operationality of an EWS, maintenance of all components of the system is indispensable. Sensors and hardware have a limited lifetime, in particular under harsh high-mountain conditions.Also, the software needs to be constantly updated to new technological standards. The costs of such maintenance work need to be considered in the budget of the authority or institution responsible for the operation and maintenance of the EWS.

4.6.6 Case study of a GLOF Early Warning System at Lake 513, Cordillera Blanca, Peru

Site history

The glacial lake Laguna 513 (9°12'45''S, 77°33'00''W) is located situated at 4428 m a.s.l., at the foot of Mt. Hualcán (6104 m a.s.l.) in the tropical Andes of Peru (Fig. 4.12).

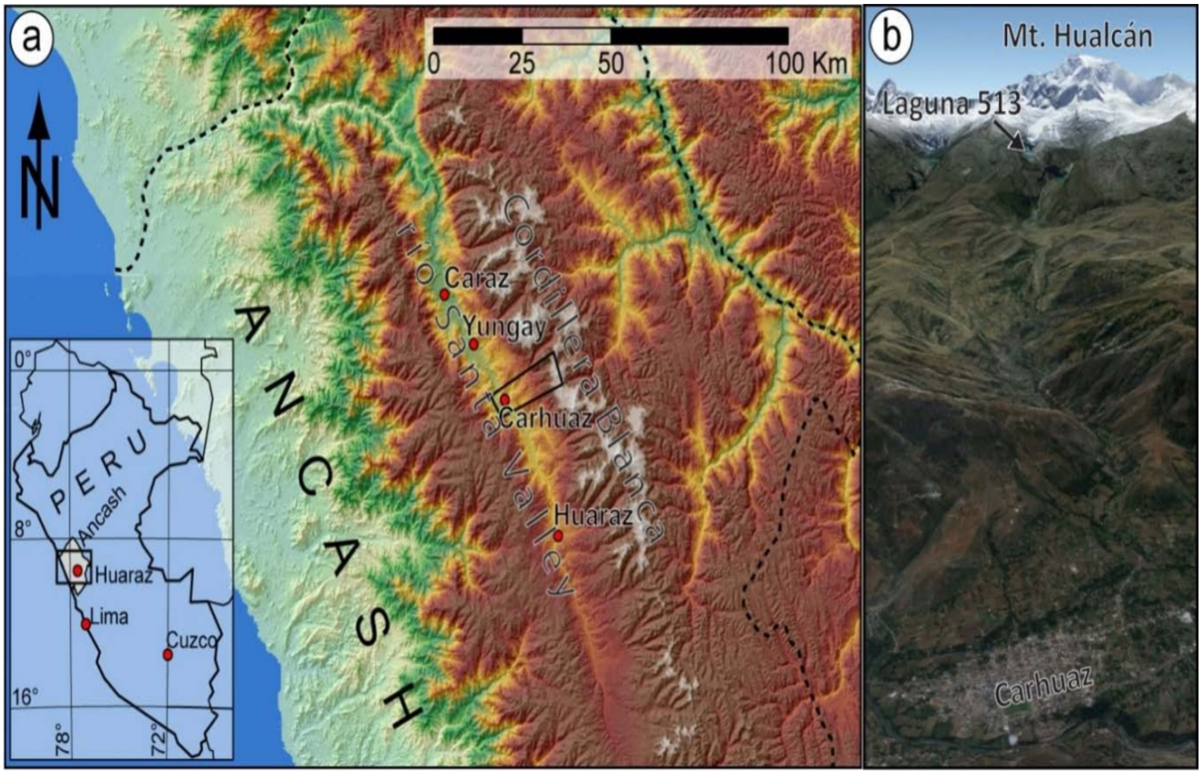


Figure 4. 12: (a) Location of the Cordillera Blanca, Peru. Black rectangle indicates the location of b; (b) Oblique view of Mt. Hualcán, Laguna 513, and the city of Carhuaz in the foreground *(GoogleEarth™)*

On 11 April 2010, at about 8 a.m. local time, a rock-ice avalanche with a volume of about 450,000 m^3, detached from the SW slope of Mt. Hualcán (Carey et al., 2012). The avalanche impacted Laguna 513, causing a tsunami-like push-wave, resulting in a spillover at the dam, despite the 20 m freeboard (Fig. 4.13). Traces of the wave indicate an overtopping of the dam by about 5 m, corresponding to a wave height of about 24–25 m, and causing a very high peak discharge (Schneider et al., 2014). The resulting GLOF damaged several bridges along its trajectory and eventually reached the debris fan of the city of Carhuaz (about 20,000 inhabitants), where the coarse material of the GLOF was deposited. 0.689 km^2 of agricultural land was buried and the Santa Valley highway was affected, but no lives were lost.

Risk knowledge

This lake outburst from 2010 was reconstructed by simulating the process cascade with an iterative approach of coupled, physically-based models. This model chain was then used to simulate potential future scenarios of different magnitudes, following the hazard assessment procedures described in this document, which finally resulted in a hazard map for GLOF hazards for the entire catchment (Schneider et al., 2014).

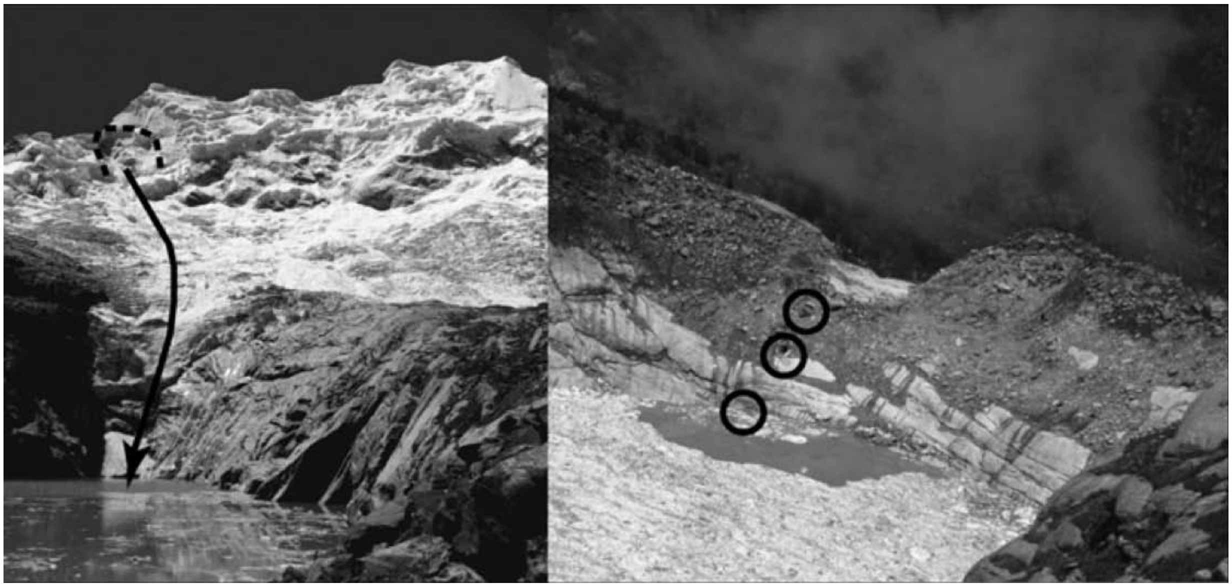


Figure 4.13: (a) Detachment zone and trajectory of the rock-ice avalanche from Mt. Hualcán, (b) Rock dam with overlaying morainic material and the breach that was formed by the overtopping wave *(Circles indicate entrances of drainage tunnels. Avalanche ice is still floating on the lake)(Source:Carey et al. (2012))*.

Monitoring and warning

Based on the gained insights and the improved process understanding from the reconstruction of the 2010 outburst and the modeling of the potential future scenarios (Risk knowledge element), a GLOF EWS has been designed and implemented in the catchment.

The EWS comprises two stations, one located at the dam of Laguna 513, one in the Pampa Shonquil, a data center located in the building of the Carhuaz municipality, and a repeater station for transferring the signal from the lake to the data center (Fig. 4.14).

Figure 4.14: The four stations of the EWS

(Dashed arrows indicate the direction of the signal transfer; the dashed line corresponds to the catchment margins. Background: topographic map from the Austrian Alpenverein and the GLOF hazard map)

The stations are equipped with the following instruments:

1. ***Data center*** **(2640 m a.s.l.):** Receiving antenna, screen with real-time data access, server for data storage, infrastructure for launching alarms (not implemented yet)
2. ***Repeater station*** **(3189 m a.s.l.):** Receiving and sending antenna
3. ***Station Laguna 513*** **(4491 m a.s.l.):** 2 cameras taking photos every 5 seconds during daylight times, one looking at the face of Mt. Hualcán, one observing the dam (cf. Fig. 4.16). 4 geophones located close to the station, continuously measuring and sending data in 5 second intervals. Receiving and sending antenna and data logger.
4. ***Station Pampa Shonquil*** **(3600 m a.s.l.):** Pressure sensor located in the riverbed, Meteorological station with sensors for measuring air temperature and humidity, precipitation, wind speed, and solar radiation. Sending antenna and data logger.

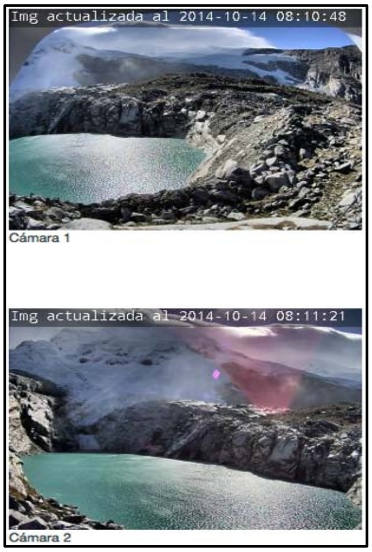
All stations are equipped with solar panels and batteries for energy generation and storage, have a mast where most of the instruments are fixed, a concreted and lockable box for the electronic equipment, and a protection fence (cf. Fig. 4.15). Energy availability is a limiting factor, in particular at the Station at the glacier lake, because the peaks of the Cordillera Blanca experience a much higher frequency in cloud coverage that regions further away from the main peaks. Additionally, for preventing data losses and interrupted access in case of blackouts, emergency power aggregates are available in the building of the municipality.

The geophones (devices recording ground movements and converting them into voltage) are the principle instruments to register a potential GLOF trigger. The cameras are used as a backup and possibility for overlooking the current situation; and, particularly during the test phase of the system, for relating geophone measurements to the magnitude of (avalanche) events. The pressure sensor in the riverbed at the Pampa Shonquil station adds redundancy to the system on the one hand; and, if calibrations measurements are taken, can be used for constantly recording the runoff. Next to the station at Pampa Shonquil a permanently manned hut of the wardens of the freshwater intake of Carhuaz is located. This warden would warn the authorities in case of an event (as it was the case in the 2010 event), which as well is a complementary redundancy to the system.

Figure 4.15: (a) Station Laguna 513 (inset showing the two cameras), (b) Station Pampa Shonquil (c) Repeater Station, (d) Data Centre at the municipality of Carhuaz *(Source: CARE Peru).*

Data Centre and Website

All recorded data is stored first in the data logger at the respective station, then after data transmission (5 seconds intervals), on a server located in the data center and backed up on a server cloud. All data is directly transferred to a website to allow for a real-time remote access (Fig. 4.16). In the data center itself – a separate office in the municipality of Carhuaz – a screen is constantly showing the data from this webpage (24/7).



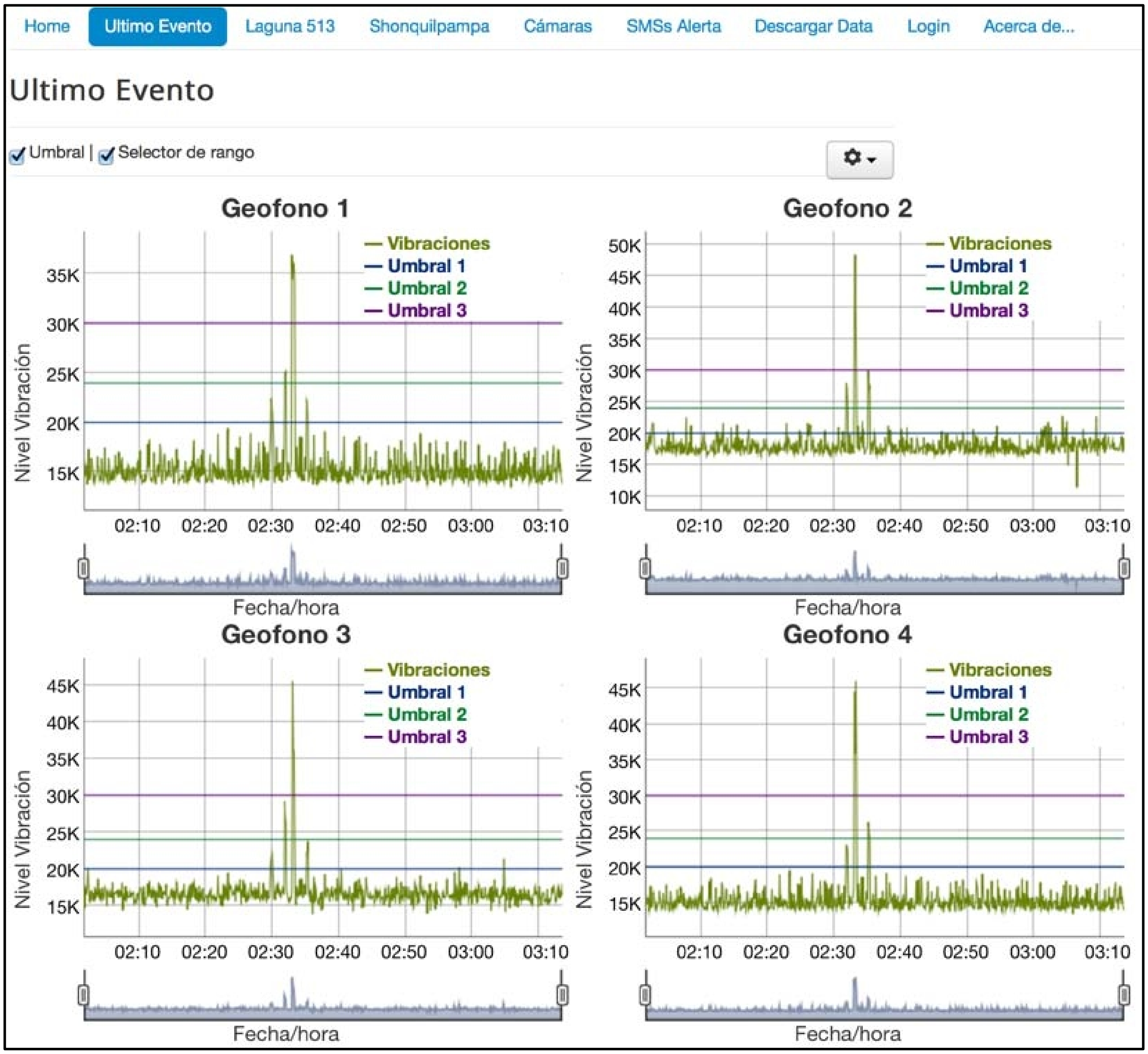


Figure 4.16: (Above) Screenshot from the photos on the dam (top) and Mt. Hualcán (bottom); (Below) Screenshot from the last event sub-page of the website, showing the geophone data registered during a smaller ice avalanche (which did not cause an impact wave); **Horizontal lines indicate the three thresholds.**

Warning procedure

An action plan has been developed, indicating all actions to take. Related bases for decisions are indicated for different warning levels in a protocol. For establishing such an action plan, local, regional and national laws, rules and guidelines had to be considered. Involved authorities include the members of the local emergency operation center (COEL), civil defense, selected government members, and the mayor, who has the power to launch the alarm initiating evacuation. This action plan is accompanied by a list of responsible persons and their phone numbers.

Dissemination and communication

If the measurements of one geophone overpass a defined threshold, an SMS is automatically sent out to all involved persons to immediately check the EWS data and information. Subsequent steps are then to be taken based on this action plan and on the available data. No alarm is launched automatically by this EWS.

The alarm module consists of two long-range sirens to cover the entire area of the city of Carhuaz. In parallel to the acoustic alarm, the system has the possibility to send out predefined text messages to district leaders.

Response capability

In order to achieve a good response capability, a series of information events have been held together with the population at risk. During these events, the concept and functionality of the EWS, as well as its potentials and limitations, and clear instructions on actions that need to be taken in case of an alarm have been explained and discussed. Related instructions include the directive to immediately escape the endangered zones, and a clear indication of the evacuation route and safety zones. A detailed map with all evacuation routes was developed by the civil defense of Carhuaz on the basis of the hazard map described above. Knowledge of the cultural background and the perception of both the natural environment with its related hazards and the EWS itself, were of fundamental importance for a successful communication and a positive response.

Due to the permanent seismic hazard in Peru, several emergency simulations are scheduled every year for the entire country. Such simulations, some of them taking place at nighttime, have been used to not only expose both the population as well as the responsible authorities to a test evacuation und near-realistic conditions, and to familiarize with the EWS.

4.6.7. Case study of GLOF Early Warning in Sikkim State

In a collaboration work by the Swiss Agency for Development and Cooperation (SDC) and Sikkim State Disaster management Authority (SSDMA), the following framework has been constituted under the Early Warning System for GLOF early warning consists of four readiness levels and a threshold-based automatic alarm system. Every glacial lake in Sikkim state is designated a readiness level. Only the most critical lakes, for example those with a readiness level of 1 or 2 are monitored on a daily to weekly basis by the State Emergency Operations Centre (SEOC), managed by the SSDMA.

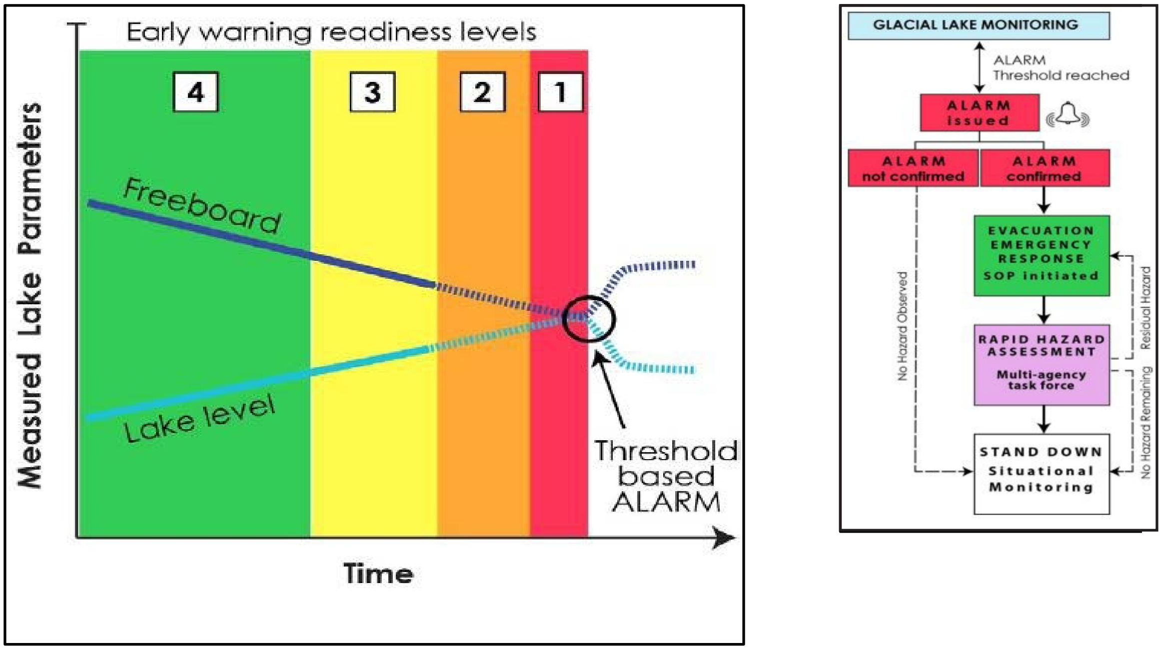


Figure 4. 17: Early Warning Readiness

(Source: GLOF Management Policy (SDC & SSDMA) Alarm System for Glacial Lake Monitoring)

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4.6.8. Early warning system in the Sutlej river basin, India

Some measures have been put in place in the Sutlej River basin for monitoring, forecasting, and early warning to deal with flash floods, especially from cloudbursts. As GLOFs are one of the causative factors in propagating flash floods downstream, these measures also act as an early warning system for a GLOF. Telemetry stations set up by the Snow and Hydrology Division of the Central Water Commission in Sumdo, at the confluence of the Parechu and Spiti rivers, and Khaab, at the confluence of the Spiti and Sutlej rivers, and by the Naptha-Jhakri project at Dubling, are intended to monitor any increase in the water level and to relay information. They were introduced in response to the gap in early warning that was felt after the floods in 2000, and also for the protection of hydropower projects. Similarly, a wireless network at ReckongPeo, used by security personnel with connections to border outposts, and the Doordarshan Satellite Earth Station and All India Radio Relay Centre, have been very useful in generating warnings and in communicating during emergencies (UNDP 2008).

LLOF example need to be given. The big landslide of August 2014 in Nepal part for Sun Koshi River can be given as an example. Similarly, October 2018 landslide damming in TAR region of China and subsequent flooding/high peak in Brahmaputra river can be provided.

Chapter 5: Awareness & Preparedness

5.1 AWARENESS

Given the rarity of the events like GLOFs and LLOFs, local communities are not too much aware about their disastrous effects. Since outburst floods are sudden, and cause disasters that affect localised areas resulting in segregated losses, these do not receive appropriate attention due to their transitory nature, and short-lived human memory. Hence, the level of awareness about GLOFs and LLOFs has been quite low compared to other disasters like earthquakes, cyclones, Tsunamis, etc. While the Kedarnath Tragedy of 2013 in the state of Uttarakhand in Western Himalayas did bring about some awareness about GLOF in the IHR, there is still a long way to go.

State governments/SDMAs of affected areas, in collaboration with the nodal agency and other key stakeholders, will make special efforts to mobilise communities to support in carrying out GLOF/LLOF mitigation efforts. Electronic and print media will also be associated in the endeavor to create greater public awareness about GLOF/LLOF hazard and importance of land use zoning practices. Organisations and institutions like the GSI, NIDM, IITs, CDDM, and other knowledge-based institutions including some NGOs will be entrusted with the responsibility of preparing material for awareness generation campaigns pertaining to the GLOF/LLOF vulnerable states in the country in a scheduled manner. Experience from other countries has shown that building knowledge around GLOFs, LLOFs, and other climate-related disasters, can be most effective if packaged within a broader framework of awareness raising around climate change and related environmental issues.

5.2 CREATION OF COMMUNITY AWARENESS ON GLOFs AND LLOFs RISK REDUCTION

The following are the short, mid and long - term strategies which may be adopted to create community awareness on GLOFs and LLOFs risk reduction:

A. Short Term

1. **Automated Alert Services:** In collaboration with the various government and private travel agencies including Indian Airlines, Indian Railways and mobile network operators, NDMA can send automated SMS and e-mail messages on precaution to be taken while travelling in the GLOF/LLOF vulnerable areas at the time of booking of travel tickets to these areas.

2. **Toll free number or smart-phone based application for GLOFs/LLOFs reporting**: Each state in the very high and high-risk zones can initiate a mechanism for GLOFs/LLOFs reporting upon receiving reports of early signs of GLOFs and LLOFs from people. NDMA in collaboration with the leading technical institutions of the country like Indian Institute of Technology (IIT) can design a computer/smart-phone application for disaster management. The application can be used to know about the latest information on disasters (including GLOFs/LLOFs) across the country.

3. **Creation of common signage for GLOFs/LLOFs vulnerable areas:** A common signage for GLOFs/LLOFs vulnerable areas can be designed and displayed in GLOFs/LLOFs vulnerable areas across the country, advising people to be aware of rapidly rising rivers, and where to find safe ground.

4. **Use of local mass media:** A well designed mass media campaign (both print & electronic) can be undertaken in the vulnerable and affected states. The campaign must be designed in the local languages.The local community radio can broadcast programmes on awareness. It can also transmit early warning messages regarding the occurrence of GLOFs/LLOFs in the area.

5. **Use of posters, wall paintings and hoardings:** Posters and hoardings on the various aspects of awareness regarding GLOFs/LLOFs can be designed and displayed at all important public places. Wall paintings depicting GLOFs and LLOFs vulnerable zones can be displayed at prominent public locations in order to increase the awareness among the locals. The campaign material should be translated into local languages.

6. **Use of Global Disaster Preparedness and Response Apps** : There are a number of globally recognized disaster preparedness and response apps serving the needs of people affected by disasters. These top mobile apps could prove fruitful in providing assistance to aid workers and volunteers (Aapda-Mitra) in better preparedness and response to the disaster.

B. Medium Term

1. **Awareness through documentary**: NDMA should initiate a programme using documentaries/presentations for Government organisations, schools and hospitals, Soldiers, NGOs, local nodal agencies, local community organisations and youth clubs, and local people focusing on the role and responsibility before, during and after the landslide or flood disaster.

2. **Creation of village task force:** The not-for profit organizations or community based organisations should constitute a village task force in each village of the vulnerable states. The members of the task force should be made aware of the various aspects of glacial landslide mitigation and post-glacial landslide activities.

3. **Creation of a citizen science application for environmental monitoring:** NDMA in collaboration with the leading technical institutions of the country like Indian Institutes of Technology (IITs) can design an application for smart-phones, allowing citizens to record key environmental parameters, such as lake or river levels. By engaging communities in scientific monitoring, they are more likely to respond positively to any warnings or alerts.

C. Long Term

1. **Awareness programme on GLOFs/LLOFs hazard :** There is need for emphasis on a robust awareness programme for GLOFs/LLOFs hazard. There is a need for

enhancing public awareness about signs and events that manifest that a GLOFs/LLOFs is imminent so that personal safety measures may be taken in a timely manner. Some of these signs include: (a.) fragments of ice/debris from moraines in the river waters, (b.) calm waters in the river showing and unusual turbid nature, (c.) damming/ blockage of the river body by local landslide or extra-large erratic boulders which may lead to rise in the level of river water, (d) cracking sounds from the glaciers upstream, (e.) change in the colour of river water showing suspension of sediments due to landslide/collapse of moraine dam upstream, (f.) cracks in Glacier/Moraine Dammed wall along the boundary of glacier lake, etc.

2. **Use of traditional art forms/ traditional knowledge:** Due to modernization and tech savvy nature of 21st century generation, traditional disaster management practices are dying/losing relevance. Therefore, it is necessary to document and disseminate old traditional best practices available in mountainous regions of India through community participation in trainings. Traditional art forms are important media of awareness generation. Traditional knowledge and modern technologies can be combined to design glacial landslide and flood Early Warning System (EWS).

3. **Awareness through Participatory Approach:**A participatory planning and implementation process is recommended in order to maintain the sustainability of the programs launched by the administration for disaster management. It is necessary that the government and the communities together evolve a joint action plan aimed at enhancing community education and development of community leadership. The Community Based Family Disaster Preparedness and mitigation (CBFDP) is one such process to capacitate communities to prevent, mitigate and cope with disasters effectively.The elements of participatory learning can be applied at different levels such as organizational level (headquarters, branches, schools, businesses, workplaces), community level (village, town, cities) and population level (marginalized, vulnerable sections).

4. **GLOFs/LLOFs education plan:** An illustrated booklet with information on GLOFs/LLOFs awareness can be prepared in local languages. This can be circulated among the Panchayati Raj Institutions (PRIs) members, Front Line Health Workers (FLHW), School Teachers, Youth Leaders, members and other important stakeholder groups in these areas.

5. **Involvement of Not-for-Profit Organisations**: NDMA should identify not-for-profit organisations to undertake the awareness building activities in the vulnerable States. The organisation should be asked to submit a targeted awareness generation plan.

6. **Awareness among local youth:** The not-for-profit organisation can hold periodically regular awareness generation camps with the members of National Cadet Corps (NCC), Scouts and Guides, and National Service Scheme (NSS) volunteers. These camps should be conducted in coordination with the state and district teams of these organisations.

7. **National Data Centre on GLOF/LLOF**: It would integrate various data sources, a geo-portal to address the data needs and thus, enable an effective response. A step towards building the same has been taken by the GIS team at NDMA.

8. **Awareness among policy makers and government officials:** The policy makers are key stakeholders in disaster management. State Disaster Management Authority (SDMA) can hold workshops with policy makers and government officials of all departments to reinforce their role in ensuring that people conform to the various land use policies.

5.3 AWARENESS DRIVE FOR SPECIFIC TARGET GROUP

1. **Communities based on the downstream:** GLOF/LLOF hazard poses a high level of risk to the communities living in close proximities to the potential critical lakes and rivers. Downstream settlements which are situated along the drainage basin of the glacier lake or river are at a major risk. It is of utmost importance that these communities are aware to the threat that GLOFs/LLOFs pose and they should know about the preparedness measures to be taken to mitigate the disaster.

2. **Special Focus on Women, Children and senior citizens**: Since the areas vulnerable to GLOFs mostly lie in the mountainous regions, it has been observed that most of the men migrate out to cities in search of employment or taking up jobs whereas the household, fields, and rest of the family are managed by the women. Therefore, special focus should be given to provide awareness and develop capacity of the women in these areas to act as disaster managers. Awareness about GLOF/LLOF and other glacial or permafrost-related hazards should be introduced into the books for children.

3. **Urban Planners, Architect, Geologists and Civil Engineers:** A important aspect of the resilience to disaster is the ability of the infrastructure to bear the disaster with minimal strain. Professionals like Urban planners, Architect and Civil Engineers should be trained to build strong structures which can minimize the impact. Knowledge exchange should be facilitated with professionals from other countries facing similar challenges. It should be made necessary by the State/Central Government to implement the rules which are to be strictly followed to build infrastructure in these regions which include resilience against GLOF/LLOF. Structural stability should be promoted and public should be made aware about the implementation of these rules.

4. **Administrative Integration among the Government Department/Agencies/ NGOs/ Civil Bodies:** The government bodies should work in collaboration with various NGOs, Civil Bodies, Agencies to integrate the operation on creation of Awareness and Preparedness. Trainings should be imparted to them with a holistic and collaborative approach to develop a mechanism of action to spread awareness and preparedness measures to the last mile. The Government can work with international bodies like UNDP, WHO ICIMOD etc. to help develop the ,

mechanism, and to facilitate broader exchange of knowledge and experiences at a regional (e.g. pan-Himalaya) level.

5.4 PREPAREDNESS

Preparedness to a disaster refers to measures taken to reduce and mitigate the effects of a disaster, and forms a core component of the proactive stage of disaster risk management Preparedness can much relieve the severity of impact during the scenario of a disaster. In case of GLOFs and LLOFs, not much is known to the community given the rarity of the situation in the IHR. But this is high time, as predicted by recent studies, glacial thinning and retreat in the Himalayas, coupled with degradation of permafrost, will lead to accumulation of melt water and formation of new glacial lakes which pose a greater threat of flash flooding and associated hazards like landslides, avalanches etc. to the communities situated in the region. Greater the preparedness measures taken up by the community, lesser will be the impact of such threats. The Central and State Governments in collaboration with various stakeholders and NGOs need to work closely to implement measures of preparedness on the ground.

5.4.1 Government Agencies and other Stakeholders

SDMA/State Government is one among the early responders and must work in close cooperation with local government/non-government bodies and agencies in the region to provide aid and relief at the earliest. A network with additional responsibilities must be handed to the government officials in the region for decision and support for pre, during and post phase of the disaster. Non-Structural support is one of the main aspects to be pursued here as the Structural support may to some extent (embankments, artificial drainages, etc) is feasible but in a broader sense is not viable because of the inadequate technology, financial and logistics constraints (inaccessibility to mountain reaches). The non-structural support includes NGOs and other social societies in the region to be trained for providing their support for spreading awareness of the preparedness measures that need to be taken at local and the community levels.

The main stakeholder is the community, based in regions vulnerable to GLOFs/LLOFs as they are the first and the last responders to the disaster as they will witness it firsthand and are the ones who have to deal with the long-term consequences in the region. As the community preparedness measures have been discussed in section 5.4.3. The Community Based Family Disaster Preparedness and mitigation (CBFDP) is a process to capacitate communities to prevent, mitigate and cope with disasters effectively.

5.4.2 Medical Preparedness

5.4.2.1 After effects of GLOFs/LLOFs requiring Medical Attention

Catastrophic natural disasters like GLOFs and LLOFs have a high potential to cause incidences of mass injuries, causalities and subsequent health outbreaks. There is risk of drowning, burying under debris or glacial mass and physical trauma along with the threat of diseases associated with contamination of water and the creation of mosquito breeding sites. Direct health effects of a flood may include: drowning; injuries like cuts, sprains, fractures, electric shocks; diarrhea, vector and rodent-borne diseases like malaria, leptospirosis; skin& eye infections; and psychological stress.

a) Creation of Trained Medical First Responders

The state governments/SDMAs must ensure creation of trained medical first responders for first aid and resuscitation measures for burying and drowning cases. Medical staff must know how-to pull-out water from the respiratory tract and how to carry out cardiopulmonary resuscitation. A list of trained medical and paramedical staff must also be made available to all the relevant agencies. Medical Stores and medical kits must be prepared for the management of GLOFs casualties. Intravenous (IV) fluid, ventilators, oxygen, dressing materials, tetanus toxoid, antibiotics, vaccines, anti-snake venom and anti-diarrhoea drugs will be the most commonly needed medical resources. Large-scale medical stores from where these materials can be procured in a timely manner must be identified. State governments/SDMAs must make available emergency medical equipment and drugs for resuscitation.

b) Patient Evacuation Plan

State governments/SDMAs will make available emergency medical equipment and drugs for resuscitation. Paramedical staff must be trained for resuscitation, triage and to maintain vital parameters like pulse, blood pressure, respiration and intravenous drip during evacuation. Heli-ambulances need to be deployed to aid in the evacuation of casualties from the affected region. Within identified risk hot-spots, safe zones should be established, where medical supplies can be stored, and Heli-landing sites demarcated. It is important that such safe zones are well outside the zone of residual risk, including from secondary hazards. The ambulances should have Standard Operating Procedures (SOPs) for treatment.

c) Emergency Routes and Medical Mock Drills

Since the areas vulnerable to GLOFs/LLOFs are often remote and rugged, providing immediate medical attention would be a challenge in itself. Emergency routes should be demarcated based on the results of hazard mapping (see Chapter 3) and frequent medical mock drills by the trained medical professionals must be conducted.

d) Disaster Management Plans

Disaster Management Plans need to be prepared by all hospitals. Medical facilities, training of medical personnel, creating awareness about drowning and its management must be a part of the plan. Hospitals must nominate an officer for coordinating management of casualties. Contingency plans must be prepared for providing additional beds. Oxygen cylinders, Continuous Positive Air Pressure (CPAP) ventilators, dressing materials, blood and IV fluid for transfusion must be stocked. The hospital casualty room must be equipped with resuscitation equipment like suction apparatus, airways laryngoscope, pulse oximeter, defibrillator and lifesaving drugs. In addition, the aftermath of GLOFs/LLOFs, public health response is one of the prime responsibilities of medical authorities. They will ensure safe water supply and clean food availability along with maintenance of hygiene and sanitation by proper bio-waste disposal. Water testing and food inspection is required to be carried out regularly to prevent outbreak of any epidemic. An effective communication system is an essential requirement for prompt medical response.

5.4.3 Community Preparedness

If the community facing the disaster or vulnerable to associated hazards is well prepared, it will greatly reduce the impact of the disaster. At district/village level, local authorities like gram panchayat with help from NGOs and volunteers will prepare and implement community-based DM plans. A database of these groups, their contact details and field of specializations will be maintained at the village/district and state levels. The state governments/SDMAs will set up appropriate disaster management mechanisms to act as links between the DDMAs and different organisations. Frequent workshops and training will be imparted by professional to the community which will help the community prepare for situation of GLOF and LLOF. Particular emphasis should be given to ensure the participation of highly vulnerable communities (such as Women and Children) in the training activities.

Simulation exercises, mock drills and awareness programmes for the GLOF/LLOF prone district need to be developed and made an essential part of the preparedness programme. The entire cycle of an exercise programme from orientation seminar to full scale exercise takes about 6 to 12 months. Complete exercises in disaster prone districts of the Himalayan states vulnerable to GLOF and LLOF events must be conducted at least once in three years after careful planning so that grey areas in the preparedness programme are identified and efforts are made to make the necessary modifications.

CHAPTER 6: CAPACITY DEVELOPMENT

6.1 INTRODUCTION

A successful and sustainable implementation of this framework for GLOF and LLOF risk assessment and management require different kinds of capacities~~,~~ including engineering, scientific, socio-economic, organisational, and institutional in various forms. The complexity of task requires an interdisciplinary approach with a collaboration of engineers, hydrologists, geomorphologists, modelling experts, remote sensing specialists, infrastructure planners and builders, environmentalists and sociologists, and authorities at local, state and national level. In addition, it is essential to develop experiences from events and situations and to document and analyse cases and extract lessons learnt to develop best practices.

In this section, aspects of education and capacity building at university level, training of professionals involved in the assessment and management of GLOF and LLOF risks, and capacity building within local, potentially affected communities is discussed. Eventually, recommendations for the documentation of past GLOF events and related insights are ~~given~~ shared.

6.2 GLOFs AND LLOFs EDUCATION

University education is the foundation for the basic training of the different types of experts involved in GLOFs and LLOFs risk assessment and management.

For the assessment of GLOFs and LLOFs hazards and risks, a thorough understanding of natural processes and their complex interactions in glaciated high-mountain regions is required, including knowledge of the past and future developments at different spatio-temporal scales. Theis understanding needs to be complemented with technical skills, such as remote sensing, cartography, and development and application of numerical models for the simulation of these processes (Figure 6.1).

For the evaluation of the vulnerability component of risk, specialists from social sciences are needed to assess and understand the social, cultural and economic background of the potentially affected population. This allows to get access to the local knowledge of past and ongoing processes, the perception and prioritization of risks, and hence, to identify the most efficient, beneficial and sustainable risk management strategy, tailored to the needs of the local population.

In case of an emergency situation, engineering skills are needed for design and implementation of short, medium and long-term hazard and risk reduction. For the implementation of Early Warning Systems (EWS, cf. Section 5.5), electronic and communications engineers, and programming experts are required.

For response in case of catastrophic events, efficient relief capacities and resources are needed which requires managerial and response implementation capacities.

6.2.1. Education of Professionals

All glaciated regions and mountain/hill ranges are likely to be affected by GLOFs and LLOFs risks. The research related to the evaluation and management of hazards and risks in mountain/hill ranges has seen a rising trend over the past decade due to extensive climate change studies, development of physical and numerical models to understand the nature of these risks and explore options for risk management.

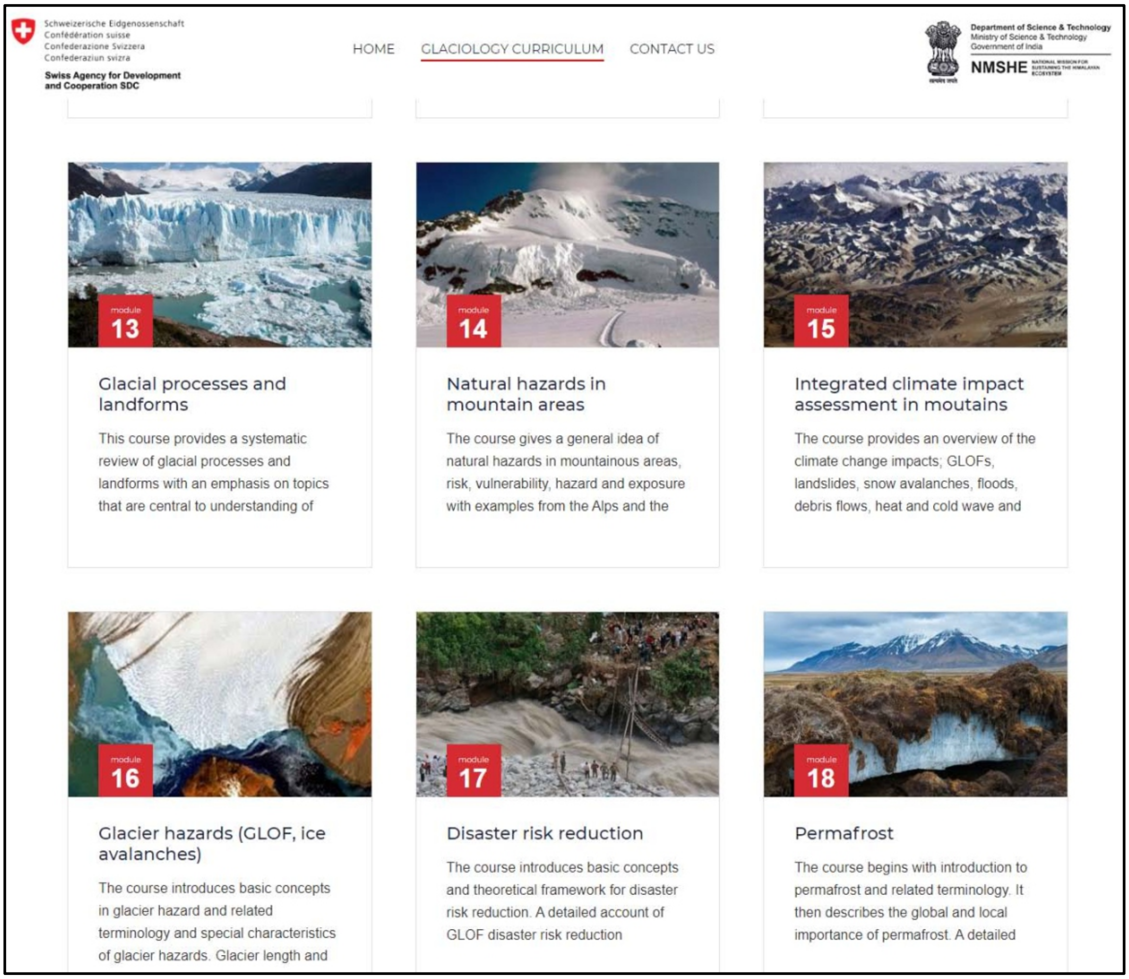


Figure 6. 1: Training modules relating to glacier hazards and disaster risk management

(Produced under the Indo-Swiss Capacity Building Programme on Himalayan Glaciology, organised by The Department of Science and Technology (DST), Government of India and the Swiss Agency for Development and Cooperation in 2019 - http://glaciology.in/curriculum/*)*

Knowledge exchange and experience sharing with scientists and practitioners working on GLOFs and LLOFs issues across different mountains ranges and hilly regions of the world is, therefore, an important part of the continuous further education of professionals and experts. Organizing and participating at workshops and conferences, bringing together GLOFs and LLOFs risk assessment and management experts is a key means to benefit from experiences gained in other regions. Online resources like the Training modules relating to glacier hazards and disaster risk management developed under the Indo-Swiss Capacity Building Programme on Himalayan Glaciology can also support education of professional.

Further, to strengthen the education of professionals, there is a need for the documentation of past and recent events (cf. Section 7.5) and development of best practices. Such a database allows for constant development of expertise, based on the lessons learnt from past events.

6.2.2. Community Education

Building capacities in communities potentially threatened by GLOFs and LLOFs is important in order to improve response capacities in case of a catastrophic event. Such capacity development activities should involve the following aspects:

- Information of the reasons and causes of a potential risk, including changes in the environmental and climatic conditions over the past years.
- Current risk situation and potential scenarios of outburst events, including expected impacts at different sites relevant for the community.
- Development and implementation of a risk reduction strategy, including warning and alarming procedures, if available.
- Individual risk reduction measures (avoid unnecessary presence in the riverbed, location of immobile assets outside the hazard zone, etc.).
- Behaviour in case of an event, potentially involving drills and simulations of early warning and alarming systems.

Positive experience has been made by including such capacity building in the curricula of local schools. Such programs may include climate change and related local impacts in general, different hazardous processes that can occur in the zone of the school, and specific aspects of GLOFs and LLOFs aiming at an improved response in the case of an event.

Community education efforts should be embedded in a set of activities with the potentially affected communities, involving the evaluation of local knowledge and risk perceptions related to past and current GLOFs and LLOFs risk, surveys and interviews for the vulnerability assessment (cf. Section 3.5), the planning of risk management options (cf. Section 5.4.2 and 5.5.4), etc.

Education and awareness raising also needs to extend to reach transient populations, such as recreational and religious tourists (pilgrims) exposed to GLOFs and other associated hazards.This could be achieved, for instance, through information signs, infographics, and brochures.

6.3 TRAININGS

6.3.1. Training of Professionals

Regular workshops for professionals of institutions involved in the assessment and management of GLOFs and LLOFs risks should be held once the present guidelines are implemented. This is on the single hand to familiarize the professionals with the approach and concept of the risk assessment framework and the risk management options.

Pilot studies developed to demonstrate the risk assessment and management strategies of these guidelines can be used to illustrate the approaches as practical examples. Also, such workshops will foster cross-organisational collaborations that are required for a comprehensive and strategic management of related risks.

The mapping, monitoring and modelling of potential glacier or landslide lakes is usually done by various Earth Observation (EO) system such as polar orbiting satellites, aerial and UAV based platforms. Once lake is identified the GLOF/LLOF simulations are done using one- or two-dimensional hydrodynamic models, with topographical and hydrological inputs from field observations and remote sensing. Therefore, specialized training modules or online webinar for such basic and advanced topics can be organized for professionals/users working in this area, by the concerned institutes in India (IIRS, NIH, NRSC, IITs), in collaboration with NDMA and NIDM.

Over the time, these pilot studies can be replaced by real cases, which will emerge according to the present guidelines. Such trainings can be used to get inputs from international experts and specialists for providing updated knowledge to the students and practitioners.

6.3.2. Training of Decision makers

As the policy and decision makers regulate and manage the disaster preparedness and response system, it is necessary that they are aware of the gaps in the disaster preparedness and what communities face during such disasters. For that, trainings and workshops for policy and decision makers should also be conducted periodically. This will enhance the efficiency and regularity in the system to mitigate the GLOF/ LLOF disaster risks and hazards.

6.4 CAPACITY UPGRADATION

6.4.1 Documentation

It is recommended to establish a systematic database of past GLOFs and LLOFs disasters and emergency situations developed according to the approaches presented in these guidelines. Such a database is important in order to extract best practices and lessons learnt from past events eventually, which will contribute to further refining of these guidelines according to newer insights gained over time. NDMA is well placed to develop and host such a database, and moderate related educational efforts.

The GLOF and LLOF events database should include the following aspects for each case or lake:

- Observed environmental conditions, if available before, during and after an outburst, should be described
- Consequences of event. Assessment of outburst susceptibility and scenarios of possible future developments
- Institutional roles and responsibilities, as well as communications between institutions
- Risk reduction and mitigation measures taken
- Critical reflection and lessons learnt
- Actions to be taken further

Chapter 7: Response

7.1 INTRODUCTION

Magnitude of disasters like GLOFs and LLOFs can vary from small scale to large scale and the response measures are required to be taken at the appropriate levels. Prompt and effective response systems at the central and state government levels and especially at the district and the community levels are required in the affected/vulnerable areas. Under response measures, there is an utmost need under response measures to provide immediate assistance to maintain life, improve health, provide initial repair to infrastructure and support the morale of the affected population.

Systems will be institutionalized by the DMAs at the various levels for coordination between different agencies like central governments ministries and departments, state governments, district administrations, ULBs, PRIs and other stakeholders for an effective post-disaster response. The initial assessment will be handled by SDMAs, GSI and CWC based on which appropriate alerts will be disseminated.

Agencies like BRO/state PWDs, state DGMs, forest departments, and municipal/panchayat bodies will immediately communicate information on the occurrence of GLOF and LLOF events along with the preliminary data like its location, magnitude and damage caused, etc. to the district emergency centre or disaster management control room. These designated bodies will communicate this information to the state disaster management commissioner for onward transmission to primary nodes like GSI and other nodes like MHA and NRSC identified for this disaster. This will help the nodal agencies and central government to undertake field observations for making an accurate assessment and planning follow up action.

Since GLOFs and LLOFs can also occur due to earthquakes and landslides, Government/Non-Government bodies providing relief should also be prepared for the danger of secondary events striking again during the response phase as they sometimes occur in the continuity of the previous disasters. Deposits from an outburst event can themselves block river tributaries, leading to the development of secondary lakes and new outburst threats. Proper assessment of the situation and therefore required actions should be taken to provide relief and aid. The action plan should prioritize the relief and aid to be given to disabled, senior citizens, children and women.

7.2 EMERGENCY SEARCH AND RESCUE OPERATION

7.2.1 Local Community

The local community in the affected neighborhood is always the first responder after a disaster. Experience has shown that over 80 per-cent of search and rescue is carried out by the local community before the intervention of the state machinery and specialised search and rescue teams. Thus, trained and equipped teams consisting of local people must be set up in GLOF and LLOF vulnerable and prone areas to ensure immediate and effective response. Regular updating/revision of the training, and participation in mock drills will be important to ensure readiness to respond.

7.2.2 Search and Rescue Teams

Community level teams will be developed in each district with basic training in search and rescue. Training modules will be developed for trainers of community level search and rescue teams by the NDRF training institutes. On the ground, besides others, the NDRF battalions will also assist the state government/district authorities in training the local communities. They will be further assisted by the ATIs, CD, Home Guards and NGOs. The state governments, through the ATIs, will develop procedures for formally recognizing and certifying such trained search and rescue team members; they will also provide suitable indemnity to community level team members for their actions in the course of emergency response following a flood. Youth organisations such as the NCC, NSS and NYKS will provide support services to the response teams at the local level, under the overall guidance and supervision of the local administration.

7.3 EMERGENCY RELIEF

Trained community level teams will assist in planning and setting up emergency shelters, distributing relief packages among the affected people, identifying missing people, and addressing the needs for food, health care, water supply and sanitation, etc. Members of these teams will be made aware of the specific requirement of the disaster-affected communities, based on information coming out of rapid needs assessments. It will be ensured by the concerned authorities that the stockpiling of the essential commodities has been carried out. These teams will also assist the government in identifying the most vulnerable people who may need special assistance following the disaster. Emergency relief can only be effective if it is underpinned by effective disaster preparation (see chapter 6), and these components need to be closely linked.

7.3.1 Emergency Medical Response

7.3.1.1 Emergency Treatment at Site

Prompt and efficient emergency medical response will be provided by Quick Reaction Medical Teams (QRMTs), mobile field hospitals, Accident Relief Medical Vans (ARMVs) and Heli-ambulances where areas are inaccessible by roads. They will be activated to reach the affected areas immediately, along with dressing material, splints, portable X-ray machines, mobile operation theaters, resuscitation equipment and life-saving drugs, etc. Resuscitation, triage and medical evacuation of victims who require hospitalization will be done in accordance with SOPs. Heli access may be critical in remote mountain regions, and road access can be destroyed by the event itself. However, weather conditions, particularly during monsoon, can prevent safe helicopter access, and hence, alternative routes into affected areas should be identified in advance.

7.3.1.2 Medical Facilities and Medical Treatment at Hospital

A well-rehearsed medical preparedness plan is required to provide intensive care to cases rescued from drowning and those buried under the debris. An emergency medical plan will be triggered immediately on receiving information about imminent threat of GLOF/LLOF. The action will be immediately initiated for crisis expansion of required number of beds. The medical superintendent should be able to forecast the requirement of enhanced manpower and medical stores after knowing the number of causalities likely to be received at the hospital. Special efforts will be made for the availability of IV fluid, antibiotics vaccines etc. Children, women, elders and other vulnerable casualties will be attend on priority basis.

7.3.1.3 Mortuary Facilities and disposal of Dead Bodies

The state will develop contingency plans to have sufficient mortuaries to preserve the dead bodies. After proper identification, dead bodies will be immediately disposed of through district authorities, to prevent outbreak of an epidemic and environmental pollution.

7.3.1.4 Public Health Issues in Aftermath

Safe and sufficient drinking water will be ensured. Protecting existing water sources from contamination, adding chlorine tablets in the water for residual disinfection effect and provision of latrine and proper waste disposal to avoid contamination through flies and other insects are important steps required immediately in the aftermath of a GLOF/LLOF. Vector control will be done by spraying of shelters with residual insecticides. Provisions of insecticides treated mosquito nets are recommended.

7.3.1.5 Psychosocial Aspects

A large number of victims will suffer from psycho-social effects in the aftermath of the disasterevent. The psycho-social impact of floods could manifest as a reaction in the form of post-traumatic stress disorders (PTSD) and other psychosocial ailments among the displaced populations. A team comprising of a social worker, a psychologist and a psychiatrist will provide counselling to such people.

7.3.1.6 Documentation of Medical Response

Documentation of the medical response provided after a GLOF/LLOF event will be done by a medical administrator. This documentation will be used as feedback for future improvement of the response strategies.

7.4 INCIDENT RESPONSE SYSTEM

All response activities will be undertaken at the local level through a suitably devised Incident Response System (IRS) coordinated by the local administration through the Emergency Operations Centers (EOCs). State governments will commission and maintain EOCs at appropriate levels for the coordination of human resources, relief supplies and equipment. Standard Operating Procedures (SOPs) for the EOCs will be developed by state governments and integrated within the framework of the IRS, which will take advantage of modern technologies and tools, such as GIS maps, scenarios and simulation models for effectively responding to disasters. GIS maps available from other sources, such as the city planning departments will be compiled considering their potential application after a disaster. The state governments/SDMAs will undertake the training of personnel involved in the IRS. Some of the state governments have already adopted this system.

7.5 COMMUNITY-BASED DISASTER RESPONSE

7.5.1 Institutionalizing the Role of Community Based Organisations, Non-governmental Organisations etc. in Incident Response System

A number of organisations, like NGOs, self-help groups, CBOs, youth organisations such as NCC, NYKS, NSS etc., women's groups, volunteer agencies, CD, Home Guards, etc. normally volunteer their services in the aftermath of any disaster. Village level task forces will also be constituted on a voluntary basis for better preparedness of the community including shepherds/Himalayan nomads. The state governments/ SDMAs and DDMAs will coordinate the allocation of these human resources for performing various response activities. State governments will work with these agencies to understand and plan their roles in the command chain of the ICS, and incorporate them in the DM plans.

7.5.2 Support of Stakeholders

Large scale natural disasters draw overwhelming humanitarian support from different stakeholders. The relief and response activities carried out by such stakeholders must comply with the norms prescribed by the appropriate authorities. A proper channel should be setup at the state and central government level to channelise the support in order to reach everyone in need. The allocation of support should be based on a rapid needs' assessment.

7.5.3 Dissemination of Information

Soon after the disaster, accurate information will need to be provided on the extent of the damage and other details of the response activities through electronic and print media. The state governments will utilise different types of media, especially print, radio, television and internet, to disseminate timely and accurate information.

7.6 LOGISTICS

7.6.1 Emergency Logistics/Equipment :

Specialized heavy earthmoving and search and rescue equipment are required immediately after a GLOF/LLOF to help clear debris and carry out search and rescue operations of trapped people under huge masses of debris. Also, Motor launches, country boats, inflatable rubber boats, life jackets, lifebuoys and other equipment will be required immediately after floods to carry out search and rescue of trapped people. State governments will compile a list of such equipment, identify suppliers thereof and enter into a long-term agreement for their quick mobilization and deployment in the event of floods and a landslide disaster.

The IDRN, which is a web-based inventory of information on emergency equipment and response personnel available in every district, will be revised and updated every three months.

7.6.2 Relief Camps

The setting up of relief camps (RahatGhar) for the people whose houses have been damaged by floods/landslides and the provision of basic amenities in such camps involves complex logistics of mobilizing relief supplies, tents, water supply and sanitation systems, transport and communication systems, and medical supplies. Most importantly, site selection for relief camps based on best available scientific information (hazard mapping etc.)should be part of the disaster preparedness phase. Relief camps, and access corridors to these camps, should be outside of zones of residual risk, and safe from any potential secondary hazards.

A temporary shelter building, where the locals can find shelter during the times of disaster should be erected/built in a raised location to ensure resilience to landslides and floods. The building will include a raised plinth which will safeguard it from flood waters and needs to be built with landslide resistance standards of the highest orders.

7.6.3 Establishing the Accessibility

The primary challenge in the response to natural calamity in the Himalayas is ensuring accessibility to the affected areas, due to likelihood of choking of the limited communication lines. In case of the Himalayas, the heavy earth moving machinery might not be useful and relevant in the immediate response stage. Hence, innovative methods using locally available natural resources will have to be used and local agencies and population will have to be trained for the same. It is important to innovate and design lighter machinery, which are more suitable to be carried in the mountains in a disassembled form.

7.7 POST DISASTER DAMAGE AND NEED ASSESSMENT

Assessment of the damage due to GLOF/LLOF is very important to understand whether it will be possible to treat it economically or not. The loss can be categorized as direct or indirect.

Direct losses include the impact on infrastructure, vehicles, life loss, etc. Some examples of indirect landslide losses are:

- **i)** The loss of industrial, agricultural, and forest productivity; and tourism sector revenues as a result of damage to land or facilities, or interruption of transportation systems.
- **ii)** Reduced real estate values in areas threatened by GLOFs/LLOFs.
- **iii)** The loss of tax revenues on properties devalued as the result of GLOFs/LLOFs.
- **iv)** Measures that are required to be taken to prevent or mitigate additional landslide damage.
- **v)** Adverse effects on water quality in streams and irrigation facilities at and near the GLOFs/LLOFs affected region.
- **vi)** The loss of human or animal productivity because of injury, death, or psychological trauma.
- **vi)** Secondary physical effects, such as landslide-caused flooding, for which losses are both direct and indirect.

Indirect losses many a times exceed direct losses. Unfortunately, most indirect losses are difficult to evaluate and are therefore either ignored or estimated rather conservatively. Also, usually people and entities prefer to keep their financial losses discrete and not disclose these publicly. Restoration of direct assets will also lead to improvement in the indirect losses but much effort is required to be made by all the local organisations/NGOs/Communities to regain the indirect assets.

Physical damage assessment is done through airborne videography/imagery, satellite data and field surveys. Much of the work on damage assessment nowadays is based on the Earth observation data i.e. optical and SAR satellite data. It is highly useful to identify places clogged with water and those hit by landslides. Precise measurements can give results of movement at millimeter (mm) scale.

7.8 STANDARD OPERATING PROCEDURE (SOP)

STANDARD OPERATING PROCEDURE (SOP) ON AVERTING THREATS EMANATING FROM GLACIAL LAKE OUTBURST FLOODS (GLOFs) AND LANDSLIDE LAKE OUTBURST FLOODS (LLOFs) IN HIMALAYAN REGION

General

Glacial retreat due to climate change/variability occurring in most parts of the Hindu Kush Himalaya, has given rise to the formation of numerous new glacial lakes which are the major cause of GLOFs.

GLOF events have killed thousands in many parts of the world and some of the largest events have occurred in the Himalayas. One of the such incident in recent times was the Kedarnath Floods occurred in June 2013, which impacted the lives of more than 1,00,000 people, led to the deaths of thousands, and caused immense damage to the infrastructure.

Post these incidents, a need was felt to prepare a Standard Operating Procedure on averting threats emanating from Glacial Lake Outburst Floods and Landslide Lake Outburst Floods in the Himalayan regions in order to ensure speedy and appropriate response by various agencies so that the threat is mitigated/eliminated.

The SOP lays down the guidelines and actions to be taken by the various agencies during the crises event of disaster. The Incident Response System (IRS) for managing the GLOFs and LLOFs in a standardized manner will be effective to incorporate in line with procedures. The SOP is implemented in **three stages** which are given in succeeding points.

Pre-Operational Phase (Stage I)

a) Preparation of an inventory of the glacial/landslide lakes through remote sensing and GIS and prioritisation of the lakes according to the GLOF/LLOF risk assessment framework. **[Action**: State/UT Admin/ District Admin/ NRSC/NTRO/ CWC/ National Mission for Sustaining the Himalayan Ecosystem (NMSHE)-DST]

b) Mapping of glacial/landslide lakes and relevant waterbodies in IHR as well as classification of lakes based on the susceptibility as Highly Susceptible, Moderately Susceptible and Low susceptibility. **[Action**: NRSC/NTRO/ CWC/ NMSHE/ MOJS/ NLRTI]

c) Preparation of Hazard Zonation Maps and mapping of unsafe areas for human settlements that are likely to be at risk from a susceptible GLOF/LLOF.

d) Ensure continuous monitoring of highly susceptible lakes followed by field survey in terms of change in the area of the lake, change in water level, position of a lake in relation to moraines and associated glaciers, the activity of lakes and condition of the dam.

e) Involvement of the shepherds/guides /porters and local communities in monitoring of glacial/landslide lakes with high risk- boundary conditions and discernible terrain changes.

f) Seek inputs from Indian Meteorological Division (IMD) and Snow & Avalanche Study Establishment (SASE), CWC, Survey of India (SOI) to ensure continuous weather monitoring and to facilitate decision making in case of emergency. **[Action**: State/UT Admin]

g) In case of abrupt expansion of the lake, ascertain the cause at the earliest through satellite/aerial and physical means. **[Action**: State/UT Admin/NRSC]

h) Ensure availability of satellite communications (SAT Comms.). **[Action**: State/UT Admin/ DoT]

i) Convene a meeting at District/State level to tackle the issue. Inform NDMA and provide regular updates.**[Action**: State/UT Admin]

j) Refer the situation to the National Disaster Management Authority (NDMA) if it is beyond the capability/resources of State Govt. **[Action**: State/UT Admin/ NDMA]

k) National Crisis Management Committee (NCMC) to convene a meeting at the earliest depending upon the severity of the situation. Simultaneously, the Defence Crisis Management Group (DCMG) meeting may also be held, ifrequired. **[Action**: Cabinet Secretariat/ NDMA/MoD]

l) NDMA / SDMA to activate the Control Rooms and update all records.Establish telephonic and video contact with all concerned officials includingofficials of the concerned State Control Room, IMD, CWC, NRSC and NationalTechnical Research Organization (NTRO) obtain satellite images of theaffected area. NDRF / SDRF alerted to be on standby. **[Action**: NDMA/ SDMA (State/UT Admin)/NDRF /SDRF /NRSC/ NTRO/ IMD/ CWC]

m) Based on the lessons learnt, the affected State to organize a Team of Experts from those agencies which are likely to be involved. These could be some or all of the following suggestive list of institutions: - **[Action**: State/UT Admin/NDMA]

(I) Central Water Commission (CWC)

(ii) India Meteorological Department (IMD)

(iii) Survey of India (SOI)

(iv) Geological Survey of India (GSI)

(v) Central Institute of Mining & Fuel Research (CIMFR)

(vi) National Mission for Sustainable Himalayan Ecosystem (NMSHE)

(vi) National Institute of Hydrology (NIH)

(vii) Snow & Avalanche Study Establishment (SASE)

(viii) Border Roads Organization (BRO)

(ix) MoD / Integrated Defence Staff (IDS)

(x) Hydro Power Developers

(xi) Dept of Science & Technology (Suitable representative from State Govt.)

(xii) Official media personnel.

(xiii) Other Departments.

a) State/ UT Admin. to take immediate precautionary and preventive measures to ensure safety to life and property. These include: -

(I) Informing the populace living both down/upstream of the impending danger.

(ii) Installing water level monitoring gauges at suitable locations.

(iii) Preparing (rehabilitation) relocation plans.

(iv) Establishing communication facilities at the likely affected areas.

(v) Alerting and preventing locals/ tourists from venturing into affected areas by establishing check posts/ check points.

(vi) Erecting banners/ boards with warning signs.

(vii) Taking immediate steps to relocate personnel from high risk zones.

b) The Expert Team / essential members to conduct an on the spot assessment of the GLOF/LLOF and carry out recce to ascertain: -

(i) Free board available i.e. difference between current water leveland dam height.

(ii) Type and texture of the dam.

(iii) Possible time available before a sudden dam break.

(iv) Seepage towards downstream if any.

(v) Any threat likely to develop due to impounded water.

(vi) If physical intervention to drain the lake is required, then alignment and dimension of channel required to be created to be worked out.

(vii) How the channel is to be created, i.e. by using earth or manual clearing of debris (where earth movers cannot be deployed).

(viii) Whether explosives can be used for creating of channel? If so, resources required i.e. manpower, equipment, explosives, etc.

(ix) Any site-specific requirements.

(x) Photography and videography of the site and surrounding areas.

c) Set up of Expert team by NDMA / SDMA to assist State in preparing a detailed action plan giving out: -

(i) Transportation

(ii) Communication

(iii) Medical

(iv) Safety

(v) Logistics stocking, replenishment and reserves

(vi) Induction, execution and de-induction phases

(vii) Media plan, photography & videography of events

<u>Operational Phase (Stage II)</u>

a) Installation of Automatic Water Level Recorders (AWLR) and Water Gauges at the susceptible lakes for continuous monitoring of water level in the lake.

b) Ensuring controlled breaching of the dam by reducing the volume of the water in the lake via construction of an outlet control structure, pumping or siphoning of the water from lake and tunneling through the moraine barrier or under an ice dam. **[Action**: State/UT Admin]

c) CWC to prepare pre-run scenarios and generate flood inundation/DEM Chart to indicate level of potential threat in the event of the dam break/overflow scenario.

d) Planning of evacuation strategies on the basis of results from flood inundation modelling. **[Action**: State/UT Admin/CWC/ CAPF/Local Police]

e) Ensure installation of Early Warning Systems (EWS) involving threshold based automatic alarm system monitored on a daily or weekly basis by State Emergency Operating Centre (SEOC) and managed by State Disaster Management Authority. **[Action**: SEOC-SDMA/ DEOC-DDMA]

f) Securing and establishment of shelter homes, camp site and forward staging areas. **[Action**: State / UT Admin/ Army/ ITBP/ CAPF]

g) Establishing communication facilities (including HF/ VHF/ HAM/ satellite phones) at the site, staging areas and District Control Room. **[Action**: State/UT Admin/ CAPF/ ITBP/ Army]

h) Installing safety devices like anchors, ropes, harnesses etc. where required.**[Action**: NDRF/ SDRF/ CAPF/ ITBP/Army/NIM]

i) Stocking of logistics like ration, equipment and machines, fuel, medicines, explosives and accessories, lighting arrangements. **[Action**: State/UT Admin/CAPF/ITBP/ BRO/Army]

j) Relocating the likely affected people from low lying areas at least 48 hours before actual commencement of work at the site. **[Action**: State/UT Admin/ District Admin]

k) Detail a lookout team to alert members at the work site from falling stones, loose land mass etc. **[Action**: Expert team leader]

l) Marking the alignment of the channel to be created at the blockage site.**[Action**: Expert team leader]

m) Controlled use of explosives to break boulders/ dislodge compacted earthmass. Expertise of CIMFR, BRO & Army Engineers and others may be sought for use of explosives. **[Action**: Explosive Experts in State/UT Admin/ Army/ BRO]

n) Manual clearing of debris along the marked alignment. **[Action**: Expert team leader/ CAPF/ Army]

o) Manual clearing of debris and use of explosives can be alternately followed until the desired width, depth and length of channel is created for free flow of impounded water. **[Action**: Expert team leader/ CAPF/ Army]

p) Use of earth movers (JCB) if it is possible to reach them at the site. These can even be dismantled in parts, carried by helicopters under slung and assembled at the site (As done during Nepal River Sunkoshi blockage in 2014). **[Action**: State/UT Admin/ Airforce/ Army Engineers]

q) Loose debris can even be washed away using high pressure water jets at places subject to deployment of heavy-duty compressors. **[Action**: State/UT Admin/ Army]

r) Photography and videography of events for future reference. Representatives of media should be associated. **[Action**: State/UT Admin/ Expert Team Leader]

s) Heli-Ambulance/ air support to be requisitioned to National Emergency Response Centre (NERC) / Joint Secretary (Air). **[Action**: State / UT Admin/ MHA/MoD]

t) Bill for such air support to be raised against SDRF allocation**. [Action**: Air Force/ MHA]

u) Obtain daily weather reports to the plan for next day's activity. **[Action**: Team leader/Air Force/IMD]

v) Media briefing and press release at the end of the day's activity by the designated representative of State associated with the team. **[Action**: State/ UT Admin / District Admin/ NDMA/ Army PRO]

w) Ensure effective coordination and seamless communication among central and state agencies for quick, clear, effective dissemination of warnings, information and data. **[Action**: State / UT Admin/ District Admin]

k) Generate awareness and provide training support about GLOF/LLOF for ITBP, Local police, SDRF, community members and volunteers.

<u>Post Operational Phase (Stage III)</u>

a) Round the clock monitoring from the Lookout Post till the situation normalises. **[Action:** State/UT Admin/ Army]

b) Obtain satellite imageries, from NRSC & NTRO to compare pre and post activity changes in volume of impounded water upstream, status of flow of water through channel and flow of water downstream. **[Action**: State/UT Admin/ CWC/ NRSC/ NTRO

c) Periodical aerial recee and videography of the site without connectivity to know the latest status. **[Action**: State/UT Admin/ Army/ Air Force/ Expert Team]

d) Sectoral assessment of the damage such as infrastructure damage, livestock damage, agriculture damage. **[Action**: State / UT Admin/ IMCT]

e) Ensure calculation of the compensation required to be provided to the population exposed to the hazard. **[Action**: State / UT Admin]

f) Decide on rehabilitation of population once impounded water has drained out. CWC can assist in advising the safe levels. **[Action**: State/ UT Admin/ CWC/NRSC/NTRO].

g) In cases where the dam has breached, Post Breach Analysis and Assessment by team of experts shall be carried out and further course of action recommended. **[Action**: State / UT Admin]

h) All concerned / involved Ministries and Govt. organizations must ensure theyhave adequate well-trained experts so that they can be speedily moved to the disaster site. **[Action** : State / UT Admin/ CWC/ SASE/ SOI/ BRO/ CIMFR/ ITBP]

I) Compendium of recommenda-tions and lessons learnt shall be drawn and shared with all concerned agencies/ Departments. **[Action** : State/ UT Admin/ Expert Team Leader]

CONCLUSION

The Himalayan region is highly prone to earthquakes and landslides; since it is in Seismic Zone-IV & V. Also, the climate change has resulted in the increase of the formation of glacial lakes thus making the Indian Himalayan Region extremely vulnerable to the events of GLOF/ LLOF.

The SOP on "Averting Threats Emanating from Glacial Lake Outburst Floods (GLOF) and Landslide Lake Outburst Flood (LLOFs) in Himalayan Region" gives out detailed actions/ steps to be taken by respective authorities in the event of GLOF/ LLOF. It is, by no means, exhaustive but a referral document which needs periodical modification with sharing of experiences and best practices across the country.

CHAPTER 8: RESEARCH AND DEVELOPMENT

1.1 INTRODUCTION

Typically, GLOFs increase to peak flow then gradually or abruptly decrease to normal levels once the water source is exhausted. Therefore, outburst flood peak flow is directly related to lake volume, dam height and width, dam material composition, failure mechanism, downstream topography, and sediment availability. In order to get the maximum GLOF peak at any location, the breaching of moraine dams of above glacial lakes have to be considered along with channel routing. GLOFs tend to entrain large amounts of sediment, with the potential to transport massive boulders, particularly in the upper reaches where channel gradients in high mountain catchments are often steep. This is particularly true for floods from moraine dammed lakes, which frequently transform into debris or hyper concentrated flows following the entrainment of material from the moraine and immediate downstream channel. Due primarily to their large flow depths and locally high energy gradients, GLOFs produce erosive forces far greater than typical meteorological floods would for the same stream conditions. In long stream channels such as in the Himalayas and the Andes, dynamic flow transitions are often observed for GLOFs, from initial debris flow types to hyper-concentrated flows and possibly back to debris flows depending on channel slope and availability of erodible material. Flood paths extending up to 100 km and even more have been observed (Carey et al., 2012; Cenderelli and Wohl, 2003; Schwanghart et al., 2016). A time series water sampling of trans-boundary fluvial systems and their hydro-geochemical analyses has been done to trace the origin of the flash floods in the headwaters of Himalayan Rivers (Rai and Singh, 2007). Towards this, the collected discharge data of CWC may be used for the validation. Further, atmospheric phenomenon like cloud bursts and intense rainfall may be studied by establishing advanced instrumentation like Doppler RADAR systems and Automatic Weather Stations (AWS) at high altitudes.

8.2 RESEARCH ISSUES & CHALLENGES

The purpose of the modelling is to reconstruct a historical GLOF, or to investigate the impact of a potential future GLOF. The models are required to give the user an estimated peak breach discharge, and time to peak discharge, and require prior knowledge of the moraine geometry (e.g. its height, width, length) and/or the glacial lake (e.g. it's volume, depth, and surface area), which can be plugged into a simple equation.

Key challenges that modelers face here stem in large part from the incredible complexity of these flows. Assessment of the accuracy of such models also requires the availability of pre- and post-flood DEMs, which allow the modeler to see whether the modelled patterns of erosion and deposition match those observed in reality for documented GLOFs. However, these data are rarely available due to the logistical (and financial) challenges associated with producing repeat topographic surveys of often remote and largely inaccessible valleys, as well as predicting if and when a given moraine will fail. Further, for most glacial lakes, a hazard assessment cannot rely on information from past GLOF events (such as observed erosion patterns, for instance), as lake outbursts often are single events, without historical precedence. Nevertheless, current scientific state-of-the-art techniques for GLOF hazard modelling relies on scenario-based, future-oriented numerical models, that are coupled according to the chain of processes involved in a GLOF (cf. Chapter 3, as well as GAPHAZ 2017, Jain et al., 2012, Schneider et al. 2014, Frey et al. 2018, Mir et al., 2018). Recent efforts include modeling approaches that are able to simulate entire chains of mass movement processes within a single modeling framework (Mergili et al. 2017, 2020). There is still a large research potential both in the development of hazard scenarios and the estimation of related uncertainties, as well as the numerical modeling of mass movements involved in a GLOF.

A wider area of research is related to the use of local knowledge for disaster risk management. Local population in the IHR has a long-standing experience in dealing with hazards and risks from glacial lakes. In particular when considering the common lack of observational data in remote mountain regions, local knowledge can indeed provide valuable information on past conditions and events. Further, involvement of the local population in disaster risk reduction efforts is indispensable (cf. Chapter 4). Another area with research potential includes the integration of socio-economic assessments and developments in risk assessments and management strategies, which requires the involvement of and collaboration with social scientists.

8.3 Effect of future climate change

In relation to climate warming and cryospheric changes, a primary challenge concerns the anticipation and assessment of hazards resulting from a fundamental change from glacial to peri-glacial landscapes (Haeberli et al., 2016). Disappearance of glaciers, permafrost degradation, landscape evolution and corresponding changes in inter-connected surface processes are cumulative developments that lead far beyond historical precedence. Future conditions will in many places be far removed from the past and present and therefore limit the value of historical event inventories. Quantitative, future-oriented and scenario-based system approaches must therefore be applied (see Chapter 3). However, modelling future high-mountain landscapes with their complex systems of interacting surface processes and landforms is a young, emerging research field, and uncertainties are inherently large. Individual components within the complex system have strongly diverging characteristics in their response to climate change. By comparison, due to slow heat diffusion and retarding effects from latent heat exchange in subsurface ice, permafrost degradation is a slow process with long-term commitments. Corresponding de-glaciated landscapes can therefore be expected to turn into peri-glacial landscapes characterised by slowly degrading permafrost, numerous new lakes and pronounced disequilibrium in conditions concerning vegetation cover, slope stability and sediment cascades. In view of the large uncertainties involved with anticipating such conditions, focussed monitoring using advanced space-borne and terrestrial technology is required in case of high hazard or risk levels, coupled with regular re-assessment of the general conditions and specific hazard situations. The formation of new lakes located within increasingly close proximity to steep and destabilizing mountain headwalls has the potential to greatly enhance regional risks from far-reaching flood waves. Corresponding hazard and risk management relating to low-probability events with extreme damage potential is especially difficult for planning, policymaking and decision taking. Furthermore, the expected penetration of humans with their infrastructure for tourism, traffic or hydropower, etc., into previously un-accessible or even avoided high mountain areas must be taken into account.

CHAPTER 9: REGULATION AND ENFORCEMENT

9.1 INTRODUCTION

The Himalayan and sub-Himalayan region are vulnerable to one or multiple disasters including GLOF/LLOF which may be triggered by cloud burst and flash flood, landslides or earthquakes which are considered to be one of the most dangerous and destructive natural hazards in terms of loss of live and property in the Himalaya. The widespread loss of property and life during the recent GLOF events (such as the Kedarnath disaster) have shown that most construction plans are ill conceived and do not follow the building standards or design codes. Climate change is expected to alter and potentially increase the probability for lake outbursts in the future posing potential threat in the downstream settlements. Unplanned and unregulated developmental activities in mountain regions including huge investments in construction of non-engineered roads in rural areas and lack of drainage are exacerbating and increasing hazard of GLOF events. Urban centers, towns and some villages in mountain areas are being burdened beyond their capacity by tourism and rural-to-urban migration while loss of large areas of farmland has ruined livelihoods of rural communities and affected the food security in the mountains. There is an urgent need for the existing regulations and building bye-laws to be stringently enforced. New regulations need to be framed for the Himalaya keeping in mind the hazards due to GLOF/LLOF and the causative factors of cloud burst, flash flood, earthquakes. A well drafted techno-legal regime focused on in urban and rural areas located downstream of GLOF hazards is necessary to prevent future developments from taking place in the hazardous areas and protect the existing ones. Master Planning, Zonal Planning, Development Control Regulations and Building bye-laws provide the mandatory techno-legal framework for regulating the built environment. In the case of existing structures, as it is difficult or impossible to alter land use, specific construction codes are required to reach the desired protection level. Regulations and enforcement are required on two fronts - namely, (i) a no habitation/construction zone in the GLOF hazard area as determined from flood plain zoning studies; and (ii) the strict enforcement of the existing building standards/regulations which have been derived from various laws pertaining to planning and development. Subsequently, it is necessary for their implementation by the multiple agencies in a holistic manner.

9.2 IDENTIFIED GAPS

There is a need for a Himalaya GLOF/ LLOF Mitigation Policy and a Himalaya GLOF/LLOF Mitigation Strategy. The following needs are identified for the Himalaya: -

(1) Himalaya GLOF/ LLOF Mitigation Policy (HGLMP) which is a must for Himalaya GLOF/ LLOF Mitigation Strategy (HGLMS) should be common all over the Indian Himalaya States. HGLMS must be developed by the States and be area/problem specific but must reflect the HGLMP. Emphasis must be given to prevention/preparedness in HGLMP/HGLMS.

(2) The existing bye laws/regulations at local body or state/central level should be incorporated in the HGLMP and HGLMS. They should not contradict each other. The HGLMS must focus on implementation and enforcement of laws/ regulations and accountability.

(3) Necessity of flood hazard zonation, slope and land-use maps to guide urban planners for clearing constructions. For this, cloud burst forecasting, flash flood modelling and slope instability analysis reflecting the potential for extreme rainfall, flooding, landslides representing the ongoing event/process are required and should be two separate components of HGLMS.

(4) HGLMP and HGLMS should not contradict National Environment Policy and therefore, they should be validated by the MoEFCC.

(5) Best practices which are used to mitigate floods and landslides at local level and activities which can be held responsible for the GLOF/ LLOF hazard should be documented in the HGLMP.

(6) There is a need to have specific land use policy for the Indian Himalaya Region for the regions facing GLOF/ LLOF hazard, especially at the micro-level under the jurisdiction of the local bodies. Coordination among the panchayats, line departments, forest department and municipal authorities for management of water bodies and drainage outside municipal limits is also required.

(7) State specific GLOF/ LLOF mitigation strategies to be formulated to address specific issues of each mountain state.

(8) The municipal bye-laws must provide for regulating construction activities in areas that fall in hazard zones or areas close to rivers, springs and watersheds of the towns. In many cases these provisions exist in the bye-laws but need to be strictly enforced.

(9) As there is no specific standards/code(s) are available with respect to GLOF/LLOF hazards, the same must be developed by BIS.

9.3 TECHNO-LEGAL REGIME

Management of GLOF/ LLOF should aim at minimizing the exposure of communities to the adverse effects of flooding in cities, towns and villages located along the streams, rivers, lakes and other water bodies. To ensure disaster resilient construction, the state governments/SDMAs, must in consultation with their hazard safety cells establish the necessary techno-legal regimes. This is to ensure that all stakeholders like builders, architects, engineers and government departments, responsible for regulation and enforcement adopt safe construction practices and provide for safety in all design and construction activities in such a way that acceptable safety benchmarks are satisfied. To address the special problems of towns and villages located in GLOF/ LLOF susceptible areas, necessary modifications must be made to the Model Town and Country Planning Legislations (2016), Zoning Regulations, Development Control, Building Regulations/Bye-laws taking into consideration the special conditions of the Indian Himalaya Region. Such laws are mainly state legislations as the state is competent to legislate and make laws on such subjects. Continuous interaction with State Governments through workshops and further follow up action including capacity building exercises must be conducted for ensuring adequate and effective techno-legal regime in the region. The Environmental Regulations and Environment Impact Assessment (EIA) according to the notifications of the Ministry of Environment, Forest and Climate Change (MoEFCC) must also be included in the Techno-Legal regime.

9.3.1 Model Building bye-laws 2016

Building bye-laws are legal tools used to regulate coverage, height, building bulk, and architectural design and construction aspects of buildings to achieve orderly development of an area. The Town and Country Planning Organization under the Ministry of Housing and Urban Affairs has recently prepared the "Model Building Bye-laws - 2016" for the guidance of the State Governments, Urban Local Bodies, Urban Development Authorities, etc. which is an improvement over the previous Model Building Bye-laws brought out in 2004. Under the natural hazards, the committee has included the hazards due to earthquakes, cyclones, floods, and landslides. However, no specific mention of GLOF events is given. Salient features of the model town and country planning legislation, zoning regulations, development control, building regulations/bye-laws are given below:

- Addition of definition of Natural Hazard, Natural Hazard Prone Areas, Natural Disaster and Mitigation;
- Consideration of existing map(s) to indicate hazard provisions of the area;
- Consideration of natural hazard proneness in preparation of Development Plans by Local Planning Authorities; and
- Consideration of the Regulations pertaining to Land Use Zoning and necessary protection measures in perspective and Development Plan of State, district and local planning areas.

9.3.2 Regulations for Land Use Zoning for Natural Hazard Prone Areas

Zoning regulations are legal tools for guiding the use of land and protection of public health, welfare and safety. Such regulations also include provision for the use of premises/property and limitations upon shape, size and type of buildings that are constructed or occupy the land. The regulations for land use zoning for natural hazard prone areas are notified under Town and Country Planning Act as applicable in the respective States as and when Master Plan/ Development Plan of different cities/towns/areas are formulated. These zoning regulations are implemented through the provisions of Development Control Regulation/Building Bye-laws, wherever the Master Plan are not in existence or not formulated.

A detailed guideline for land use zoning has been prepared with an objective to regulate land use in hazard prone areas to minimize the damage caused to the habitat, as a result of natural hazards viz. earthquakes, cyclonic storms, landslides and floods. These include:

Prioritization of types of buildings for land use zoning:

Priority 1: Defense installation, industries, public utilities, lifeline structures like hospitals, electricity installations, water supply, telephone exchange, aerodromes and railway stations; commercial centers, libraries, other buildings or installations with contents of high economic value.

Priority 2: Public and Semi-Public institutions, Government offices, and residential areas.

Priority 3: Parks, playgrounds, wood lands, gardens, green belts, and recreational areas.

Regulation for land use zoning shall be an overriding effect on any other regulation.

For any relaxation, adoption of safeguard and protective measures to the satisfaction of the Competent Authority will be incumbent on the part of user.

State Governments must suitably incorporate the modification in their respective Planning Legislation(s), so that regulation for land use zoning for natural hazard prone areas may be notified by the Competent Authority under the above legal provision. Key features of the layout approvals and building permissions having relevance to flood management in cities, towns and villages are highlighted:

(i) The layout proposal shall ensure that there will be side drains for the roads and channelization of nallahs/ storm water drains for allowing storm water runoff in such a way as to conserve or harvest the water in nearest water body or public open space, etc. Sizes of the water harvesting structures must consider the high flows during very severe flood event and the necessary overflow arrangements for the same.

(ii) Every building proposed for construction shall be provided with required facilities and infrastructure for conservation and harvesting of rainwater such as percolation pits or trenches, terrace water collection arrangements according to the relevant IS codes.

(iii) Special methods as recommended by the technical committee for GLOF areas must be adopted in each construction taken up. In case the layout area exceeds 50 Ha, the NOC from Central Pollution Control Board/ MoEF&CC is mandatory.

The following restrictions shall apply on building activity in vicinity of certain areas:

a.) No building/ development activity shall be allowed in the bed of water-bodies like river or nallah/ storm water drain and in the Full Tank Level (FTL) of any lake, pond, tank or pond/ tank bed lands. Moreover, these water bodies and courses shall be maintained as recreational/ green buffer zone, and no building activity other than recreational use, shall be carried out within limits as prescribed by the local body. Greenery/landscaping and development shall conform to the guidelines and provisions of the NBC of India, 2016.

b.) In case of buildings exceeding built up area of 1,50,000 sq. m, No Objection Certificate from Central Pollution Control Board/MoEFCC is mandatory.

Details of various BIS codes, relating to structural safety for natural hazards shall be followed by the professionals to design the structures/buildings, keeping in view the provisions

9.3.3 Indian Standard Codes

The National Building Code published by the Bureau of Indian Standards in 2016 and subsequent revisions are advisory in nature and not mandatory. It lays down a set of minimum provisions designed to protect the safety of the public regarding structural sufficiency, fire hazards and health aspects in buildings. So long these basic requirements are made, the choice of materials, method of design and construction is left to the ingenuity of the architect and the engineers and other experts engaged in such projects. The code also covers aspects of administrative requirements and bye-laws including building services.

As landslides and GLOF are closely interrelated, for protection of landslide hazard, two IS codes are mentioned for ready reference- (i) IS 14458 (Part 1): 1998 Guidelines for retaining wall for hill area: Part 1 Selection of type of wall; and (ii) IS 14458 (Part 2): 1997 Guidelines for retaining wall for hill area: Part 2 Design of retaining/breast walls. (iii) IS 14458 (Part 3): 1998 Guidelines for retaining wall for hill area: Part 3 Construction of dry-stone walls, (iv) IS 14496 (Part 2): 1998 Guidelines for preparation of landslide – Hazard zonation maps in mountainous terrains: Part 2 Macro-zonation

Note: Whenever an Indian Standard including those referred in the National Building Code or the National Building Code is referred, the latest revision of the same shall be followed except specific criteria, if any, mentioned above against that code.

9.3.4 Related NDMA Guidelines

The NDMA has also issued guidelines on landslides, floods and urban flooding and a National Landslide Risk Management Strategy (2019) which are relevant to GLOF. However, considering the special characteristics of the GLOF/ LLOF events, there is a need for special regulations for areas situated downstream of GLOF/ LLOF hazard areas.

9.3.5 Initiatives of the Ministry of Environment, Forest and Climate Change (MoEFCC)

The Ministry of Environment, Forest and Climate Change (MoEFCC) is the nodal agency in the administrative structure of the central government for planning, promotion, co-ordination and overseeing the implementation of environmental and forestry programs. Certain initiatives of MoEFCC are relevant in the context of flooding in hilly areas. Environmental Impact Assessment (EIA) is one of the proven management tools for incorporating environmental concerns in development process and in improved decision-making. The EIAs were initiated with the appraisal of river valley projects and now includes other sectors like industrial projects, thermal power plants, mining schemes and infrastructure projects, new projects relating to construction of townships, industrial townships, settlement colonies, commercial complexes, hotel complexes, hospitals, office complexes for 1000 persons and above, or discharging sewage of 50,000 liters per day and above, or with an investment of Rs 50 crore and above, and new industrial estates having an area of 50 hectares and above etc., storm water drainage. Guidelines will be issued to State EIA Authorities to subject even smaller projects to meet EIA norms.

9.3.6 State Level Legislation

The planning and development are state subjects and therefore, the development in the states is based on the legislative support as applicable in that state. The legislative support in the state is applicable to formulate Master Plans, Zonal Development Plans and Area Planning layouts for their implementation and enforcement.

9.3.7 Legislative Support at the Local/ Municipal Level

At the local level, the Municipal Authorities and Panchayats regulate the development/ construction of buildings through the building bye-laws as followed in their respective areas. The State Governments/UTs from time to time issue directions/guidelines for safety against natural hazards, which are followed by local bodies while granting permission for construction of buildings/ structures.

9.4 TECHNO-LEGAL REGIME AND RISK MANAGEMENT IN SWITZERLAND

Switzerland is a mountainous country that has a long history of living and responding to natural hazards, including GLOFs. The Federal Flood Protection Law and the Federal Forest Law came into force in 1991. The purpose of these laws is to protect the environment, human lives and property from the damage caused by water, mass movements, snow avalanches and forest fires. As a result of these regulations, greater emphasis has been placed on preventative measures, and cantons are legally required to establish registers and maps denoting areas of hazards and to take them into account in their guidelines for land use planning.

Hazard maps, according to the federal guidelines express three degrees of danger, represented by corresponding colours: red, blue and yellow (see also Chapter 3). This ensures homogeneous and uniform means of assessment of the different kinds of natural hazards affecting Switzerland. The estimated degrees of danger have implications for land use. They indicate the level of danger to people and to animals, as well as to property.

RED: high hazard

People are at risk of injury both inside and outside buildings

A rapid destruction of buildings is possible

or: Events with a lower intensity, but a higher probability of occurrence. In this case, people are mainly at risk outside buildings, or buildings can no longer house people

The red zone mainly designates a prohibition domain (area where development is prohibited)

BLUE: moderate hazard

People are at risk of injury outside buildings. Risk is considerably lower inside buildings

Damage to buildings should be expected, but not a rapid destruction as long as the construction type has been adapted to the present conditions

The blue zone is mainly a regulation domain, in which severe damage can be reduced by means of appropriate protective measures (area with restrictive regulations)

YELLOW: low hazard

People are at slight risk of injury

Slight damage to buildings is possible

The yellow zone is mainly an alerting domain (area where people are notified of the possible hazard)

YELLOW–WHITE HATCHING: residual danger

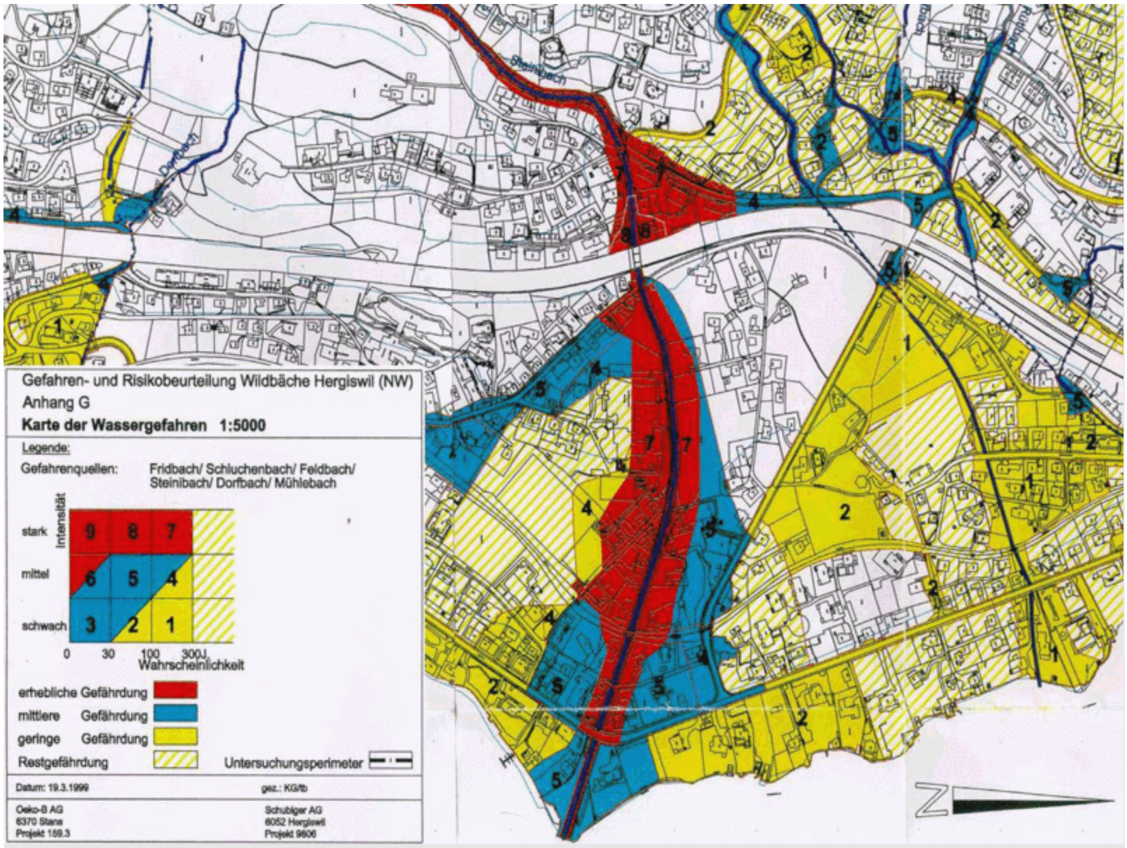
Low probability of a high intensity event can be designated by yellow–white hatching.

The yellow–white hatched zone is mainly an alerting domain, highlighting a residual danger

WHITE: no danger or negligible danger, according to currently available information

Importantly, hazard maps are compiled for all the different processes that are relevant for a specific site or settlement. This has important implications for spatial planning, since being outside the GLOF hazard zone, for example, does not necessarily imply to be safe from avalanches or other flood hazards. Hence, risk management follows a multi-risk approach.
As the basis for land-use planning, hazard maps are to be considered when:

- Elaborating or improving the Cantonal Master Plan and Communal Local Plans for land use.
- Planning, construction and transformation of buildings and infrastructures.
- Granting of concessions and planning for construction and infrastructure installations, as well as for laws related to land use.
- Granting of subsidies for building and development (road and rail networks, residences), as well as for slope stabilization and protection measures.



Example of a flood hazard map for the village of Hergiswil, central Switzerland (http://www.planat.ch/en/authorities/hazard-maps)

Conflicts occur when hazard maps are compared with existing land use. As it is difficult or impossible to alter land use, specific construction codes are required to reach the desired protection level. Hazard maps are also valuable when planning protective measures including the installation of warning systems and emergency plans.

This short summary is based on: Raetzo H, Lateltin O, Bollinger D, Tripet JP. 2002. Hazard assessment in Switzerland - Codes of Practice for mass movements. Bulletin of Engineering Geology and the Environment 61: 263–268.

9.5 RECOMMENDATIONS

There are no widely accepted procedures or regulation in India for land use planning in the GLOF/LLOF prone areas. A committee should be constituted to formulate specific regulations need to be developed concerning the increased risk of future GLOF/LLOF events and give its recommendations within a year. The following actions are recommended for preparing techno-legal regime for cities, towns and villages in GLOF hazard areas also considering the associated hazards of cloudburst, flashflood, earthquakes and landslides.

9.5.1 Policy Level Recommendations

The State Governments / Sanctioning authorities should have a panel of reputed and technical personnel including SDMA, who can assist the building sanctioning authority in formulating GLOF specific regulations. They should take into consideration the Government Orders issued by the various State Governments which contain a number of provisions to be followed while sanctioning the building plans by the Development Authority, Special Area Development Authority, Corporation, Municipal Board and also by the concerned government department while formulating the regulations. At present there are several Acts/Rules/ Regulations applicable in the states. There should be single legislation to control development and building activity which could be formed taking into consideration present legislative framework and incorporating the suggestions made and should follow strictly the provisions suggested for safety against natural hazards e.g. the provision of Indian Standards. EIA should also consider the expected GLOF event(s) for future projects in GLOF hazard areas.

9.5.2 Technical Level Recommendations

The regulations should make it mandatory for all buildings, especially hospitals, schools, community halls to be designed according to the latest specifications and codes, for example the National Building Code of India, 2016. The special technical committee should recommend additional measures to be included in GLOF hazard areas.

9.5.3 Community Level Recommendations

There is a need to bring awareness at all levels of society starting with a high-level awareness program for decision makers regarding safety against natural hazards and the techno-legal regime. Awareness / training program is required for engineers / officials working with local authorities regarding bye-laws, regulations, codes and manuals for disaster resistant construction.

9.5.4 Tourism Level Recommendations

The regulations should be made to create the buffer zone to restrict the tourism in GLOFs prone areas and nearby region to reduce the impact of pollution in those areas. This should be monitored by state tourism committee to reduce the frequency of GLOF occurrences and recommend additional measures to be included in GLOF hazard areas. Awareness programmes/ notices should be disseminated for instructions, in collaboration with local authorities for disaster resistant tourism services.

Chapter 10 : Implementation of The Guidelines— Preparation of GLOF & LLOF Management Plans

10.1 PLAN OF ACTION

Comprehensive DM plans will be prepared at the National, State and District levels. At the National level, the DM plan will focus on various aspects of DM including preparedness, mitigation and response. These plans will clearly identify the roles of key stakeholders for each disaster level and also include assessments of their own response capacities.

There is no Nodal Ministry and Agency identified for the subject on glacial studies including Glacial Lake Outburst Flood (GLOF) and Landslide Lake Outburst Flood (LLOF). Although, Central Water Commission (CWC) was monitoring the glacial lakes including water bodies from the year 2009 onwards and also identified to provide mitigation measures for landslide dams in the NDMA Guidelines on Management of Landslides and Snow Avalanches (June, 2009). Therefore, it is proposed to identify the Ministry of Jal Shakti (MoJS) as Nodal Ministry and CWC as Nodal agency for the glacial studies including GLOF and LLOF.

[**Action:** The MoJS]

These plans will be subjected to approval from NDMA, will include various aspects of Glacial and Landslide Hazard management especially GLOF and LLOF. The main features to be included in the plan are as follows:

i) Preparation of state and district level DM plans with the aim of managing GLOF and LLOF hazard events.

ii) Revision of town planning bye-laws and adaptation of model land use bye-laws in hilly areas.

iii) Wide dissemination of model land use practices in hilly areas.

iv) Training of trainers in professional and technical institutions.

v) Training of professionals like engineers and geologists for hazard assessment and mapping, investigation techniques, analysis and observational practices

vi) Launching Public awareness campaigns on GLOF & LLOF hazard and risk reduction, and sensitizing all stakeholders on hazard mitigation.

vii) Establishing appropriate mechanisms for compliance review of all land use bye-laws in hilly areas.

viii) Preparing an inventory of past and recent GLOF and LLOF events.

ix) Developing an inventory of critical lakes including attributes based on Geo-spatial and on field analysis like topography, rock type etc.

x) Assessing the status of risk (exposure and vulnerability) of the existing built environment.

xi) Preparation of the DM plans by educational and health institutes/organisations, government offices, etc., and carrying out mock drills for enhancing preparedness in vulnerable areas.

xii) Strengthening the EOC network.

xiii) Streamlining the mobilization of communities, government agencies, the corporate sector, and other stakeholders.

xiv) Preparing community and village level DM plans, with specific reference to the management of GLOFs and LLOFs.

xv) Developing simple and effective information and warning dissemination systems that can reach affected communities in far flung areas clearly and in time.

xvi) Introducing GLOF and LLOF safety education (as a sub-group to Landslide and Flood education) in schools, colleges and universities.

xvii) Strengthening hazard safety R&D in professional technical institutions.

xviii) Preparing document on the lessons learnt from previous GLOF and LLOF incidents, and their wide dissemination.

xix) Preparing an action plan for upgrading the capabilities of organisations and institutions involved in Glacial, Landslide and Flood disaster management studies with clear roadmap and milestones.

xx) Developing appropriate risk transfer instruments by collaborating with insurance companies and financial institutions.

xxi) Enforcing and monitoring the compliance of land use and town planning bye laws, and other safety regulation in areas vulnerable to GLOF/LLOF.

The proposed timeline for the implementation of the various activities in Guidelines are both important and very necessary especially in case of the non-structural measures for which no clearance is required from central and other agencies. Structural measures will be dealt with precise schedules evolved in the GLOF/LLOF management plans that will be followed at the central/state ministries, duly taking into account the availability of financial, technical and managerial resources. A strategy plan of implementation of various activities in the guidelines needs to be devised at the state and central level.

10.1.1 Short Term (1-2 years)

i) Formation of Specialized Committee under MoJS/CWC in consultation with NDMA involving expert agencies/ institutes dealing with research and development on Glacial, Landslide and Flood Hazards to formulate specific land use zoning, development control, building construction regulations etc.

[**Action:** The MoJS/CWC in consultation with NDMA]

ii) Taking up pilot projects at least at 10 sites in the next two years to strengthen up the existing methodology right up to hazard and risk level.

[**Action:** The MoJS/CWC in consultation with concerned State/UT Disaster Management Authorities and other stakeholders]

iii) Hiring group of expert agencies to identify susceptible sites through Remote Sensing and GIS. Also, create a priority list by examining the vulnerability and associated risk for which immediate attention is required.

[**Action:** The MoJS/CWC in collaboration with NRSC and other stakeholders in consultation with NDMA]

iv) Development of Early Warning System (EWS) based on Ground Instrument, Water level sensors and Seismicity in consultation with Expert Institutes (such as NIH-Roorkee, C-DAC) and other nodal agencies.

[**Action:** The MoJS/CWC in consultation with concerned State/ UT Disaster Management Authorities and other stakeholders]

v) Set up a regular monitoring system using remote sensing satellites and GIS.

[**Action:** The MoJS/CWC in collaboration with NRSC and other stakeholders]

10.1.2 Medium Term (3-4 years)

I) Already available BIS codes with respect to water projects are not sufficient for GLOF/LLOF; therefore, BIS needs to developed the same on different aspects of GLOF/LLOF in coordination/ collaboration with Nodal Ministry/ Agency.

[**Action:** The BIS in coordination with MoJS/CWC and other stakeholders in consultation with NDMA]

ii) Improve and upgrade the current Early Warning System keeping in view the validity and benefits of the results that were acquired during its active session.

[**Action :** The MoJS/CWC in consultation with concerned State/UT Disaster Management Authorities and other stakeholders]

iii) Enhancing the mitigation measures by implementing the Risk Reductions Techniques namely: Water lowering by Tunnel/ spillway and Hazard Reduction by Dam Construction.

[**Action :** The MoJS/CWC in consultation with concerned State/UT Disaster Management Authorities and other stakeholders]

iv) Design of animated character for spreading awareness on disaster management (including GLOF/LLOF): An animated character can be designed in partnership with computer animators.

[**Action :** The MoJS/CWC]

v) Creation of a disaster management application: NDMA in collaboration with the Indian Institute of Technology (IIT) can design a computer application for disaster management. The application can be used to know about the latest information on disasters (including GLOF/LLOF) across the country.

[**Action :** The NDMA in collaboration with MoJS /CWC and other Expert Institutions]

vi) Awareness through documentary: The National Disaster Management Authority (NDMA) should initiate a programme on power point documentary/presentation for Government organisation, School and Hospital organisation, Soldiers, NGOs, Local nodal agencies, Local club, and local people focusing on the role and responsibility before, during and after the GLOF/LLOF disaster.

[**Action** : The NDMA in collaboration with MoJS/CWC and concerned State/UTDisaster Management Authoritiesand other stakeholders]

vii) **Creation of village task force and volunteers:** The not-for-profit organizations should constitute a village task force and volunteers (Aapda-Mitra) in each village of these states. The members of the task force should be made aware of the various aspects of GLOF/LLOF mitigation and post-disaster activities.

[**Action** : State/UT Disaster Management Authorities in consultation with NDMA]

10.1.3 Long Term (5-8 years)

I) **Use of web-based and app-based dissemination tools** for the preparation of maps for common use not only by the administrators but also by the community, tourists etc.

[**Action** : The MoJS/CWC in collaboration with Expert Institutions]

ii) **Wireless sensor network (WSN)** based ground instrumentation and real time monitoring of GLOF/LLOF.

[**Action** : The MoJS/CWC in collaboration with Expert Institutions and consultation with State/UT Disaster Management Authorities]

iii) **Incorporation of latest and advanced mitigation measures** to reduce the risk.

[**Action** : The MoJS/CWC in collaboration with Expert Institutions and consultation with State/UT Disaster Management Authorities]

iv) Incorporation of the advanced Evacuation and Emergency planning measures.

[**Action** : The MoJS/CWC in collaboration with Expert Institutions and consultation with State/UT Disaster Management Authorities]

v) **Awareness programme on GLOF/LLOF hazard:** Government (National/ State) has also emphasized on a robust awareness programme for GLOF/LLOF hazard. Public awareness is being enhanced about signs and events that manifests that a GLOF/LLOF is imminent so that personal safety measures may be taken.

[**Action** : The MoJS/CWC, NDMA and State/UTDisaster Management Authoritiesin consultation with Expert Institutions]

vi) **Use of traditional art forms/traditional knowledge:** Due to modernization and tech savvy nature of 21stcentury generation, old traditions disaster management practices are dying up. Therefore, it is necessary to document and disseminate old traditional best practices available in mountain regions of India through community participation in trainings. Traditional art forms are important mediums of awareness generation. Traditional knowledge and modern technologies are also useful in designing Early Warning System (EWS).

[**Action:**The MoJS/CWC, NDMA and State/UTDisaster Management Authorities in consultation with Expert Institutions]

vii) **Awareness through Participatory Approach:** The planning and implementation process is recommended in order to maintain sustainability of the programs launched by the administration for disaster management. It is necessary that the government and the communities together evolve a joint action plan aimed at enhancing community education and the development of community leadership. The elements of participatory learning can be applied at different levels such as organizational level (headquarters, branches, schools, businesses, work places), community level (village, town, cities) and population level (marginalized, vulnerable sections).

[**Action** : The MoJS/CWC, NDMA and State/UTDisaster Management Authorities in consultation with Expert Institutions]

viii) **Involvement of Not-for-Profit Organisations:** NDMA should identify not-for-profit organisations to undertake the awareness building activities in these States. The organisation should be asked to submit a targeted awareness generation plan.

[**Action:**The MoJS/CWC, NDMA and State/UTDisaster Management Authorities in consultation with Expert Institutions]

ix) **Awareness among school children, their parents and teachers:** The not-for-profit organisations can organise sessions for school children, their parents and teachers from Class IX onwards on various aspects of GLOF/LLOF occurrence and their mitigation. A one-day training module can be designed for the participants.

[**Action:**The MoJS/CWC, NDMA and State/UTDisaster Management Authoritiesin consultation with Expert Institutions]

x) **Awareness among local youth:** The not-for-profit organisation can hold a day long awareness generation camp with the members of the National Cadet Corps (NCC), Scouts and Guides, and National Service Scheme (NSS) volunteers. These camps should be conducted in coordination with the state and district teams of these organisations.

[**Action** : The MoJS/CWC, NDMA and State/UTDisaster Management Authorities in consultation with Expert Institutions]

xi) **Awareness among members of Panchayati Raj Institutions:** On similar lines; the not-for-profit organizations can also hold a one-day awareness generation workshop for the Panchyati Raj Institution (PRI) members of the various panchayats in the district in the district headquarter. The Community Based Family Disaster Preparedness and mitigation (CBFDP) is a process to capacitate communities to prevent, mitigate and cope with disasters effectively.

[**Action:**The MoRD and State/UTDisaster Management Authorities in consultation with Expert Institutions]

xii) **Awareness among policy makers and government officials:** The policy makers are key stakeholders in disaster management. State Disaster Management Authority (SDMA) can hold workshops with policy makers and government officials of all departments to reinforce their role in ensuring that people conform to the various land use policies.

[**Action:** The MoJS/CWC, NDMA and State/UTDisaster Management Authorities in consultation with Expert Institutions]

xiii) **National Data Centre on GLOF/LLOF:** It would integrate various data sources, a geo-portal to address the data needs and thus, enable an effective response.

[**Action :** The MoJS/CWC in consultation with NRSC-ISRO]

xiv) **Climate Change related GLOF/LLOF risk management:** The past incidences clearly indicate the high frequency as well as intensity of the hydro-meteorological hazards in the mountain region such as heavy rainfall, landslides, riverine floods, cloud burst, Glacial Lake Outburst Floods (GLOFs), droughts etc. Therefore, local communities require awareness, specialized training and right information to cope up with disasters in the mountains.

[**Action:** The MoJS/CWC, NDMA, NIDM and State/UT Disaster Management Authorities in consultation with Expert Institutions]

Section 7.11 of NDMP (2019) may also be referred for any other specific responsibilities of Central/ State agencies related to GLOF.

10.2 IMPLEMENTATION AND MONITORING

10.2.1 Institutional Mechanisms

The National Disaster Response Force (NDRF)/SDRF mandated by the DM Act, 2005, will address, in close collaboration with all other field level agencies, all concerns regarding the response to the threat of GLOF/LLOF disaster or other disasters if and when these arise or occur.

The NDRF/SDRF personnel will be equipped with the most modern search and rescue equipment and will undergo GLOF/LLOF specific training to be able to effectively deal with diverse types of GLOF/LLOF and other mass movements and familiarise themselves with the case records of some of the major GLOF/LLOF events.

The projects prepared by the central ministries, departments, state governments, district authorities, rural bodies, urban local bodies, and other stakeholders in accordance with these Guidelines will be implemented by them in accordance with in-built schedules. These plans will indicate clearly the structure of the monitoring as per Govt. of India norms and the reports to be generated at various levels together with the agency to which the report is to be sent, its format and the frequency/timing.

10.3 FINANCIAL ARRANGEMENTS

10.3.1 Main streaming of Disaster Management in Developmental Plans

The central and state ministries/ departments will mainstream disaster management efforts in their developmental plans. In the annual expenditure plans, specific allocations will be made for carrying out disaster awareness programmes, maintaining preparedness and for undertaking mitigation efforts. Wherever necessary and feasible, the corporate sector should also be involved in supporting risk management efforts as part of Corporate Social Responsibility (CSR).

10.3.2 Plans of Central Ministries/ Departments

The various measurement for GLOF management recommended in the Guidelines will be funded by the central ministries/departments and state governments concerned by making provisions in their Five-Year and annual plans. Additional funds will also be made available through special mitigation projects to be formulated and implemented by the state governments/SDMAs under the overall guidance and supervision of the NDMA. Besides this, 10 per cent of the Calamity Relief Fund (CRF) could also be utilized for the purchase of equipment for GLOF preparedness and mitigation, and for rescue and relief operations.

[Action: SDMAs in collaborations with Central Ministries]

10.3.3 State Plans

GLOF management schemes would be planned, funded, executed and maintained by the state government themselves as per their own priorities. Central plan assistance would be in the form of block loans and grants and would not be tied to any sector or project. Allocations for the GLOF sector within the overall plan outlay would have to be made by the state government themselves. The various measures for GLOF management recommended in these Guidelines will be included by the respective state government in their own plans.

[Action: State governments/SDMAs]

10.3.4 Centre for Glacial Research, Studies & Management (CGRSM)

A national level Centre for Glacial Research, Studies and Management (CGRSM) will be established by the MoJS under the umbrella of the National Institute of Hydrology (NIH), Roorkee as a premier centre with state-of-the art facilities, which would eventually grow into a national centre of excellence. It will be fully autonomous in its functioning, similar to that of the national laboratory of the Council of Scientific and Industrial Research with full operational freedom and an independent budget. It will operate within a framework of specified rules. The CGRSM will be headed by an eminent expert with a proven track record.

This initiative will help in ensuring a wider view of glacial studies as a component of the environment/climate change and bringing the existing pool of expertise in earth sciences including hydrology, geomorphology, seismology, meteorology, landslide, IT etc. to bear upon this new initiative.

The national centre will be serviced by a nation-wide chain of actual as well as virtual sub-centres (field offices) in high-altitude to ensure adequate national coverage, information flow, community participation, networking, feedback etc. It will also foster, promote and sustain a scientific culture in the glacial studies including GLOF/LLOF aiming for a paradigm shift in the culture of prevention and safety. It will aim to galvanise the existing scattered pool of scientific and technological expertise especially in subjects such as geomorphology, earth sciences, meteorology, seismology, space research, IT and communication technology, urban development, remote sensing etc. Other areas of concern to be addressed by the centre will be to learn lessons from past incidences and arranging for high quality education, research, training and documentation. To begin with sub-centres (field offices) will as far as possible, be located in one of the existing knowledge institutions to be identified in consultation with the State Government. The network could be gradually expanded in tune with the dynamics of felt needs. The establishment of virtual sub-centres will be encouraged to serve as clearing houses of information. The national capacity building initiative of the central and state governments would make adequate funding provisions to ensure a critical mass of staffing and infrastructure in the field offices, The CGRSM will nurture the field offices, eventually making them financially self-supporting within the time frame of one decade.

In the field of geotechnical investigation and research, the CGRSM will coordinate and collaborate with the national and international Institutions such as Wadia Institute of Himalayan Geology (WIHG), NCPOR-Goa, NRSC-ISRO, IIRS-ISRO, SASE-DRDO, Zurich University, SLF DAVOS, NGI etc, as well as scientific organizations such as the Standing Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA).

[**Action:** The MoJS in consultation with NDMA]

10.3.5 Centrally Sponsored/Central Sector Schemes

The role of the central government is advisory, promotional and facilitative in nature. On specific requests from the state governments, the MoJS/CWC will include some of the works/ schemes in consultation with NDMA and Technical Advisory Committee (TAC) as recommended in the Guidelines for funding under these schemes, provided that sufficient funds are available. A high level scientific and TAC which will be chaired by the Secretary, MoJS will be constituted by the MoJS in consultation with the NDMA to serve as a think tank to nurse the glacial studies with cutting edge science and technology, fresh ideas and stimulus.

TAC will also make recommendations to the GoI on various aspects of the CGRSM including its formation, aims and objectives, funding, functioning and autonomy.

The Joint Secretary, NDMA; Joint Secretary, MoEFCC; Joint Secretary, MoES; Joint Secretary, MoJS; Joint Secretary, DST and Executive Director of the NIDM will be ex-officio members of both CGRSM and TAC.

[**Action:** The MoJS-CWC]

The TAC will comprise top professionals (either national or international) drawn from multi-specialty streams of Government, Private, Independent researchers connected with glacial studies including GLOF/LLOF and it will address research, human resource and capacity development, glacial mapping, investigation, mitigation, control, preservation and protection of glacier as a component of the environment.

It will also provide full support to the human resource development and training functions delegated to the NIDM and other national institutions.

[**Action:** The MoJS in consultation with the NDMA and MoEFCC]

10.3.6 District Planning and Development Council Funds

From the funds available with the District Planning and Development Council in GLOF prone areas, a part will be allocated for the implementation of GLOF management schemes in the districts.

[**Action:** State/UT Admin**]**

10.3.7 Comprehensive and Pilot National GLOF Mitigation Projects

The NDMA has proposed to take up a pilot project and Comprehensive Mitigation Project on GLOF (CMP-GLOF) whose aims and objectives will be developed and finalized in due course. In a broader sense, it will consider the following issues:

i) Assessment of the risk and vulnerabilities associated with GLOF disasters.

ii) Reduction in the degree of the risk, severity or consequences of GLOF and improving their mitigation.

iii) Setting pace setter examples for geological and geotechnical investigations of GLOF and also for efficacy of GLOF treatment measures.

iv) Establishment of monitoring and early warning systems for susceptible glacial lakes.

v) Capacity development of institutes/organizations enhancing the capabilities of communities and training of functionaries.

vi) Identification of institutes /organizations and entrusting them with the implementation of R&D programs.

vii) Enhancing the promptness and efficacy of response to impeding threats of GLOF or their actual occurrence.

viii) Ensuring that proper arrangements are made for organizing rescue, relief and rehabilitation works.

ix) Improving the quality and increasing the speed of rehabilitation and reconstruction process.

x) Spreading awareness with a stress on preparedness and providing advice and training to the agencies involved in the management of GLOF.

[**Action:** The NDMA in collaboration with MoJS/CWC]

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Appendix 1

Factors to be considered under an assessment of ice avalanche susceptibility/stability (from GAPHAZ 2017)

Susceptibility factors for Ice Avalanches	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+	+		Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Basin
				Intensity and frequency of extreme temperatures	Low	High	Station-based or gridded climate analyses	Basin
Precipitation		+		Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Basin
Cryospheric								
Thermal conditions	+			Cold, polythermal or temperate glacier. Distribution and persistence of permafrost. Thermal anomalies due to hanging glaciers.	Expert judgement of implications for failure mechanisms and processes.		Model-based (indirect) Geophysical (semi-direct) Boreholes (direct)	Regional to basin. Site specific.

Glacier type	+		+	Cliff or ramp type situation.	Expert judgement of implications for frequency/magnitude.		Remote sensing	Regional to basin
Crevasse density and orientation	+		+	Formation of cracks across glacier. Size and depth of crevasses.	Not evident	Large and widespread	Remote sensing	Basin to site specific
Bed topography	+			Steep slope angle and sudden breaks in topography. Convex slopes. Lack of frontal abutment.	Favorab le	Unfavorable	Inferred or modelled from surface topography. Geophysical survey.	Regional to basin. Site specific.
Glacial hydrology	+	+		Distributed subglacial drainage system for ramp-type failures. Evidence of increased water pressure and or blockages (critical for polythermal glaciers), such as pooling at surface or sudden changes in discharge for large catastrophic failures.	Favorab le	Unfavorable	Remote sensing, hydrological modelling, and field studies.	Basin to site specific.
Glacier velocity	+			Increase in surface velocity, particularly below crevasse zones.	No change	Rapid increase	Remote sensing, field studies	Basin to site specific
Glacier geometric change	+			Thickening towards base of hanging glacier. Thickening of valley glacier tongue as evidence for surging.	No change	Large thickening	Remote sensing	Basin to site specific
Glacier length change	+			Retreating or advancing towards steeper topography, and/or new thermal regimes.	Favorab le	Unfavorable	Remote sensing, field studies, anecdotal evidence	Regional to basin
Ice avalanches evident	+	+	+	Frequency and magnitude of instabilities, including serac fall.	Not evident	Frequent and increasing activity	Remote sensing, field studies, anecdotal evidence.	Basin to site specific
Geotechnical and geomorphic								

Underlying bedrock stability	+	+	+	SEE ROCK AVALANCHE SUSCEPTIBILITY ASSESSMENT (Appendix 2)	Unstabl e	Stable	SEE ROCK AVALANCHE SUSCEPTIBILITY ASSESSMENT	Basin to site specific
Seismicity	+	+		Potential magnitude & frequency, ground acceleration	Low potential	High potential	Geological mapping & modelling.	Regional

Appendix 2

Factors to be considered under an assessment of rock avalanche susceptibility/stability (from GAPHAZ 2017)

Susceptibility factors for Rock Avalanches	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+	+		Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Basin
				Intensity and frequency of extreme temperatures	Low	High	Station-based or gridded climate analyses	Basin
Precipitation		+		Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Basin
Cryospheric								
Permafrost conditions	+		+	State of permafrost, distribution and persistence within bedrock slopes. Depth of active layer and unstable mass.	No permafrost or cold permafrost	Warm (melting) permafrost	Model-based (indirect) Geophysical (semi-direct)	Regional to basin. Site specific.
Glacier conditions	+		+	Retreat (thinning) from within or below rock slope.	No retreat	Significant retreat	Remote sensing, field studies, anecdotal evidence	Regional to basin

Geotechnical and geomorphic								
Rock mass quality	+		+	Lithological characteristics Degree of weathering	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Condition of Discontinuities	+			Degree of weathering, aperture, filling (e.g. breccia or gouge), seepage	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Geometry of Discontinuities	+		+	Dip, orientation, spacing, persistence	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Condition of slope	+			Overhanging, convexities, irregularities	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Slope angle	+			Topographic slope angle. Critical range or threshold angle established from local inventories.	Low slope angle	Steep slope angle	Geological mapping (remote sensing or field)	Basin to site specific
Slope height	+		+	Relative relief of the face or slope	Small	Large	Geological mapping (remote sensing or field)	Basin to site specific
Seismicity	+	+		Potential magnitude & frequency, ground acceleration	Low potential	High potential	Geological mapping &modelling.	Regional
Rockfall evident	+	+	+	Frequency and magnitude of past activity	Not evident	Frequent and increasing activity	Geological mapping (remote sensing or field)	Basin to site specific

Appendix 3

GLOF Modelling

Background theory

The essence of dam break modelling is hydrodynamic modelling, which involves finding solution of two partial differential equations originally derived by Barre De Saint Venant in 1871. These equations are:

$$(\partial Q/\partial X) + \partial (A + A_0) / \partial t - q = 0 \quad \text{(continuity equation)} \quad (3)$$
$$(\partial Q/\partial t) + \{\partial (Q^2/A)/\partial X\} + gA((\partial h/\partial X) + S_f + S_c) = 0 \text{ (Momentum equation)} \quad (4)$$

where, Q = discharge; A = active flow area; A_0 = inactive storage area;
h = water surface elevation; q= lateral flow; x = distance along waterway; t = time;
S_f = friction slope; S_c= expansion contraction slope and g = gravitational acceleration

The mathematical models which approximately solve the governing flow equations of continuity and momentum by computer simulation are the cost effective modern tools for the dam break analysis. Selection of an appropriate model to undertake dam break flood routing is very essential to ensure the right balance between modeling accuracy and cost (both in terms of software cost and time spent in developing & running the model). The objectives of dam break modeling mainly consist of i) prediction of the outflow hydrograph due to dam breach, ii) routing the hydrograph through the downstream valley to get the maximum water level and iii) qualifying discharge along with the time of travel at different locations of the river downstream of the dam. Dam break flood simulation studies can be carried out by either a) Scaled physical hydraulic models or b) Mathematical simulation models.

The essence of dam break modeling is hydrodynamic modeling, which involves finding solution of two partial differential equations originally derived by Barre De Saint Venant in 1871. These equations are:

$$(\partial Q/\partial X) + \partial (A + A_0) / \partial t - q = 0 \quad \text{(continuity equation)} \quad (8.1)$$
$$(\partial Q/\partial t) + \{\partial (Q^2/A)/\partial X\} + gA((\partial h/\partial X) + S_f + S_c) = 0 \text{ (Momentum equation)} \quad (8.2)$$

Where,

Q = discharge; A = active flow area; A_0 = inactive storage area;
h = water surface elevation; q= lateral flow; X = distance along waterway; t = time;
S_f = friction slope; S_c = expansion contraction slope and g = gravitational acceleration

Available models

A number of commercial software are available for carrying out dam break modelling. A brief description of several of these commonly used models is provided below. The list is not complete and new developments in this field are occurring.

HR BREACH

The HR BREACH model is a numerical model that predicts breach growth through flood embankments and embankment dams made from different material types and construction. It combines hydraulics, soil mechanics and structural analysis into a single breach prediction model. The model also balances speed and complexity against usability and the need for a practical tool to support dam break analyses, flood risk assessments and the possible development of evacuation and emergency action plans (Tucker et. al., 2002).
The HR BREACH Model is capable of simulation of composite or zoned structures, also including grass or rock embankment surface protection, simulation through both homogenous and non cohesive soils, and breach initiation through piping and / or over flow.

SOBEK Flood Model:

SOBEK is a powerful modelling suite for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt intrusion and surface water quality. The components within the SOBEK modelling suite simulate the complex flows and the water related processes in almost any system. The components represent phenomena and physical processes in an accurate way in one dimensional (1D) network systems and on two dimensional (2D) horizontal grids. It is the ideal tool for guiding the designer in making optimum use of resources (Vanderkimpen P. et. al., 2009).

SOBEK offers one software environment for the simulation of all management problems in the areas of river and estuarine systems, drainage and irrigation systems and wastewater and storm water systems. This allows for combinations of flow in closed conduits, open channels, rivers overland flows, as well as a variety of hydraulic, hydrological and environmental processes.

HEC RAS:

HEC-RAS is a one-dimensional steady flow hydraulic model designed to aid hydraulic engineers in channel flow analysis and floodplain determination. The results of the model can be applied in floodplain management and flood insurance studies.

The program is one-dimensional, meaning that there is no direct modeling of the hydraulic effect of cross section shape changes, bends, and other two- and three-dimensional aspects of flow. The program was developed by the US Department of Defense, Army Corps of Engineers in order to manage the rivers, harbors, and other public works under their jurisdiction; it has found wide acceptance by many others since its public release in 1995 (USACE , 2001).

FLO – 2D:

FLO-2D is a dynamic flood routing model that simulates channel flow, unconfined overland flow and street flow. It simulates a flood over complex topography and roughness while reporting on volume conservation, a key to accurate flood distribution. The model uses the full dynamic wave momentum equation and a central finite difference routing scheme with eight potential flow directions to predict the progression of a flood hydrograph over a system of square grid elements. FLO-2D is a FEMA approved hydraulic model for riverine studies and unconfined flood analyses.FLO-2D can be applied to complex flood problems including river flooding, levee breach, split flows, unconfined alluvial fan and floodplain flows and detailed urban flooding. It is used by agencies and consultants in over 30 countries (U.S. Army Corps of Engineers, 2008).

DAMBRK:

A dam-break flood forecasting model (DAMBRK) is described and applied to two actual dam-break flood waves. The model consists of a breach component which utilizes simple parameters to provide a temporal and geometrical description of the breach. The model computes the reservoir outflow hydrograph resulting from the breach via a broad-crested weir flow approximation, which includes effects of submergence from downstream tail water depths and corrections for approach velocities. Also, the effects of storage depletion and upstream inflows on the computed outflow hydrograph are accounted for through storage routing within the reservoir.

The basic component of the DAMBRK model is a dynamic routing technique for determining the modifications to the dam-break flood wave as it advances through the downstream valley, including its travel time and resulting water surface elevations. The dynamic routing component is based on a weighted four-point, nonlinear finite-difference solution of the one-dimensional equations of unsteady flow (Saint-Venant equations) which allows variable time and distance steps to be used in the solution procedure. Provisions are included for routing supercritical flows, subcritical flows, or a spontaneous mixture of each, and incorporating the effects of downstream obstructions such as road-bridge embankments and/or other dams, routing mud/debris flows, pressurized flow, landslide-generated reservoir waves, accounting for volume and flow losses during the routing of the dam break wave, considering the effects of off-channel (dead storage), floodplains, and floodplain compartments. Model input/output may be in either English or metric units. DAMBRK, developed by NWS (National Weather service station of United States), is commonly used dam break simulation software and estimates the breach outflow hydrograph. Dam and reservoir parameters such as crest height are required inputs. Breach characteristics such as size, shape and time of formation of the breach are also input to the model and derived empirically (Fread et.al., 1988).

Mike-11:

The MIKE 11 hydrodynamic model (HD) utilizes an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. It can describe sub-critical as well as super critical flow conditions through a numerical scheme which adapts according to the local flow conditions (in time and space). The bed resistance in Mike -11 can be described using three methods such as Chezy, Manning and Darcy-Weisbach (Mike 11 reference manual, 2014).

In the Mike-11 1D HD model, the dam break is simulated using two methods. 1^{st} method uses its own energy equation for simulating the breach from a dam failure and in 2^{nd} method it uses NWS DAMBRK program. In both the cases, the breach can be due to overtopping or due to piping failure. The model allow in stream sediment transport (cohesive and non-cohesive) be activated in case of dam break simulations.

BEED:

The model estimates reservoir water level, breach bottom elevation, and discharge with routing downstream. The user can utilize the model in FORTRAN 77 and BASIC computer languages. The model calculates sediment discharge employing Einstein Brown bed-load formula, relating the initiation and cessation of sediment motion to the hydrodynamic lift forces and particle submerged weight as a function of the inverse of Shield's dimensionless shear stress.

The model is used as a steady uniform flow formula. It explicitly accounts for side slope instability and collapsing. It uses the contour method to analyze the mechanics of slope collapsing assuming saturated soil conditions (Tucker et al., 2002).

DEICH-P:

The model calculates breach formation in homogeneous dams with or without a cohesive core by solving the flow and Exner equation in combination with a sediment transport formula.DEICH-P describes the breach shape with a relationship between bottom and side slope erosion rates using a coefficient similar to MIKE 11. The model transforms the calculated eroded breach volume with kinematics assumptions into vertical or side erosion change (Tucker et.al. 2002).

SMPDBK:

The Simplified Dam-Break (SMPDBK) was developed by the National Weather Service (NWS) for predicting downstream flooding produced by a dam failure. This program is still capable of producing the information necessary to estimate flooded areas resulting from dam-break floodwaters while substantially reducing the amount of time, data, and expertise required to run a simulation of the more sophisticated unsteady NWS DAMBRK, or now called FLDWAV. The SMPDBK method is useful for situations where reconnaissance level results are adequate, and when data and time available to prepare the simulation are sparse. Unlike the more sophisticated versions of DAMBRK and FLDWAV, the SMPDBK method does not account for backwater effects created by natural channel constrictions of those due to such obstacles as downstream dams or bridge embankments.

DWOPER:

An unsteady flow dynamic routing model (one-dimensional Saint-Venant equations) for a single channel or network (dendritic and/or bifurcated) of channels for free surface or pressurized flow. It is a computerized hydraulic routing program whose algorithms incorporate the complete one-dimensional equations of unsteady flow. It can be used on a single river or system of rivers where storage routing methods are inadequate due to the effects of backwater, tides and mild channel bottom slopes. The model is based on the complete one-dimensional St. Venant equations. A weighted four-point nonlinear implicit finite difference scheme is used to obtain solutions to the St. Venant equations using a Newton-Raphson iterative technique.

RAMMS (rapid mass movement simulation):

RAMMS is a 2D dynamics modelling software for rapid mass movements in 3D alpine terrain (https://ramms.slf.ch/ramms/). It allows for the prediction of runout distances, flow velocities, flow heights, and impact pressures in natural three-dimensional terrain. It provides prediction information that is not available in existing one-dimensional models (e.g. AVAL-1D). In the field of natural hazards, there is a strong need for process models or tools where both the process and interaction with proposed mitigation measures can be evaluated. RAMMS can be used for the analysis of dense flow snow avalanches, hillslope landslides and debris flows (including GLOFs). It has been developed by a team of experts at the WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL.

RAMMS allows importing topographical and GIS data, followed by calculation and animation of flow parameters. Easy export of the output data is possible in Google Earth and ArcGIS formats. Depth-averaged Navier Stokes equations are implemented in this code with a variety of options available for the flow rheologies -- Dry friction and Voellmy-Salm are two examples.

Commercial and open-source CFD codes – such as ANSYS Fluent and OpenFOAM – can be used for a full 3D flow analysis, which will help in a better design of defense structures.

R.AVAFLOW:

An open source alternative is r.avaflow (https://www.avaflow.org/). This was an initiative launched for the purpose of designing, evaluating, and promoting a comprehensive and innovative simulation model for the dynamics of various types of geomorphic mass flows. The software r.avaflow 2.0 is the result of five years of active research and development, and represents a GIS-supported open source framework for the simulation of complex, cascading mass flows over arbitrary topography and includes a Voellmy-type model and, particularly, a multi-phase flow model that allows modelling of complex cascading processes.

Composition of Task Force

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