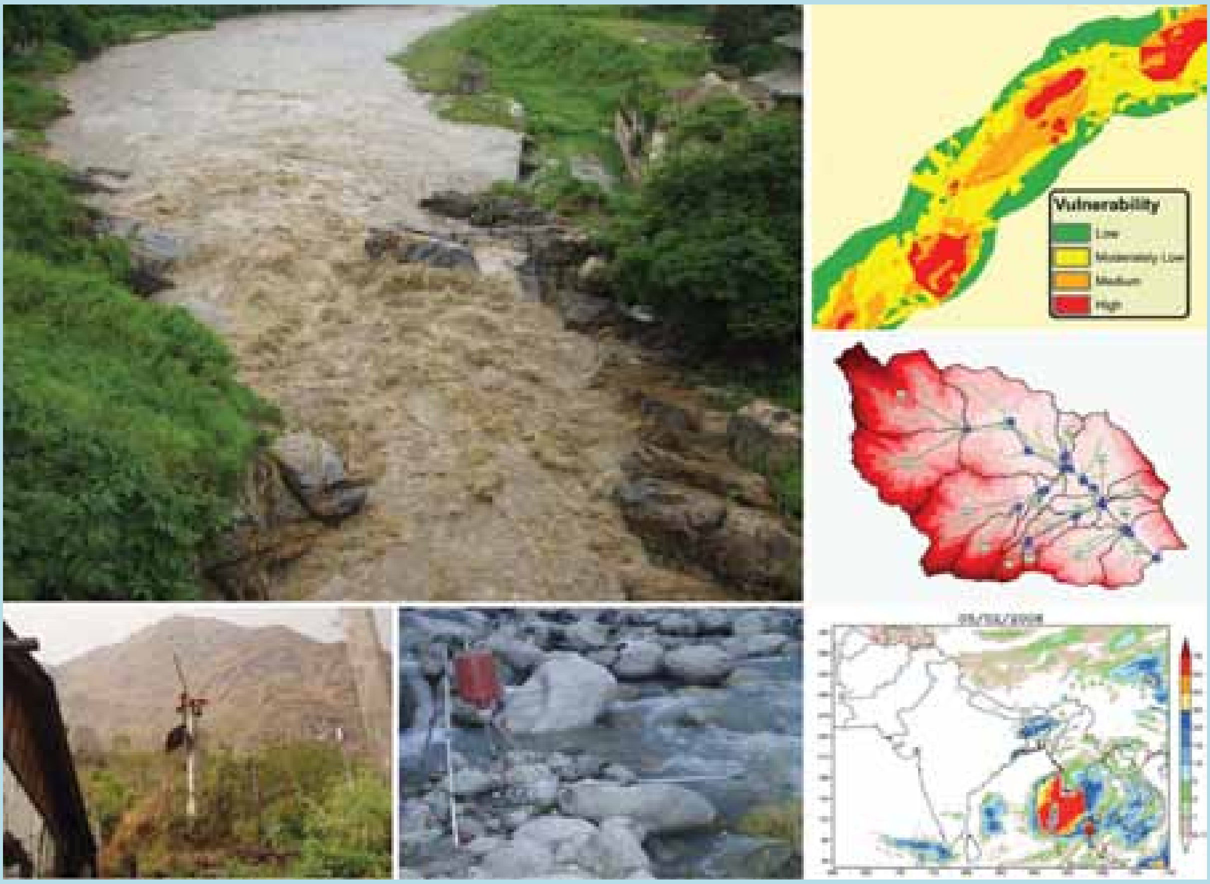
Resource Manual on Flash Flood Risk Management

Module 2: Non-structural Measures



Arun Bhakta Shrestha

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About ICIMOD

The International Centre for Integrated Mountain Development (ICIMOD) is an independent regional knowledge, learning and enabling centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and the global mountain community. Founded in 1983, ICIMOD is based in Kathmandu, Nepal, and brings together a partnership of regional member countries, partner institutions, and donors with a commitment for development action to secure a better future for the people and environment of the Hindu Kush-Himalayas. ICIMOD's activities are supported by its core sponsors: the Governments of Austria, Denmark, Germany, Netherlands, Norway, Switzerland, and its regional member countries, along with programme co-financing donors. The primary objective of the Centre is to promote the development of an economically and environmentally sound mountain ecosystem and to improve the living standards of mountain populations.

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International Centre for Integrated Mountain Development
Kathmandu
July 2008

Published by
International Centre for Integrated Mountain Development
G.P.O. Box 3226
Kathmandu, Nepal

ISBN **978 92 9115 095 3 (printed)**
978 92 9115 096 0 (electronic)

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Printed and bound in Nepal by
Hill Side Press (P.) Ltd.
Kathmandu

This publication is available in electronic form at http://books.icimod.org.

Contents

Foreword

The Hindu Kush-Himalayan (HKH) region is one of the most dramatic physiographic features on our planet. As the youngest mountain system in the world, it has unstable geological conditions and steep topography, which, combined with frequent extreme weather conditions, makes the region prone to many different natural hazards from landslides, avalanches, and earthquakes, to massive snowfall and flooding. Among these, flash floods are particularly challenging for communities.

Flash floods are severe flood events that occur with little or no warning. They can be triggered by intense rainfall ('cloudbursts'), failure of natural or artificial dams, and outbursts of glacial lakes. The frequent occurrence of flash floods within the Hindu Kush-Himalayan region poses a severe threat to lives, livelihoods, and infrastructure, both within the mountains and downstream. Vulnerable groups – the poor, women, children, and people with disabilities – are often the hardest hit. Flash floods pose a greater risk to human life and livelihoods than do the more regular riverine floods, which build up over days when there is heavy rainfall upstream. Flash floods tend to carry with them much higher amounts of debris and, as a result, cause more damage to hydropower stations, roads, bridges, buildings, and other infrastructure.

Since its establishment in 1983, ICIMOD has explored different ways to reduce the risk of disaster from natural hazards and the physical and social vulnerability of the people in the region. These have included training courses, hazard mapping, vulnerability assessments, fostering dialogue among stakeholders, and developing materials for capacity building. Recognising the important role of flash floods, ICIMOD has recently undertaken several initiatives specifically aimed at reducing flash flood risk. An 'International Workshop on Flash Floods' organised by ICIMOD in October 2005 in Lhasa highlighted the need for capacity building in this area. Since then, ICIMOD has been working towards improving the capacity of practitioners and communities to manage flash flood risk.

Resource materials related to flash flood risk management have been compiled and developed by ICIMOD together with various partners to support the capacity development and training of planners and practitioners. After testing with different groups, these resource materials are now being published to make them more widely available. The present publication is the second module of a 'Resource Manual on Flash Flood Risk Management' and looks at technology-based, non-structural measures for managing flash floods. It was produced under the project 'Capacity Building for Flash Flood Risk Management and Sustainable Development in the Himalayas', funded by the United States Agency for International Development, Office for Foreign Disaster Assistance (USAID/OFDA). The first module focuses on community-based approaches to managing flash floods. These two modules are small, but important steps towards securing the physical security of the people of the Hindu Kush-Himalayas. We hope that they will contribute towards reducing disaster risk in this vulnerable region.

Andreas Schild
Director General
ICIMOD

About this Module

Flash floods are among the most destructive natural disasters in the Hindu Kush-Himalayan region. They are sudden events that allow very little time to react. They often occur in isolated remote mountain catchments, where there are few, if any, institutions equipped to deal with disaster mitigation and where relief agencies are either absent or have limited presence and capacity to manage the results of natural disasters. Often the management of flash floods is done primarily by community-based organisations, local non-governmental organisations, or district and ward-level staff of governmental organisations. However, these people often lack adequate understanding of the processes causing flash floods and knowledge of flash flood risk management measures. Building the capacity of those working directly in flash flood-prone catchments will help to reduce flash flood risk in the region.

This manual provides resource materials for understanding the problem and managing the risk. The manual is prepared in two modules. The first concerns community-based flash flood risk management. This second module concerns technology-based non-structural flash flood risk management. Chapters 1 and 2 of this module introduce the natural setting of the region: topography, geology, climatic systems, and so on. Chapter 3 describes three major types of flash flood that occur in the region: intense rainfall floods, landslide dam outburst floods, and glacial lake outburst floods, supplemented by examples and case studies. Chapter 4 explains ways to assess flash flood risks. Chapter 5 describes general, non-structural flash flood risk management measures. Chapter 6 provides insight into some hazard-specific measures.

This module is designed for professionals from both social science and physical science backgrounds. Its objective is to build the capacity of district-level disaster mitigation and relief workers, professionals from community-based and non-governmental organisations such as hydrologists, meteorologists, engineers, and so on. The tools and models selected here are simple, but important, requiring relatively little data. Users with higher technical skills can also benefit from these tools as a first approach and use higher-level models to further enhance their analysis.

Note: Remote sensing images of the Himalayan region use ESRI as the map source with data from ICIMOD. The Hindu Kush-Himalayan outline shows an approximate boundary based on an ICIMOD working definition of mountain/hill areas linked to the mountain ranges that stretch from the Hindu Kush to the Himalayas.

Acknowledgements

This book is an outcome of the ICIMOD project 'Capacity Building for Flash Flood Risk Management and Sustainable Development in the Himalayas', supported by the United States Agency for International Development, Office for Foreign Disaster Assistance (USAID/OFDA).

We are grateful to several colleagues who have contributed to the manual. Muhibuddin Usamah, Asian Disaster Preparedness Center, provided materials on flood hazard mapping. GIS-IDC assisted in preparing the manual on using the HEC HMS model for flash flood modelling. Pradeep Mool and Samjwal Bajracharya provided the manual on spatial data input, attribute data handling, and image processing of Rolwaling Valley, Nepal; and data necessary to use the manual. Pradeep Mool and Samjwal Bajracharya also provided inputs to the section on glacial lake outburst floods. Keshar Man Sthapit provided important contributions to the section on watershed management. Professor C.J. van Westen provided the exercise and data on hazard, vulnerability, and risk analysis. We would also like to acknowledge the United Nations International Decade for Natural Disaster Reduction (IDNDR[*]) for providing the content of Annex 3, Guiding Principles for Effective Early Warning.

Our sincere thanks go to the former Manager of the ICIMOD Water and Hazard Management Programme, Dr. Xu Jianchu, for supporting the initiation of the project and development of this manual, and to the present Manager of the Integrated Water and Hazard Management Programme, Dr. Mats Eriksson, for seeing through the completion of this manual.

Dr. Narendra Khanal, Department of Geography; Dr. Megh Raj Dhital, Central Department of Geology; and Mr. Rupak Rajbhandari, Department of Meteorology of Tribhuvan University provided valuable contributions. Critical comments and constructive suggestions by two external reviewers helped improve the manuscript substantially. Ms. Ezee G.C. provided valuable assistance in preparing the manual.

Many others also contributed to this manual and have generously given permission to reproduce photographs, diagrams, instructions, maps, exercises, and other material; ICIMOD would like to thank them all.

My heartfelt thanks go to many colleagues within and outside ICIMOD, who read the manuscript and provided valuable comments and suggestions.

Thanks also go to the editorial team, A. Beatrice Murray (ICIMOD), Matthew Zalichin (consultant editor), and Susan Sellars-Shrestha (consultant editor/proofreader) for their helpful insights. Heartfelt thanks to the Dharma Ratna Maharjan for his hard work in laying out the manuscript in a very short time and Asha Kaji Thaku for editorial assistance.

[*] IDNDR (1997) *Guiding Principles for Effective Early Warning*. Geneva: United Nations International Decade for Natural Disaster Reduction (IDNDR)

Acronyms

ADPC	Asian Disaster Preparedness Center
CRU	Climate Research Unit
DHM	Department of Hydrology and Meteorology (Nepal)
DPTC	Disaster Prevention Technical Centre (Nepal)
DWIDP	Department of Water Induced Disaster Prevention (Nepal)
ESRI	Environmental Systems Research Institute
EWS	early warning system
FHM	flood hazard mapping
GIS	geographical information system
GIS-IDC	Geographical Information System Integrated Development Centre
GLOF	glacial lake outburst flood
HEC	Hydraulic Engineering Center (USA)
HF	high frequency
HKH	Hindu Kush-Himalayas/n
HMS	Hydrologic Modelling System (HEC)
ICIMOD	International Centre for Integrated Mountain Development
IDNDR	International Decade for Natural Disaster Reduction (UN)
IFFM	integrated flash flood management
ILWIS	The Integrated Land and Water Information System (ITC)
ISDR	International Strategy for Disaster Reduction (UN)
ITC	International Institute for Geo-Information Science and Earth Observation (The Netherlands)
ITCZ	Inter-tropical Convergence Zone
IWRM	integrated water resource management
LDOF	landslide dam outburst flood
masl	metres above sea level
MWRS	monitoring warning and response system
OFDA	Office for Foreign Disaster Assistance (USAID)
RGSL	Reynolds Geoscience Limited (UK)
SCS	Soil Conservation Service (now Natural Resources Conservation Service, USA)
TU	Tribhuvan University (Nepal)
UN	United Nations
USACE	United States Army Corps of Engineers (USA)
USAID	United States Agency for International Development
USGS	United States Geological Survey
VHF	very high frequency
WECS	Water and Energy Commission Secretariat (Nepal)
WWF	World Wildlife Fund/Worldwide Fund for Nature

Some Key Terms

The definitions provided here are based on the UN/ISDR Glossary[1], UNDP/BCPR (2004), ISDR (2004), and UNU-EHS (2006).

Climate, flood and related terms

Weather and climate: Weather is a term that encompasses phenomena in the earth's atmosphere, usually referring to the activity of these phenomena over short periods such as hours or days. Average atmospheric conditions over significantly longer periods of time are known as climate.

Precipitation: Precipitation is the discharge of water, in a liquid or solid state, from the atmosphere, generally upon a land or water surface. Rainfall is precipitation occurring in a liquid state.

Discharge: The volume of water per unit of time that passes through a specified section of a channel is called discharge and is commonly denoted by the letter Q. Discharge can be measured in cubic metres per second (m^3/s), sometimes referred to as cumecs. In the English system discharge is measured in ft^3/sec or cusec. A cusec is 35.29 times smaller than a cumec.

Flood: Significant rise of water level in a stream, lake, reservoir, or coastal region.

Flash flood: Flash floods are severe flood events triggered by extreme cloudbursts; glacial lake outbursts; or the failure of artificial dams or dams caused by landslides, debris, ice, or snow. Flash floods can have impacts hundreds of kilometres downstream, although the warning time available is counted in minutes or, at the most, hours.

Annual flood: The highest instantaneous peak discharge in a stream that occurs within a hydrological year is called annual flood.

Design flood: Design floods are hypothetical floods used for planning and management. As a design flood is defined by its probability of occurrence, it represents a flood that has a particular probability of occurring in any one year. For example, the 1% annual excedence probability (AEP) or 1 in 100 average recurrence interval (ARI) flood is a best estimate of a flood which has 1 chance in 100 of occurring in any given year.

Flood magnitude: The size of flood peak in discharge units (e.g., m^3/s, ft^3/s, etc.).

Inundation: The state of being submerged under water due to flood is called inundation. The depth of water at a particular location is called inundation depth, and the area under submergence is called area of inundation.

Return period: Return period, also known as recurrence interval, is the average interval of time within which the given flood will be equalled or exceeded once. For example, a flood of 10 years return period is likely to occur on average once in every ten years.

Hazard, risk and related terms

Hazard[2]: A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. Hazards can include latent conditions that may represent future threats and can have different origins: natural (geological, hydro-meteorological, biological) or human-induced (environmental degradation and technological hazards).

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[1] http://www.unisdr.org/eng/library/lib-terminology-eng.htm (Accessed June 2007)

[2] See Chapter 4 for a detailed description of hazard, vulnerability, and risk.

Hazards can be single, sequential, or combined in their origin and effects. Each hazard is characterised by its location, intensity, frequency, and probability.

Vulnerability[2]: The capacity (or lack of capacity) of a society to anticipate, cope with, resist, and recover from the impact of a natural hazard. A society's vulnerability is determined by a combination of factors that determine the degree to which life, property, infrastructure, and services are put at risk by a discrete and identifiable event.

Risk[2]: The chance of loss of life or property, or of injury, damage, or disruption to economic activity due to a particular event for a given area and reference period. Risk is the combination of hazard and vulnerability.

Acceptable risk: The level of loss a society or community considers acceptable given existing social, economic, political, cultural, technical, and environmental conditions.

Mitigation: Sustained actions taken to reduce or eliminate a long-term risk to people, infrastructure, and property from hazards and their effects; measures taken in advance of disaster to decrease or eliminate its impact on society and the environment.

Preparedness: Activities to ensure that people are ready for a disaster and respond to it effectively. Preparedness requires deciding what will be done if essential services break down, developing a plan for contingencies, and practising the plan.

Prevention: Activities designed to provide permanent protection from disasters. These include engineering and other physical protective measures, and also non-structural measures (like legislation, incentives, awareness raising, information dissemination) controlling land use, and urban planning.

Recovery: Reconstruction activities carried out after a disaster. They include rebuilding homes, businesses, and public facilities; clearing debris; repairing roads, bridges, and other important infrastructure; and rebuilding sewers and other vital services.

Coping and adaptation strategies: Short- and long-term strategies developed by communities to avoid, minimise, accommodate and/or spread the negative impacts of natural hazards on livelihoods, property and infrastructure, and life.

Structural measures: Action to reduce the effects of floods by physical interventions (like retention basins, embankments, dredging, diversions, dams, levees, floodwalls, elevating buildings, flood-proofing).

Non-structural measures: Action to reduce the effects of floods using non-physical solutions (like land use planning, floodplain zoning, forecasting, advance warning systems, flood insurance).

[2] See Chapter 4 for a detailed description of hazard, vulnerability, and risk.

Chapter 1
Introduction

The Hindu Kush-Himalayas (HKH) are the youngest mountains on earth and are still tectonically active. They are undergoing uplift and, therefore, the region is characterised by steep slopes and a high rate of surface erosion. In addition to the geological conditions, intense seasonal precipitation in the central and eastern Himalayas, particularly during the summer monsoon, and in the western Himalayas and the Hindu Kush during winter, triggers various types of natural hazards. Floods are one of the most common forms of natural disaster in this region. Intense monsoon rainfall or cloudbursts can cause devastating flash floods in the middle mountains (500–3500 masl). Rapid melting of snow accumulated during winter is the main cause of flash floods in the Hindu Kush and western Himalayas. Furthermore, the region is experiencing widespread deglaciation, most probably as a result of global climate change (WWF 2005; Mool et al., 2001; Xu et al. 2007). Deglaciation has caused the birth and rapid growth of many glacial lakes in the region. These lakes are retained by unstable natural moraine dams that tend to break due to internal instabilities or external triggers leading to a glacial lake outburst flood (GLOF) that can cause immense flooding downstream. Landslides due to intense rainfall in combination with geological instabilities can cause ephemeral damming of rivers. Another type of flash flood common in the region results from the outbreak of dammed lakes. These dammed lakes can break resulting in flash flood.

Hundreds of lives and billions of dollars worth of property and investment in high-cost infrastructure are lost in the region every year due to landslides, debris flows, and floods, along with the destruction of scarce agricultural lands. In the last decade of the 20th Century, floods killed about 100,000 persons and affected about 1.4 billion people worldwide. And the number of events as well as deaths are increasing (Figure 1 and Jonkman 2005). Statistics show that the number of people killed per event on average is significantly higher in Asia than elsewhere, and among all water-induced disasters this number is much higher for flash floods (Jonkman 2005). In Nepal, landslides, floods, and avalanches destroy important infrastructure worth US $9 million and cause about 300 deaths annually (DWIDP 2005). In Afghanistan, 362 people were killed or reported missing and 192 people were injured as a direct consequence of flash floods in 2005 (Azizi and Naimi 2005, cited in Xu et al. 2006). In total, about 100,000 people were displaced by these events. Exceptional events can exceed these numbers by many times — in 1998 the Yangtze flood in China caused an estimated US $31 billion of damage (Kron 2005).

Despite the destructive nature and immense impact they have on the socioeconomy of the region, flash floods have not received adequate attention. This is mainly because of poor understanding of the processes of flash floods and lack of knowledge of measures to manage the problem in the HKH region.

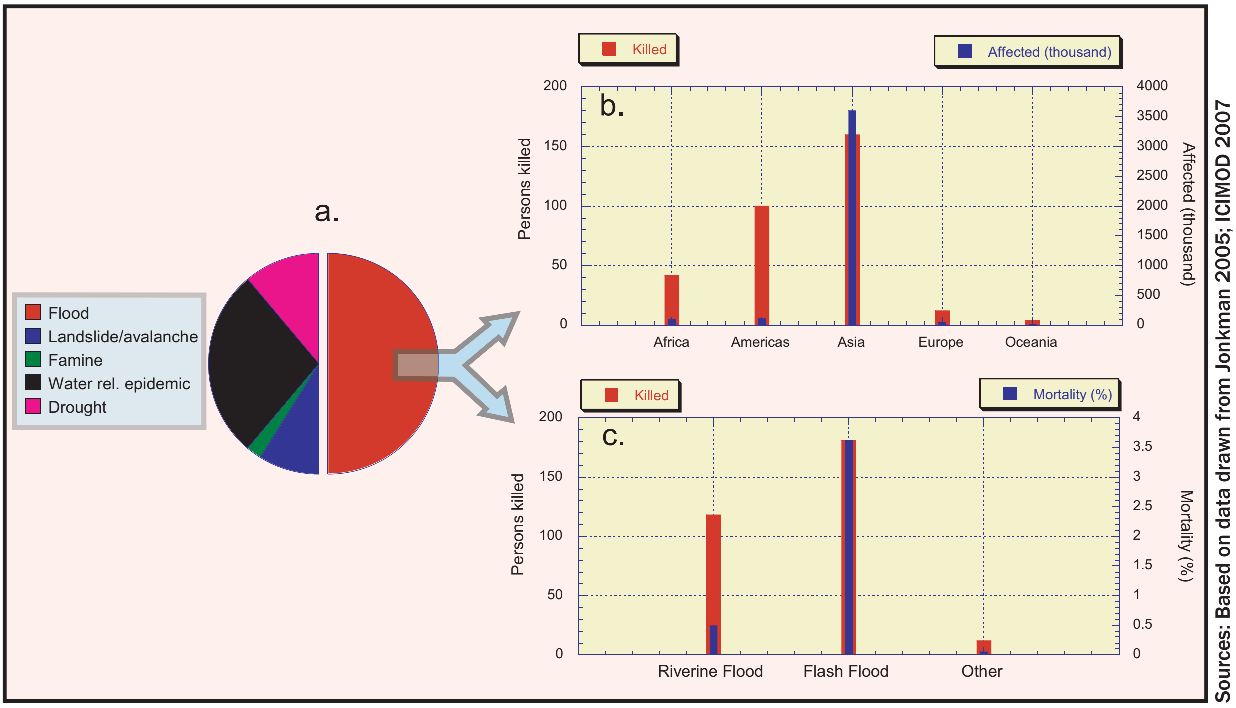


Figure 1: People killed and affected by floods: a. types of water-related disasters; b. number of people killed and affected by floods disaggregated by continent; c. number of people killed disaggregated by type of flood

Chapter 2

General Characteristics of HKH Related to Flash Floods

This chapter provides a brief review of the natural features of the region relevant to flash floods.

2.1 Climate[3]

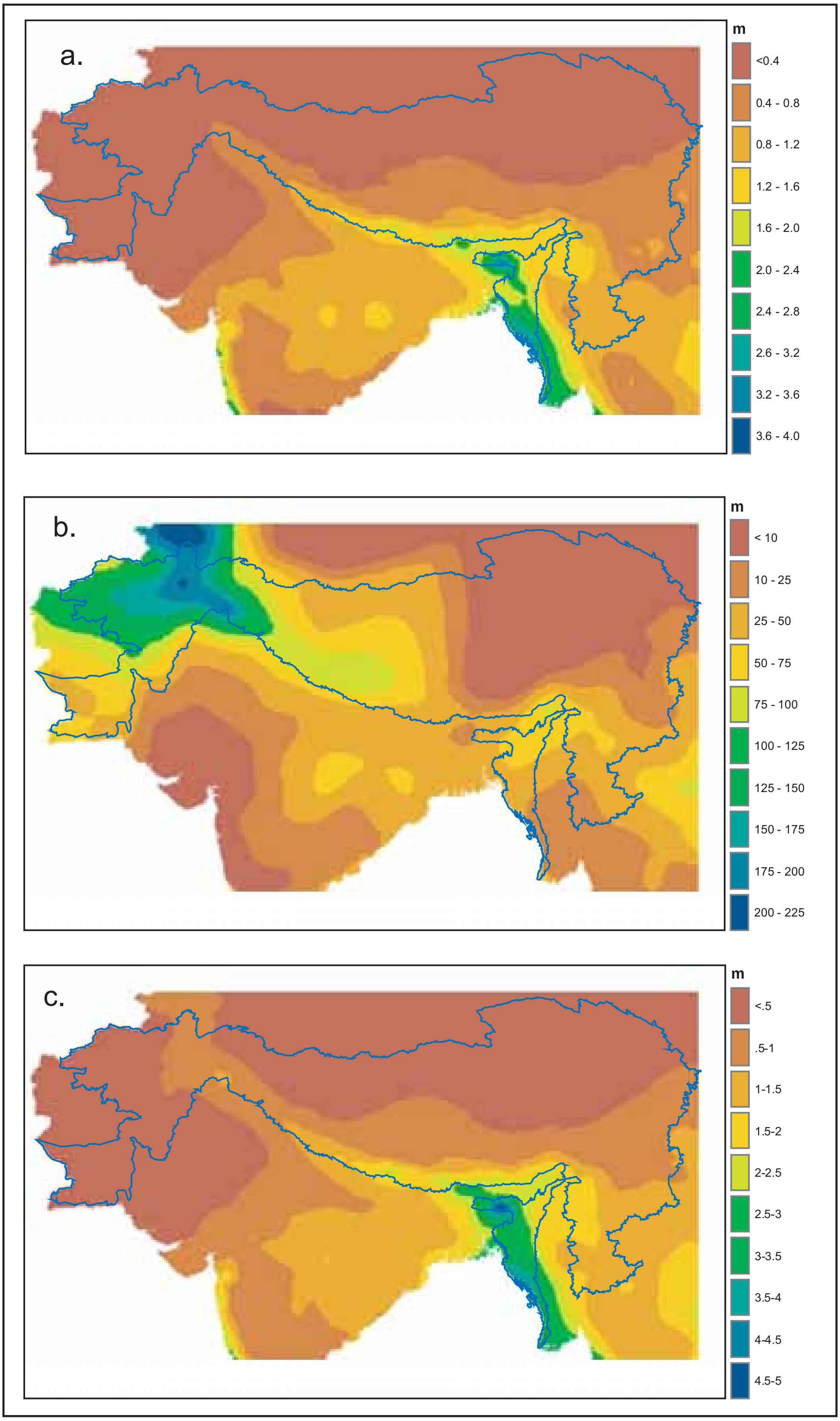
Due to its massive and high mountain systems, the HKH region acts as a barrier to atmospheric circulation, both the summer monsoon and the winter westerlies. The region's climate, although dominated by the monsoon system, can be characterised by a number of meso- and micro-climates due to topographic variations. The climate in the Himalayas, as in the other parts of South Asia, is dominated by the monsoon system. The summer monsoon originates in the Bay of Bengal and, therefore, the amount of monsoon precipitation decreases from east to west (Figure 2a). The summer monsoon is much longer in the eastern Himalayas (e.g., Assam), where it lasts for five months (June-October); it lasts for four months (June-September) in the central Himalayas (Sikkim, Nepal, and Kumaon), and two months (July-August) in the western Himalayas (e.g., Kashmir) (Chalise and Khanal 2001). The summer monsoon loses its dominance over annual precipitation in the western Himalayas (Figure 3a), where the winter westerlies deliver a significant amount of precipitation (Figure 3b). Winter precipitation is greater in the western parts of the region and less in the eastern parts. The summer monsoon has a meridional pattern as well: precipitation is higher on the windward side of the Himalayas due to the orographic effect on the monsoon air masses, while the leeward side receives less rain. Consequently the Trans-Himalayan zone and the Tibetan plateau receive very little summer precipitation. In the Tibetan Plateau summer monsoon precipitation occurs between May and September (Mei'e et al. 1985). Annual precipitation decreases from southeast to northwest: from about 800 mm at Markam and Songpan in western Sichuan to 400-500 mm at Lhasa, 200-300 mm at Tingri, and less than 100 mm at Ngari Prefecture (Mei'e et al. 1985). Depending on the location, the annual precipitation variation can be quite high (Figure 4). However, in general, the summer monsoon is the predominant source of precipitation in the region (Figures 3, 4).

Temperatures in the Himalayas vary inversely with elevation at a rate of about 0.6°C per 100m, and due to the rugged terrain, wide ranges of temperatures are found over short distances. Local temperatures also correspond to season, aspect, and slope (Zurick et al. 2006). Owing to the thin atmosphere above the Tibetan Plateau and ample and intense radiation, the surface temperature has a large diurnal variation, although its annual temperature range is relatively small. The temperature range in the northern mountainous region of Pakistan and Afghanistan is greater and the annual range of temperature is also quite large. In Chitral (1450 masl), for example, temperatures can reach as high as 42°C and as low as -14.8°C (Shamshad 1988).

High-intensity rainfall is a characteristic microclimatic feature of the region (Domroes 1979). Such high-intensity rainfalls have important implications for flash floods known as intense rainfall floods (IRFs). In July of 1993, 540 mm of rainfall was recorded in 24 hours in the central part of Nepal (Dhital et al. 1993). This caused a devastating flash flood with colossal damage to infrastructure and lives, and disrupted normal life for several months. These types of events are rather common in the HKH.

The western Himalayas and the Hindu Kush can receive large amounts of snow during the winter, caused by westerly disturbances from the Mediterranean. The snow not only affects peoples' livelihoods with avalanches and blocked transport routes, but, in case of rapid warming in spring, can also lead to flash floods caused by rapid snowmelt.

[3] With contributions from Mr. R. Rajbhandari, Tri Chandra Campus, Tribhuvan University.



Source: CRU data; New et al. 2002

Figure 2: Precipitation distribution in the HKH region: a. during the summer monsoon; b. winter; and c. annual. The blue outline shows the approximate boundary of the region

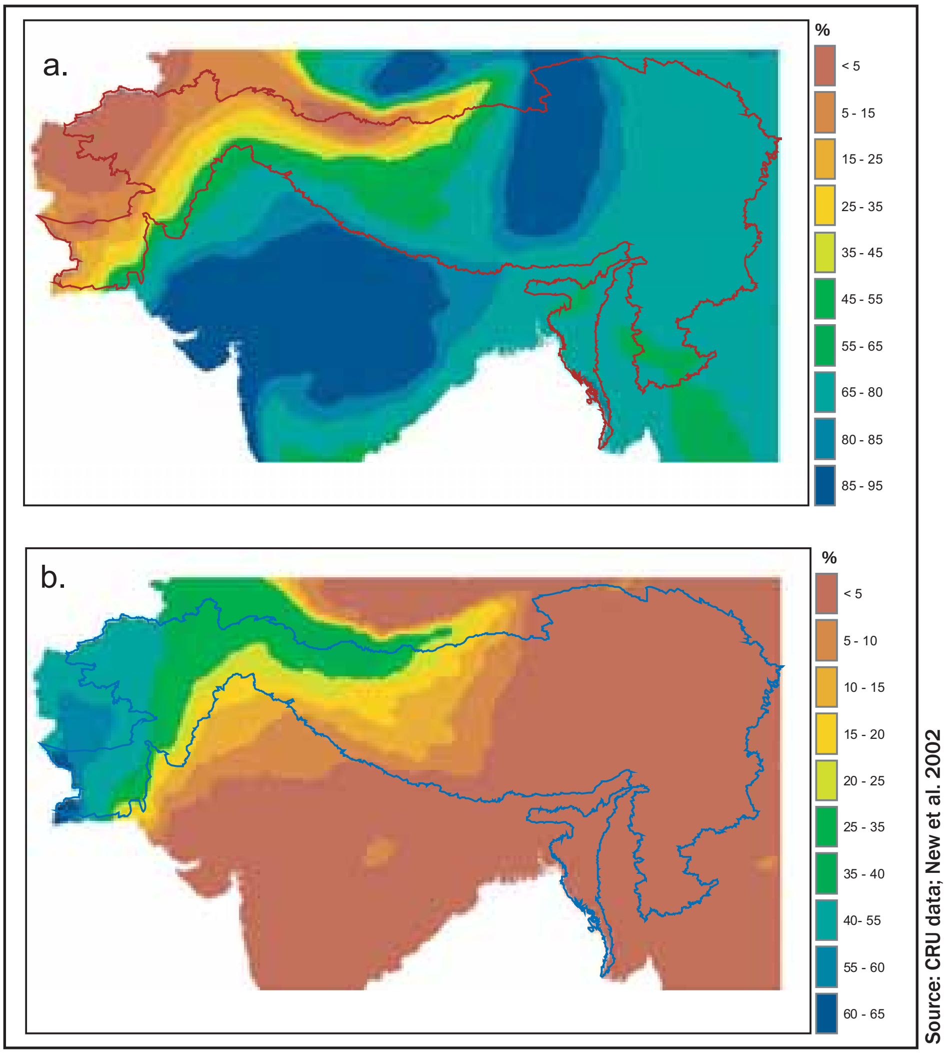


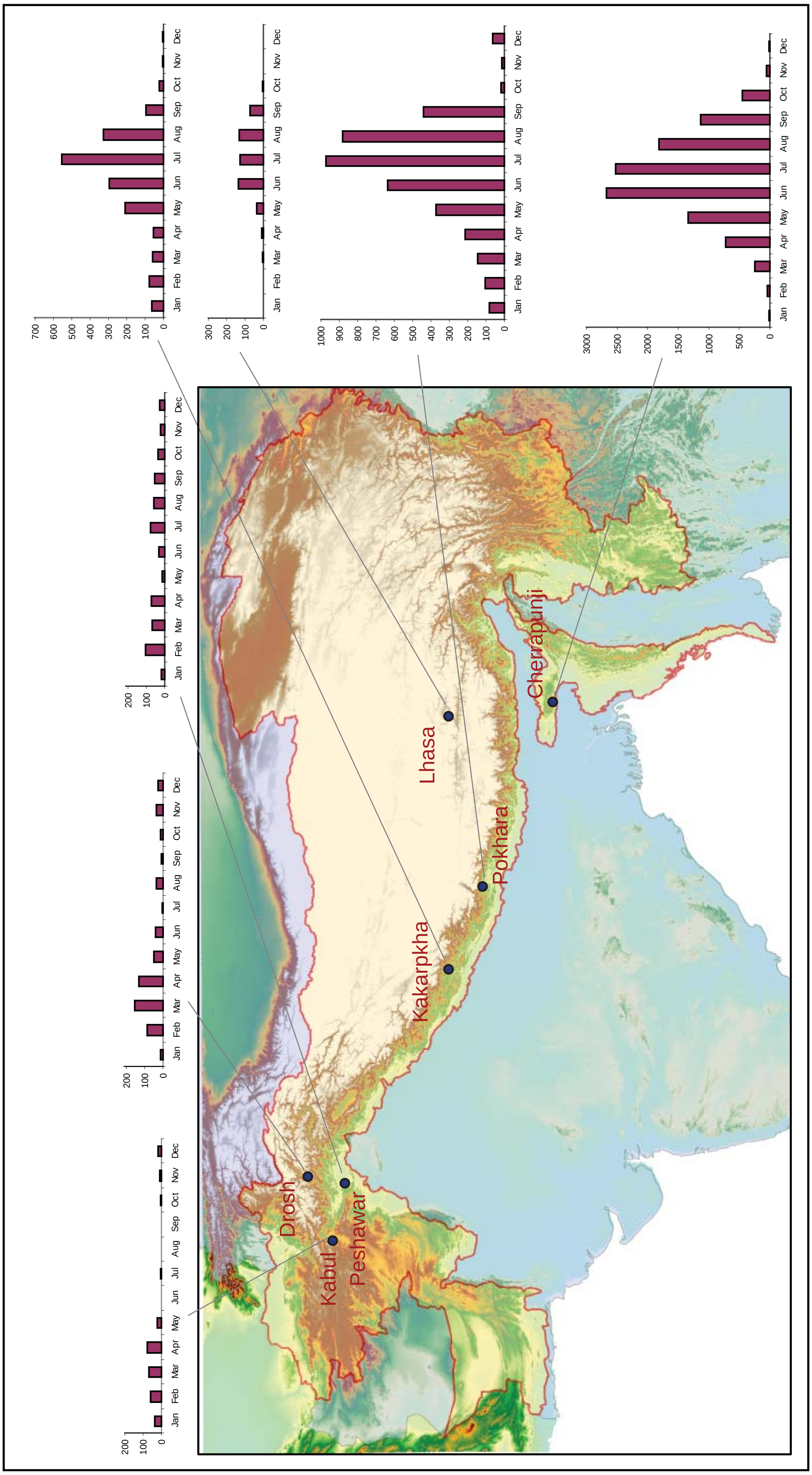
Figure 3: Fraction of annual precipitation contributed by: a. summer monsoon and b. winter precipitation. The outline shows the approximate boundary of the region

2.2 Hydrology

The Himalayan range is an important source of runoff, which is significantly higher in the summer than in the winter (Figure 5). The runoff generated in these areas sustains the flow of eight[4] major rivers that originate from the HKH region (Figure 6). Despite different locations of the river basins, their flow hydrographs generally peak during spring or summer, which supports the importance of summer precipitation in runoff generation (Figure 7).

Many Himalayan rivers originate from glaciers, which are in general retreat, probably as a result of climate change (Fujita et al. 2001; Ageta and Kadota 1992; Kadota et al. 1997; Kulkarni et al. 2005; Shing and Bengtsson 2004, 2005; Archer 2001; Shiyan et al. 1996). Retreating glaciers often leave behind voids that are filled by meltwater and are called glacial lakes. Glacial lakes can burst due to internal instabilities in the natural moraine dam retaining the lake (for example, collapse due to hydrostatic pressure, erosion, overtopping, internal structural failure) or due to external triggers such as rock/ice avalanche, earthquake, and so on. These catastrophic processes are known as glacial lake outburst floods (GLOFs). A GLOF can result in flow of water and debris several orders of magnitude greater than seasonal high flow. Bhutan, China, Nepal, and Pakistan have suffered a number of GLOFs in the past.

[4] There are now considered to be ten major river basins: eight with their main basin area within the HKH and two with only some of their area within the HKH.



Data source: ICIMOD; background: ESRI

Figure 4: Seasonal variations in precipitation at different locations in the HKH region. The red outline shows the approximate boundary of the region

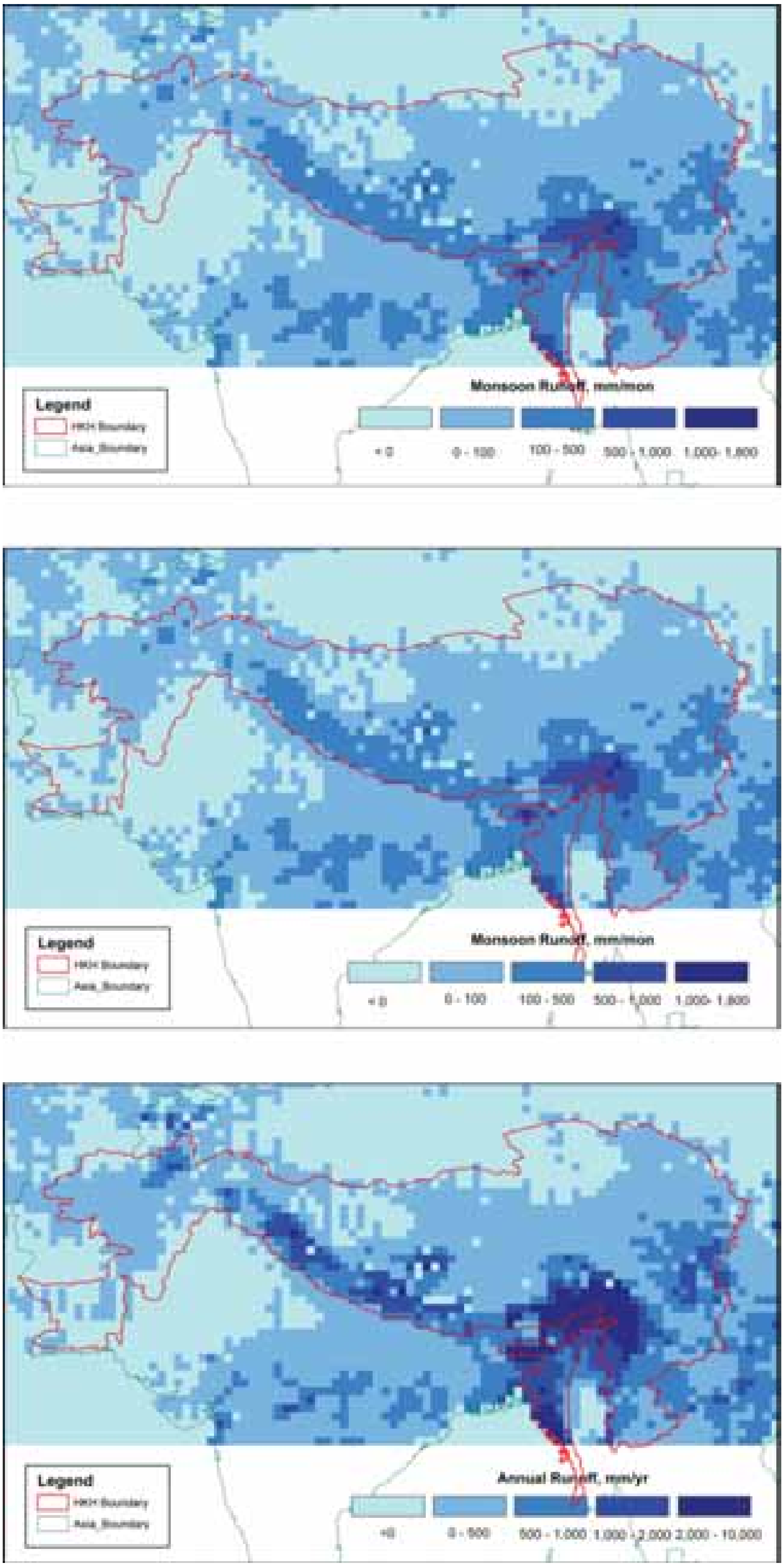
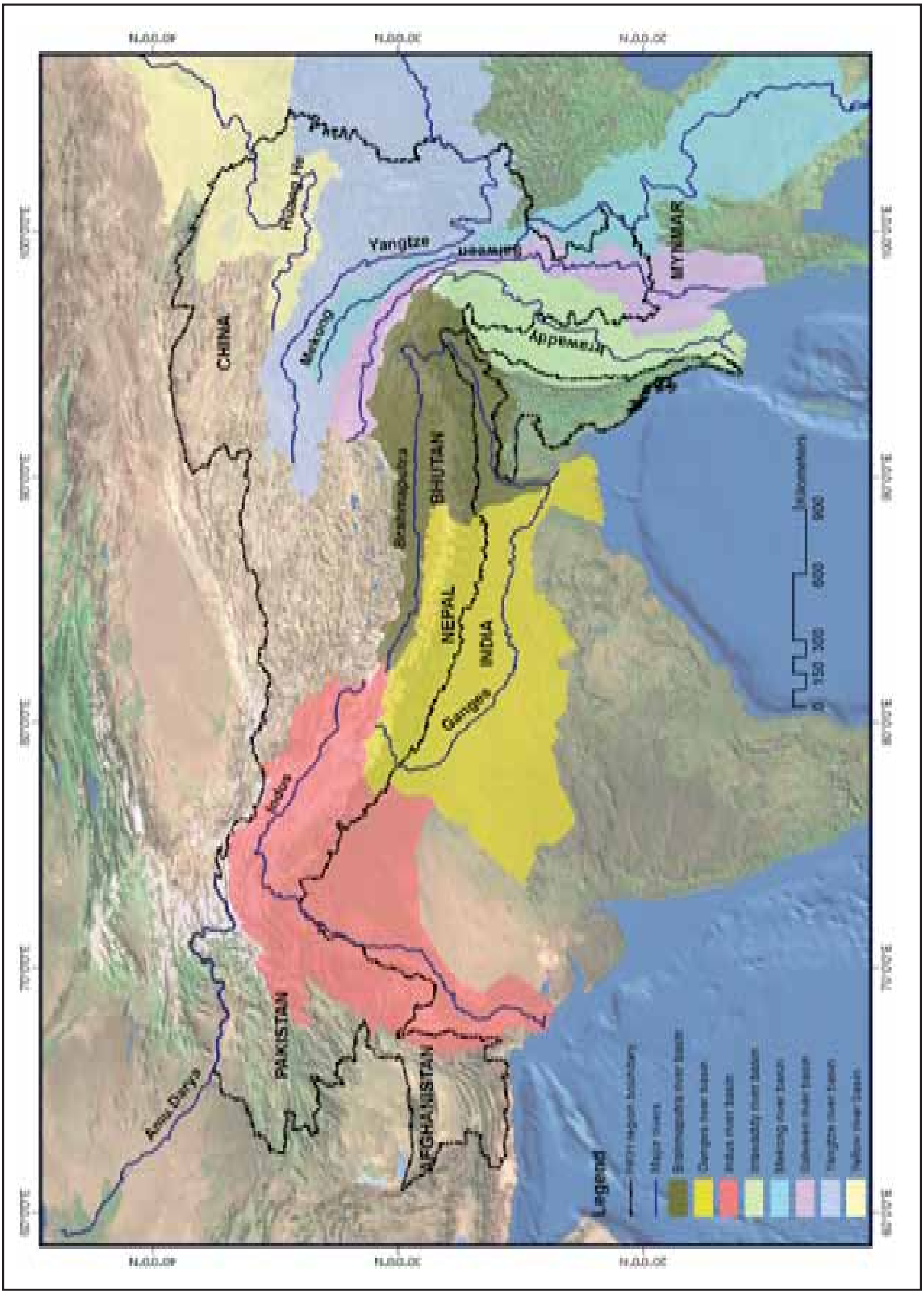


Figure 5: Runoff generated from the HKH region

Source: http://www.grdc.sr.unh.edu/ (Accessed May 2007)



Source: ICIMOD; background ESRI

Figure 6: Map of the HKH region and the eight[5] major river basins

[5] There are now considered to be ten major river basins: eight with their main basin area within the HKH and two with only some of their area within the HKH.

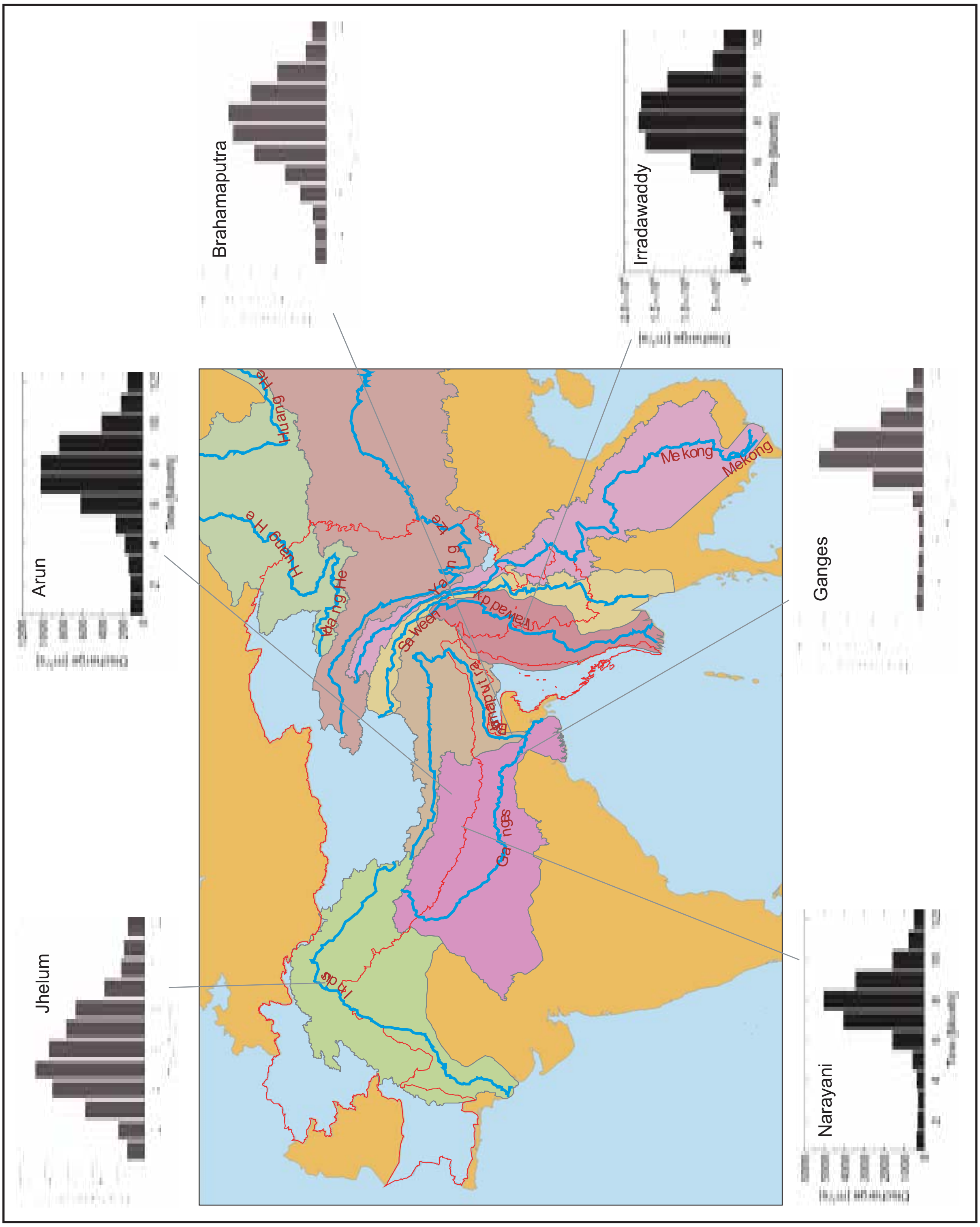


Figure 7: Seasonal variations in the flow of select rivers in the HKH region

Source: ICIMOD archive

2.3 Geology

Due to the steep and unstable slopes of the Himalayas, the region is prone to recurrent and often devastating landslides. Such landslides and debris flows, released by torrential rain or seismic activity, may cause temporary dams across river courses and result in the impoundment of immense volumes of water. Subsequent overtopping, or water breaking through the earth dam, will result in a landslide dam outburst flood (LDOF) event similar to a GLOF. Although these phenomena are well known to local people, they are sudden and unpredictable and may cause a large number of deaths and much damage to property.

2.4 Other Factors

Failure of artificial structures can also cause tremendous flash floods. As more and more river basins are being exploited by people, flash floods due to failure of human-made hydraulic structures will likely increase. Occasionally, the uncoordinated operation of a hydraulic structure causes a flash flood resulting in loss of life and property.

Chapter 3

Understanding Flash Flood Hazards

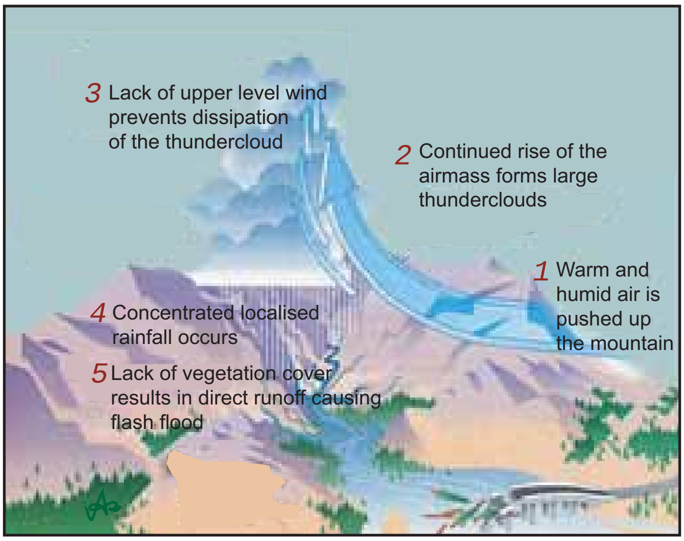
For proper flash flood management, practioners must understand the factors that cause flash floods. The main processes causing flash floods in the HKH region are intense rainfall, landslide dam outburst, and glacial lake outburst. This chapter describes the physical factors causing these and gives some examples.

3.1 Intense Rainfall Flood

Intense rainfall is the most common cause of flash floods in the HKH region. These events may last from several minutes to several days and may happen anywhere, but are more common in mountain catchments. The main meteorological phenomena causing intense rainfall are cloudbursts, a stationary monsoon trough, and monsoon depressions.

Cloudbursts

Cloudbursts are associated with the intensive heating of an airmass, its rapid rise, and the formation of thunderclouds. Interaction with local topography results in upward motion, especially where the atmospheric flow is perpendicular to topographic features. Particularly intense precipitation rates typically involve some connection to monsoon airmasses, which are typically heavily moisture laden and warm due to their tropical origin (Kelsch et al. 2001). Lack of wind aloft prevents dissipation of the thunderclouds and facilitates concentrated cloudbursts, which are often localised and limited to a small area. The cloudburst process is illustrated in Figure 8.

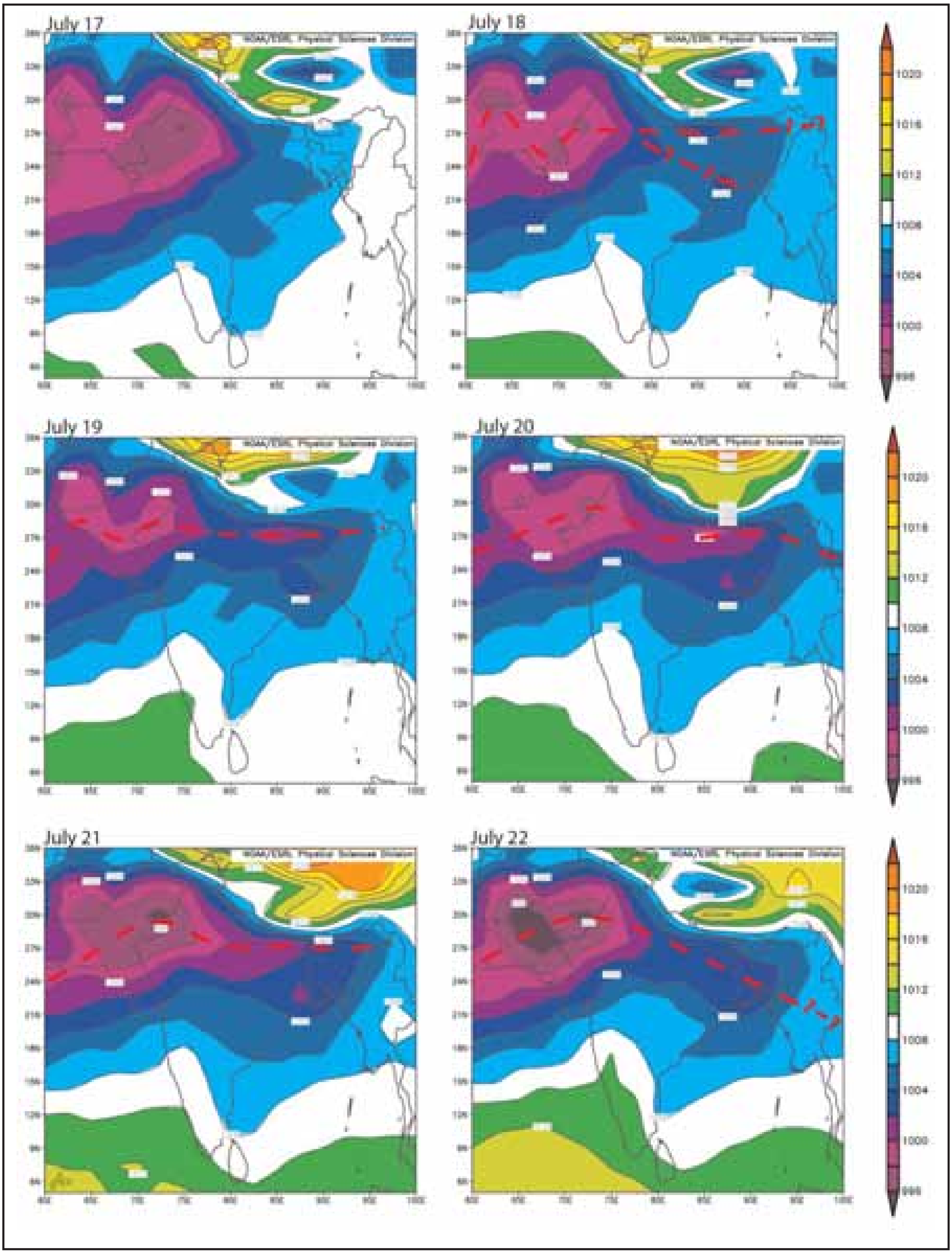


Source: Modified from Jarrett and Costa 2006

Figure 8: The mechanism of a cloudburst

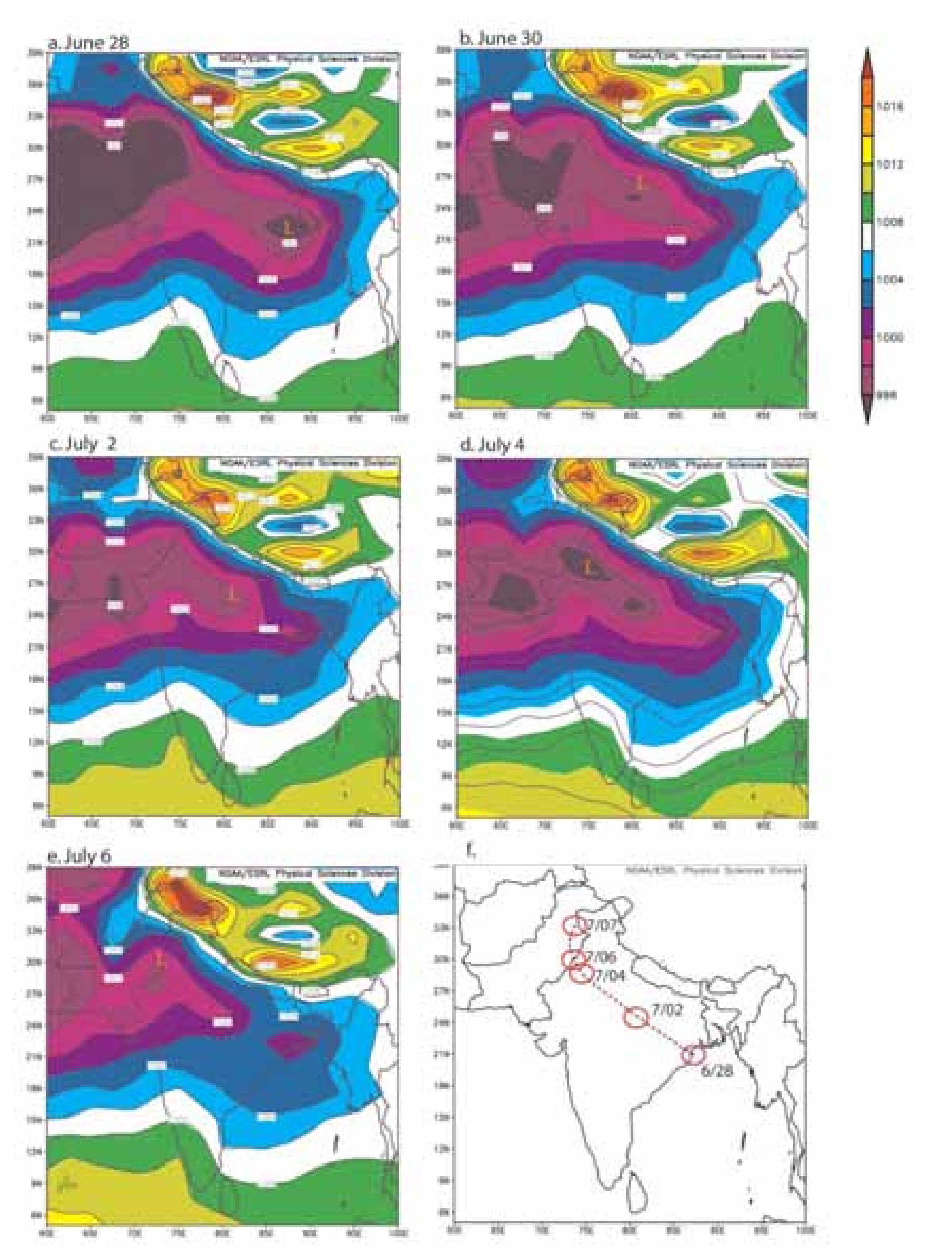
Monsoon trough

Another type of intense rainfall is caused by the prolonged stationary position of an inter-tropical convergence zone (ITCZ), commonly called a monsoon trough, an elongated zone of low pressure system, along the mountain range. This type of meteorological phenomenon occurred in central Nepal on 19-20 July 1993, bringing record-setting rainfall to the upper region of the Mahabharat Range in the central part of Nepal (Figure 9). On 17 July the monsoon trough was not well defined. There was a large area of low pressure in western India. The low-pressure zone intensified slightly and a small cell of low pressure appeared over central Nepal, although of only low intensity (1004 hPa). On 19 July the sea level pressure over central Nepal was 1002 hPa and the monsoon trough was well established. This caused a heavy downpour over the central part of Nepal. On 20 July the monsoon trough remained in the same position but the low-pressure cell intensified to 1000 hPa. The heavy downpour continued throughout the day. On 20 July, Tistung station in central Nepal measured a record 24-hour rainfall of 540 mm, and the gauge recorded a maximum rainfall of 70 mm in one hour. The trough remained almost in the same place on 21 July, but the intensity of the low-pressure cell reduced to 1002 hPa; the rain continued but with less intensity. The situation gradually changed thereafter as the trough moved southward and the low pressure cell dissipated to a large area of 1004 hPa. This event of 1993 caused excessive flooding of the Bagmati River and its tributaries. The flood at the Bagmati Barrage site was estimated at 16,000 m^3/s (DHM/DPTC 1994). This discharge exceeded the design



Data source: http://www.cdc.noaa.gov/composite/Day/ (Accessed 2 June 2007)

Figure 9: Position of the monsoon trough during the flash floods of 1993 in central Nepal



Data source: http://www.cdc.noaa.gov/composite/Day/ (Accessed 4 June 2007)

Figure 10: Synoptic maps (a-e) and location of the monsoon depression (f), which caused flash floods in Pakistan in 2007

discharge of the barrage and caused out-flanking on both sides, which caused great damage to the canal intakes, inundated hectares of land, washed out several villages, and killed 1,275 people, with many others missing or injured. The same event heavily damaged hydropower facilities, as the penstock pipe of the Kulekhani hydropower plant was washed away by debris flow in Jurikhet Khola. The intake of Kulekhani II was completely destroyed by the debris flow of the Mandu Khola River. Several other rivers and rivulets including Kamala, Manusmara, Palung, Agra, Belkhu, and Malekhu were flooded and villages, agricultural fields, bridges, and roads washed away.

Flash flood due to monsoon depressions

Intense monsoon depressions seldom reach the mountain areas during the monsoon season. When they do, it is the result of a strong westerly wave over northern Kashmir, which causes heavy to very heavy rainfall in the lower Kashmir and Jammu Valley, resulting in devastating flash floods. One such event took place in July 2005 and caused a large flood in the Chenab River in Pakistan. A monsoon low developed in the Bay of Bengal on 28 June 2005 (Figure 10). It took a west-northwest course and reached the vicinity of Pakistan on the evening of 7 July 2005. A westerly wave moving across Kashmir and the northern parts of Pakistan interacted with the monsoon depression and rejuvenated it. This depression moved into Punjab and Kashmir and caused heavy rainfall in the upper catchment of the Chenab River. Due to the steep mountain catchment, the river flooded quickly. The discharge in the Chenab River and its tributaries Jammu Tawi and Munawar Tawi were heavily swelled, and discharges at Marala (the first gauging station in Pakistan) reached 5300m^3/s. This flood wave washed away bridges and inundated the foothills of Jammu Valley in Sialkot, Pakistan, causing huge damage to infrastructure downstream.

3.2 Landslide Dam Outburst Flood

Due to weak geological formations, active tectonic activities, highly rugged topography, and heavy rainfall, landslides and debris flow are common phenomena in the HKH region, causing severe loss of lives and property. In addition to their direct impact, landslides and debris flows trigger flooding. If large amounts of material from landslides or debris flows reach a river they can temporarily block its flow, creating a reservoir in the upstream reach (Figure 11). The 1911 earthquake triggered a rock slide that blocked the Mrgab River in southeastern Tajikistan, forming a still-existing natural dam 600m high. Lake Sarez, formed by the dam, is 60km long with maximum depth of 550m and volume of approximately 17km^3 (Schuster and Alford 2004).

As the reservoir level rises due to river flow and overtops the dam crest, sudden erosion of the dam can cause an outburst. Overtopping can also be caused by secondary landslides falling into the reservoir. Internal instability of the dam might trigger an outbreak even without overtopping. Outburst events are generally random and cannot be predicted with any precision. Such a flood, commonly known as a landslide dam outburst flood (LDOF), scrapes out beds and banks causing heavy damage to the riparian areas and huge sedimentation in downstream areas.

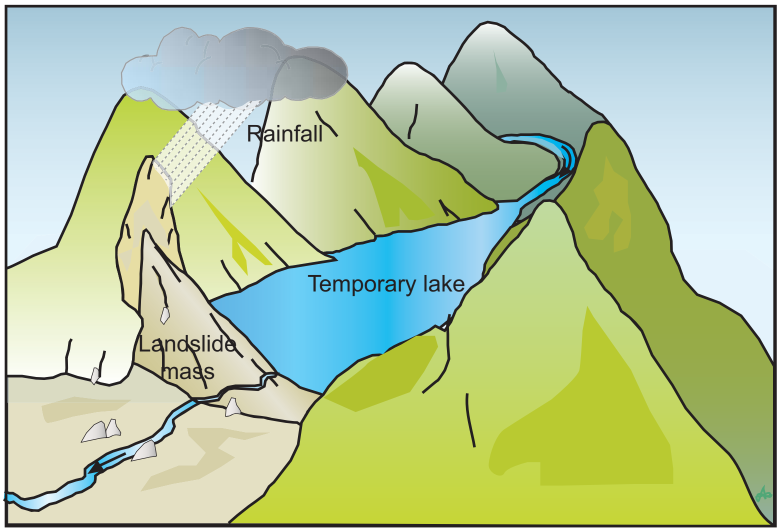


Figure 11: Formation of a natural dam (left) and photograph (right) of river damming due to a landslide

In general, high landslide dams form in steep-walled, narrow valleys because there is little area for the landslide mass to spread out (Costa and Schuster 1988). Commonly, large landslide dams are caused by complex landslides that start as slumps or slides and transform into rock or debris avalanches. The most important processes in initiating dam-forming landslides are excessive precipitation and earthquakes. Volcanic eruptions can also cause landslide dams, although there are no examples of such dams in the HKH region. Other mechanisms include stream under-cutting and entrenchment.

Landslide dams can be classified geomorphologically with respect to their relation to the valley floor (Swanson et al. 1986, in Costa and Schuster 1988). Landslide dams may form due to various causes and can vary according to the location of the dam (Table 1 and Figure 12).

In 1883, a landslide dam 350m high was created in a tributary of the Alaknanda River of the Garwal Hills, India and a 50m high flood was created when the dam broke. Nepal has also experienced several landslide dam outburst floods. The Budigandaki River has been dammed at least twice, and the Tinau River was dammed in 1978 due to a landslide after 125 mm of rainfall in the catchments. The subsequent outburst caused heavy damage to property and loss of several lives in Butwal.

Table 1: **Types of landslide dams**

Type	Cause	Effect
I	Falls, slumps	Dams are small with respect to the width of valley floor and do not reach from one side to the other
II	Avalanches, slumps/slides	Dams are larger and span the entire valley floor
III	Flows, avalanches	Dams fill the valley from side to side and considerable distances upstream and downstream
IV	Falls, slumps/slides, avalanches	Dams formed by contemporaneous failure of materials from both sides of a valley
V	Falls, avalanches, slumps/ slides	Dams formed when the same landslide has multiple lobes of debris that extend across a valley floor at two or more locations
VI	Slumps/slides	Dams created by one or more surface failures that extend under the stream or river valley and emerge on the opposite valley

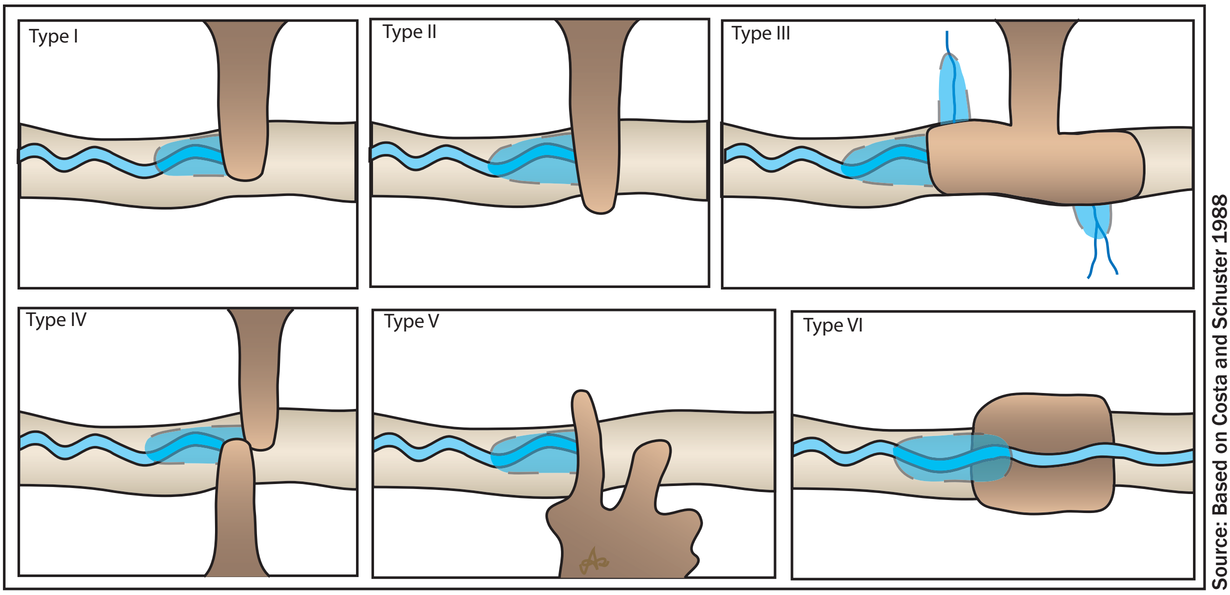


Figure 12: Types of river-damming landslides

Four case studies

Case 1: Yigong landslide dam outburst flood

One of the most striking examples of a LDOF is that of the Yigong River in eastern Tibet. As a result of sudden temperature increase, a huge amount of snow and ice melted in the region, and a massive, complex landslide occurred on 9 April 2000 in the upper part of the Zhamulongba watershed on the Yigong River, a tributary of the Yarlung Zangbo River. About 300 million cubic metres of displaced debris, soil, and ice dammed the Yigong River (Figure 13). In eight minutes a 100m high, 1.5 km wide (along the river), and 2.6 km long (across the river) landslide dam was created. The Type III landslide dam had a volume of 300 million m^3 (Shang et al. 2003). The dam blocked the Yigong River, and, due to an inflow of about 100 m^3/s from Yigong River, the lake level rose by about one metre per day. An attempt was made to dig a large trench and release the water from the lake, but it failed to avert the outburst. The outburst occurred on 10 June 2000 and created a huge flash flood downstream. The maximum depth of the flood was 57m, the maximum velocity was 11.0 m/s, and the flood was 1.26×10^5 m^3/s. The peak flood was 36 times greater than the normal flood. Tongmai Bridge, the highway between Yigong Tea Farming Base and Pailong County, and two suspension bridges in Medong County were all destroyed by the flood, but no injuries or deaths occurred on Chinese territory (Figure 14). On the Indian side of the border, however, damage from the flash flood from the dam failure was of a scale seldom seen before and resulted in the death of 30 people, with more than 100 people missing. The flood in the Brahmaputra River as it entered India was 1.35×10^5 m^3/s (Zhu and Li 2000; Zhu et al. 2003). More than 50,000 people in five districts of Arunachal Pradesh, India, were rendered homeless by the flash flood, and more than 20 large bridges, lifelines for the people, were washed away. The total economic loss was estimated at more than one billion rupees (22.9 million US dollars).

Source: Zhu et al. 2003

Figure 13: The Zhamulongba landslide that blocked the Yigongzanghu River (left) and the landslide dammed lake across the Yigongzanghu River (right)

Source: G. McCue

Figure 14: The Palung Zambo River, a tributary of the Yigongzanghu River, before (top) and after (bottom) the Zhamulongba landslide dam outburst of 10 June 2000

Case 2: Tsatichhu landslide dam outburst flood

Another example of a LDOF in the HKH region is the Tsatichhu LDOF in Bhutan. On 10 September 2003, material with an estimated volume of 7-12x10^6 m^3 failed on the wall of a valley and slid into the narrow Tsatichhu River valley. The ground shaking felt at Ladrong village, 2.5 km away, suggests that the main slide occurred over a period of 30 minutes. The slide formed a river-blocking dam 110m high. The deposited material had an estimated volume of 10-15x10^6 m^3. The dam crest extended approximately 580m across the valley (Dunning et al. 2006), and the deposited material spread a distance of 200m upstream and 700m downstream. The event caused winds strong enough to fell trees and strip vegetation.

The landslide dammed the Tsatichhu River and formed a lake referred to as Tsatichhu Lake (Figure 15). The lake extended 1 km up-valley, and had an estimated volume of 4-7x10^6 m^3 at its full level. A small surface outflow occurred in December 2003, but did not cause failure of the dam. There was also significant seepage through the dam, which together with the surface outflow maintained equilibrium with the river inflow of 0.53 m^3/s.

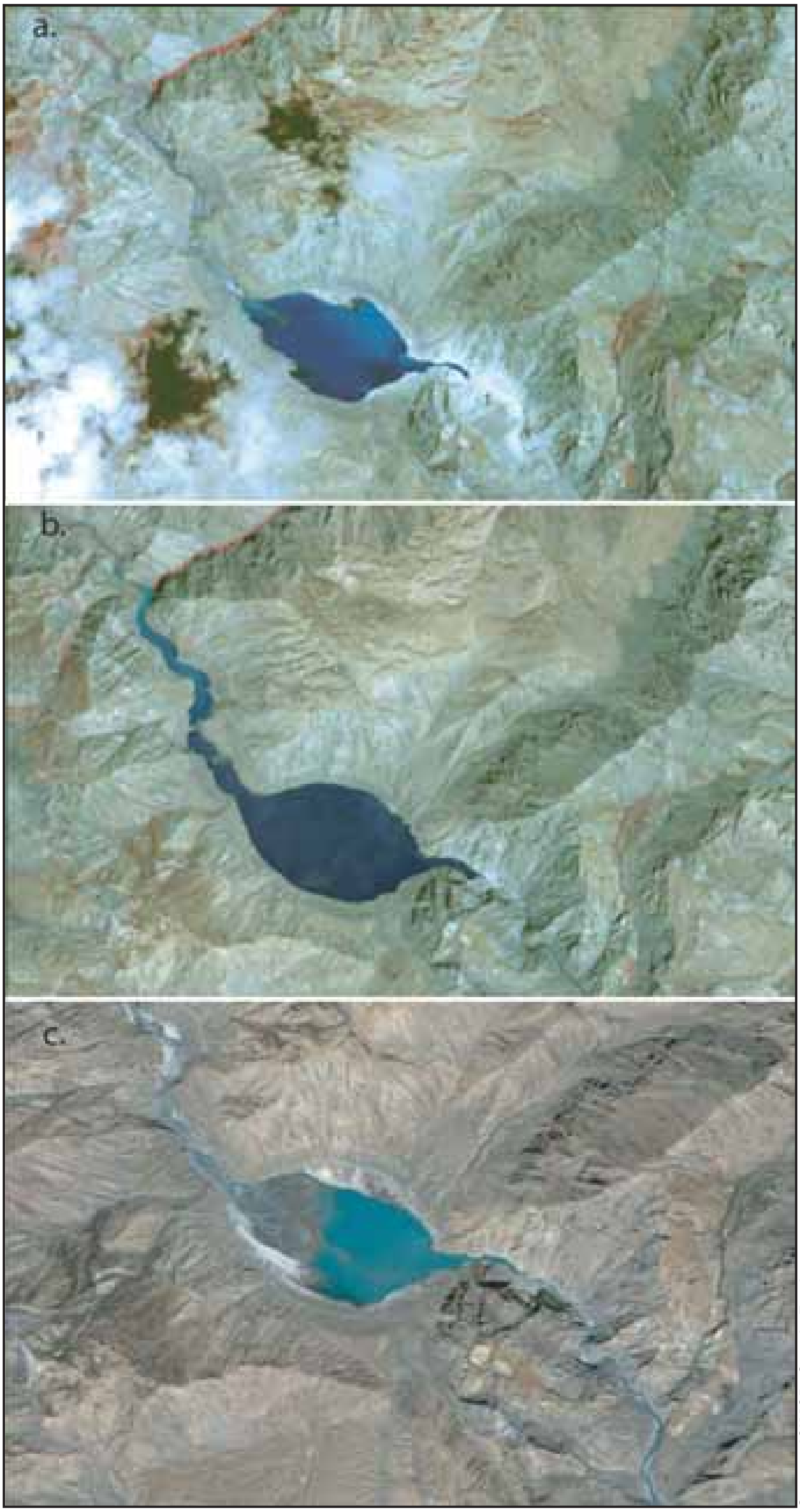
The dam survived for 10 months. From 15 to 21 May 2004, heavy rainfall caused some material from the downstream face of the dam to fail, but did not cause a major failure. On 10 July 2004, a major failure of the dam occurred after a period of prolonged intense rainfall. The exact process of the failure is unknown although it is suggested that a combination of downstream slope failure and overtopping was the cause. The failure caused an enormous flood downstream. The mass of debris blocked the Kurichu River for 45 minutes. After 80 minutes the flood arrived at Kurichu Hydropower Plant 35 km downstream, where the peak discharge was 5900 m^3/s. Later calculations estimated the peak discharge at the outflow at 7700 m^3/s. The flood wave was up to 20m high. Due to the 10 months' gap between the formation and failure of the dam, the Department of Energy had sufficient time to put an early warning system into place, which resulted in timely warning to the hydropower plant. Pre-lowering of the water level enabled the reservoir to cater to the flood with only minor damage to the infrastructure. This flash flood did not result in any human casualties, although loss of agricultural land was significant (Xu et al. 2006). A significant section of road into the Autosho village at the confluence of Tsatichhu/Wabrangchhu and Kurichhu was completely destroyed.

Case 3: Pareechu landslide dam outburst flood

On 22 June 2004, a landslide blocked the Pareechu River, which is the upper reaches of Sutlej River in Tibet. The mass of earth and rock created a natural dam, forming a water body with a volume of about 6x10^6 m^3. At 5:00am on 5 July, after holding water for 15 days, the landslide block collapsed. On 8 July, another major landslide occurred and blocked the river about 30 km from the China-India boundary, forming a new natural dam about 35m high. Due to continuous heavy rainfall, the water body within the dam grew to 1500m wide, 6000m long, and 19m deep by 4 August. The total volume of the lake was about 79x10^6 m^3 (Figure 16). As estimated by the water resources department in Tibetan Autonomous Region, about 40 m^3/s of water flowed into the dam; the water level rose at a rate of 0.48m per day; and the outflow from the dam was about 7.3 m^3/s. Chinese authorities communicated the formation and growth of the lake and eminent danger of flooding to their Indian counterparts. On 9 August armed forces and paramilitary forces were put on red alert in Himachal Pradesh, India as the artificial lake had started spilling over and could burst at any time. Chinese authorities informed the Government of India that a breach had started appearing in the lake that could give way at any time. On 13 August several Tibetan villages downstream of the lake were evacuated. The state government of Himachal Pradesh identified 56 villages along the Sutlej from Kinnaur to Bilaspurthat that could be affected (Dams, Rivers & People 2004). The dam burst on 25 June 2005. The flood damaged 200km of roads, houses, bridges, hydroelectric stations, and so on in Indian territory. The direct cost of the flood damage was estimated at US $200 million (Xu et al. 2006). Fortunately, due to good communication between China and India, no human causalities occurred.

Landslide damming is widespread in the HKH region, although many of these events are not recorded due to remoteness of the location. Li (1994) reports more than 12 well-documented landslide dams in China, of which nine have failed and caused flash floods. Shrestha and Shrestha (2005) report 18 cases of landslide dams in Nepal. There have been several such events in the India Himalaya and Bhutan.

Figure 15: Tsatichhu landslide dam: a. the source area of the landslide; b. detailed view of the dam; c. Tsatichhu lake



Source: ICIMOD; Google Earth

Figure 16: Satellite image of the Pareechu River: a. about one month after the landslide damming (15 July 2004); b. about 2.5 months after damming (1 September 2004); and c. after the outburst

Case 4: Budhi Gandaki and Larcha Khola in Nepal

The Budhi Gandaki River in Nepal was twice dammed near Lukubesi. In 1967, the river was dammed for three days after the failure of Tarebhir. Another landslide in 1968 dammed the river again with a huge amount of displaced material. The river's water level dropped from a normal level of 4m on 1 August to 0.9m on 2 August. After the breaching of the landslide dam, the water level rose to 14.61m. The peak flow was estimated to be 5210 m^3/s, which was significantly greater than the mean annual instantaneous flood (2380 m^3/s). One bridge and 24 houses at Arughat Bazaar, about 22 km downstream from the damming site, were swept away after the breach .

Bhairabkunda Khola was dammed in 1996. The landslide dam outburst flood destroyed 22 houses and killed 54 people in Larcha village. The highway bridge was swept away by the flash flood (Figure 17).

Figure 17: a. Bhairabkunda Khola a few days after the LDOF; b. debris deposited by the LDOF; c. large boulders trapped at the highway bridge; and d. Larcha village destroyed by the flash flood

3.3 Glacial Lake Outburst Flood

Flash floods resulting from the outburst of lakes of glacial origin are called glacial lake outburst floods or GLOFs. GLOF is one of the important mechanisms that cause flash floods in the Himalayas. They are a common phenomenon in Iceland, where the outburst is generally triggered by volcanic action and the phenomenon is known as jokulhaup. Many of the early studies on GLOFs were based in Iceland. Although GLOFs are not a recent phenomenon in the Himalayas, they were only given attention recently, probably because several high-magnitude events caused substantial damage in different parts of the region.

Glacial lakes are directly related to the glacier fluctuation process, which in turn is attributed to climate variability. The glaciers in the region have been in general retreat since the end of the Little Ice Age of the mid-19th Century. However, the retreat has accelerated in recent decades, most probably due to anthropogenic climate change, which is highly pronounced in the region. The retreat of glaciers leaves behind large voids to be filled by meltwater, thus forming moraine-dammed glacial lakes. These natural moraine dams are composed of unconsolidated moraines of boulders, gravel, sand, and silt. The dams are structurally weak and unstable, and undergo constant changes due to slope failures, slumping, and similiar effects and are in danger of catastrophic failure, causing glacial lake outburst floods. Moraine dams may break by the action of some external trigger or by self-destruction (Table 2). A huge displacement wave generated by a rockslide or snow/ice avalanche from the glacier terminus into the lake may cause the water to overtop the moraine, create a large breach, and eventually cause dam failure (Ives 1986). Earthquakes may also trigger dam breaks depending upon magnitude, location, and characteristics. Self-destruction is caused by the failure of the dam slope and seepage from the natural drainage network of the dam.

Table 2: **GLOF triggering mechanisms**

Internal	External
Hydrostatic pressure (increase in water level)	Overtopping of moraine dam due to rock, ice, snow avalanche into the lake
Seepage	Earthquake
Destruction of conduits within ice core	

3.4 Types of Glacial Lakes

Glacial lakes formed as a result of damming material are widely divided into two categories: ice-dammed lakes and moraine-dammed lakes. Ice-dammed lakes are created when a stream is intercepted by a glacier, often during the advance stage, while moraine-dammed lakes are confined by moraines left by retreat of the parent glacier. Ice-dammed lake failure is a complicated process and the resulting flood discharge is less 'spiky', whereas moraine-dammed lake outbursts cause sharp rises and falls in flood discharge.

Depending on the juxtaposition of the lake with respect to the glacier, the lakes can be supraglacial, englacial, or marginal. Figures 18 and 19 show schematic and real representations of typical locations of ice-dammed and moraine-dammed lakes.

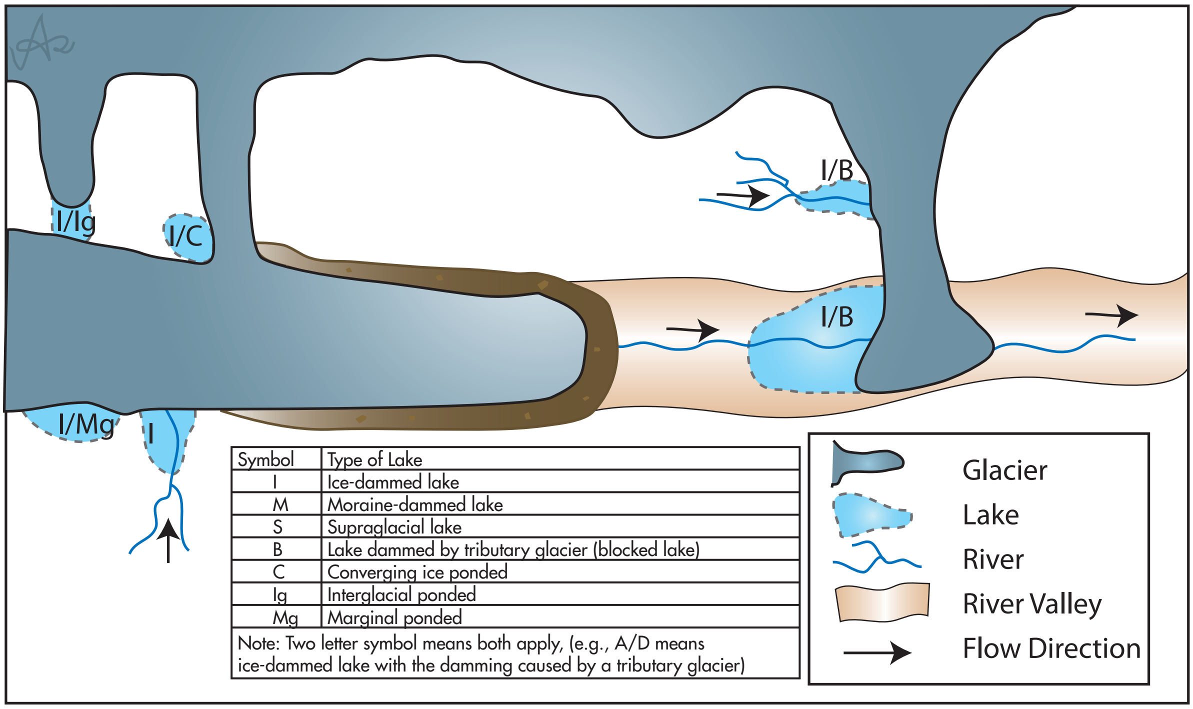


Figure 18: Types of glacial lakes

Figure 19: Typical ice-dammed (left) and moraine-dammed (right) lakes

3.5 Glacial Lake Outburst Flood in the HKH Region

There have been at least 35 recorded GLOF events in the HKH region: 16 in China, 15 in Nepal, and four in Bhutan. There have been some reports of floods of glacial origin in India and Pakistan, but details of the sources and mechanisms are not available. Many of the GLOFs in China occurred in the southern part of the Tibetan Plateau, where rivers drain into Nepal. Ten of these events led to transboundary damage and many caused major damage in Nepal. One of the most remarkable in this context is the Zhangzanbo lake GLOF of 11 July 1981. The lake burst due to a sudden ice avalanche. A breach 50m deep and 40-60m wide formed at the moraine. The peak discharge of the burst at the outlet was about 16,000 m^3/s. The main flood lasted for an hour, during which time an estimated 19 million m^3 of lake water drained. This GLOF created a great change in the landform downstream due to erosion and sedimentation, and caused considerable damage to the highway below the lake up to the Sunkoshi power station. It destroyed the friendship bridge between Nepal and China and two other bridges, one in Tibet and one in Nepal (Figure 20). The flood caused heavy damage to the diversion weir of Sunkoshi hydropower station.

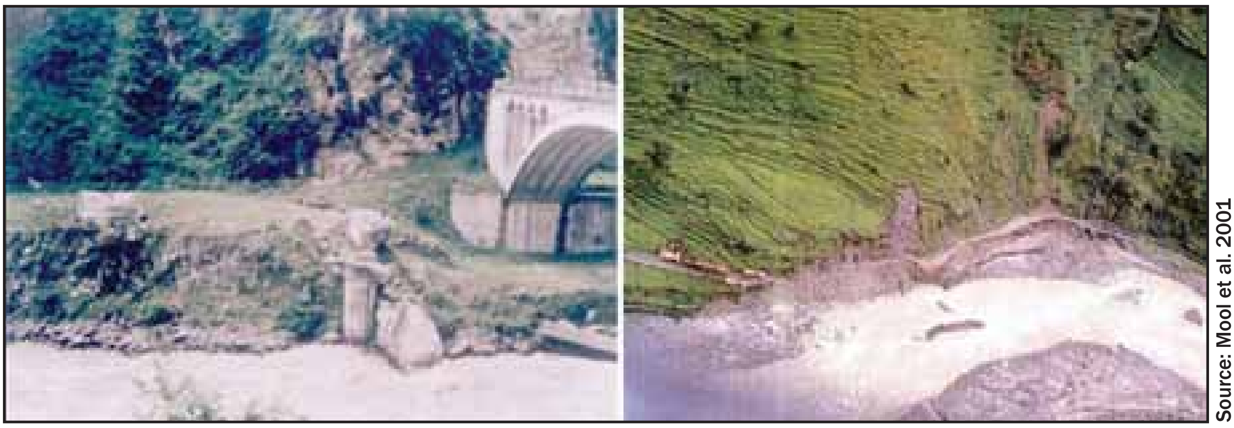


Figure 20: Remnants of a bridge pier (left) on the Arniko Highway and a section of the highway destroyed by the 1981 Zhanzangbo GLOF

One of the region's best-documented GLOF events is the Dig Tsho GLOF of 4 August 1985. Dig Tsho lake is located at the headwaters of the Bhotekoshi, a tributary of the Dudhkoshi River. The lake is in contact with Langmoche, a steep glacier. The GLOF destroyed the nearly complete Namche hydropower project. In addition, the GLOF destroyed 14 bridges, trails, and cultivated land, and caused the loss of many lives. The total damage was estimated at US $1.5 million. Figure 21 shows the Dig Tsho Lake before and after the burst.

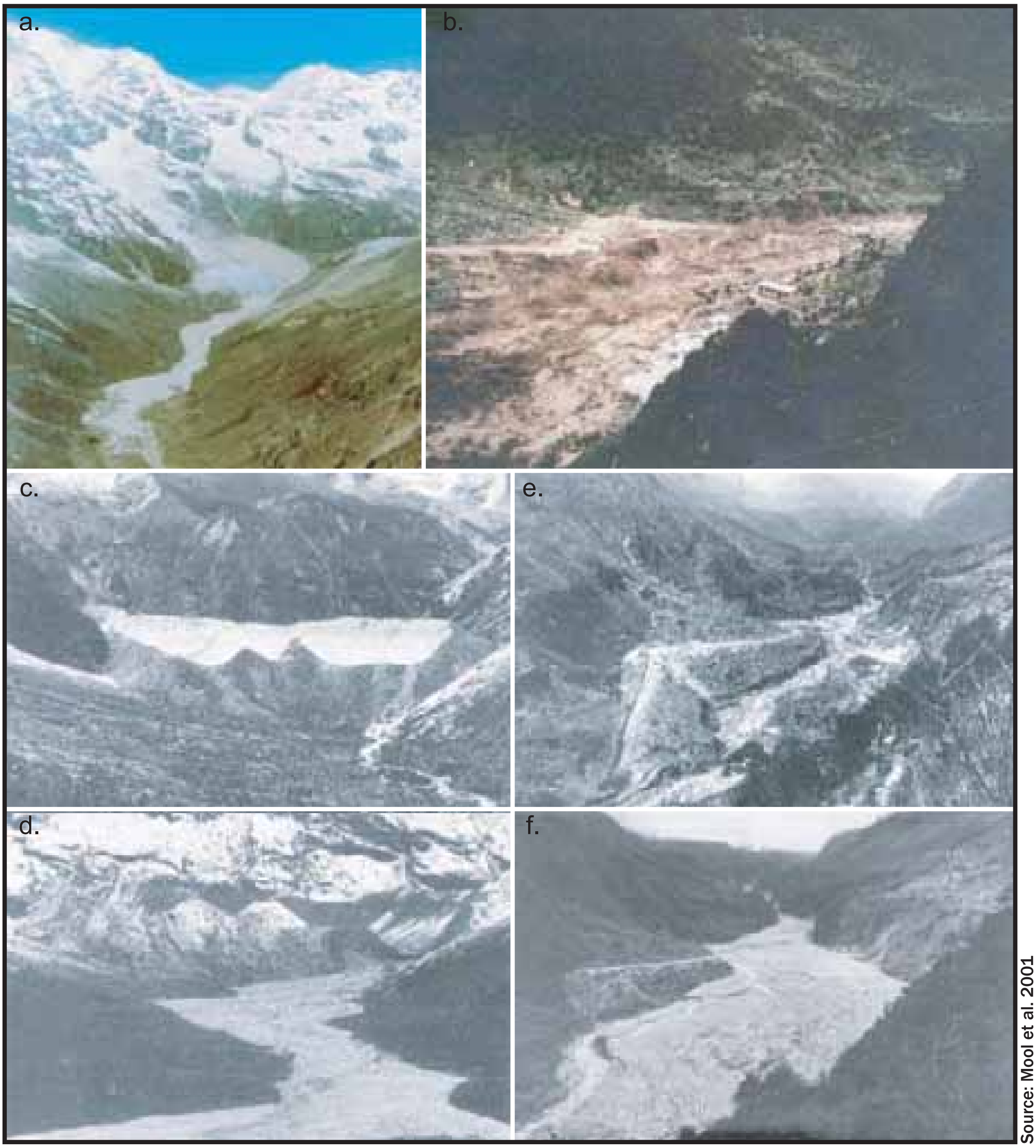


Figure 21: a. Dig Tsho lake after the GLOF outburst in 1985; b. the flash flood caused by the Dig Tsho outburst; c. the end moraine of Dig Tsho before the breach; and d. after the breach; e. the Namche hydropower station site before; and f. after the outburst

How do humans contribute to flooding?

Floods are a naturally occurring hazard that become disasters when they affect human settlements. The magnitude and frequency of floods is often increased as a result of the following human actions.

Settlement on floodplains contributes to flooding disasters by endangering humans and their assets. However, the economic benefits of living on a floodplain outweigh the dangers for some communities. Pressures from population growth and shortages of land also promote settlement on floodplains. Floodplain development can also alter water channels, which if not well planned can contribute to floods.

Urbanisation contributes to urban flooding in four major ways. Roads and buildings cover the land, preventing infiltration so that runoff forms artificial streams. The network of drains in urban areas may deliver water and fill natural channels more rapidly than naturally occurring drainage, or may be insufficient and overflow. Natural or artificial channels may become constricted due to debris, or obstructed by river facilities, impeding drainage and overflowing the catchment areas.

Deforestation and removal of root systems increases runoff. Subsequent erosion causes sedimentation in river channels, which decreases their capacity.

Failure to maintain or manage drainage systems, dams, and levee bank protection in vulnerable areas also contributes to flooding.

Chapter 4

Flash Flood Risk Assessment

Risk assessment forms the core of the flash flood risk management process. Risk assessment helps identify potential risk-reduction measures. If integrated into the development planning process, it can identify actions that both meet development needs and reduce risk. Flash flood damage can be reduced by establishing a proper flood control management structure or organ to manage flood events and reduce their negative effects. The benefits of precautionary steps, measures, and actions will bring communities, agricultural land, infrastructure, and livelihoods in flash flood-prone areas to safety with the help of government management.

4.1 What is Risk?

The term *risk* has a range of meanings depending on the specific sector in which it is used — for example, the economic, environmental, or social sector. Because the terminology of risk has been developed across a wide range of disciplines and activities, there is potential for misunderstanding of the technical terminology associated with risk assessment, as technical distinctions are made between words which in common usage are normally treated as synonyms. Most important is the distinction that is drawn between the words *hazard* and *risk*.

This manual uses the Source-Pathway-Receptor-Consequence (S-P-R-C; Figure 22) concept proposed by Gouldby and Samuals (2005): For a risk to arise there must be hazard, which is the source or initiator event (e.g., cloudburst); pathways between the source and receptors (e.g., flood routes, overland flow, or landslide); and receptors (e.g., people and property). The consequence depends on the exposure of the receptors to the hazard.

The evaluation of risk requires consideration of the following components: the nature and probability of the hazard (p); the degree of exposure of the receptors (number of people and property) to the hazard (e); the susceptibility of the receptors to the hazards (s); and the value of the receptors (v).

Therefore

$$\text{Risk} = f(p, e, s, v)$$

The first two components of risk are related to hazard and the last two components to vulnerability. In the functional form,

$$\text{Vulnerability} = f(s, v)$$

Thus, vulnerability is a sub-function of risk. This term describes the predisposition of a receptor to suffer damage.

Risk is, therefore, a statistical concept and is the probability that a negative event or condition will affect the receptor in a given time and space. Thus, risk can be understood in simple terms as:

$$\text{Risk} = (\text{Probability}) \times (\text{Consequence})$$

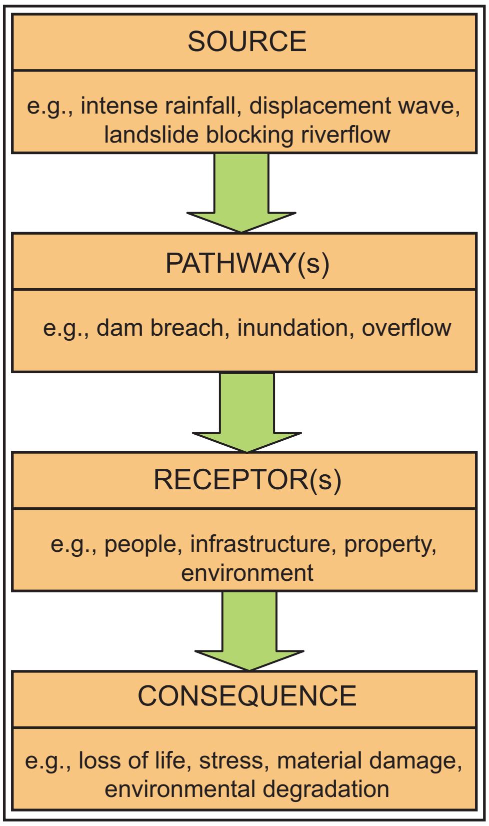


Figure 22: Source-Pathway-Receptor-Consequence conceptual model

The degree of flood hazard in an area is often measured by the return period of the flood, which relates to the probability of the flash flood hazard. Management of flash flood risk can be accomplished by managing hazard, exposure, and vulnerability. Here vulnerability encompasses both physical and social vulnerabilities. Flash flood risk management can be done through structural measures, which alter the frequency (i.e., the probability) of flood levels in the area. On the other hand, flash flood management can also be done through non-structural measures that focus on the exposure and vulnerability of a community to flash flood. Changing or regulating land use, installing an early warning system, and developing the community's resilience are examples of non-structural measures.

4.2 Major Steps in Flash Flood Risk Assessment

Risk assessment forms the core of the disaster risk management process and results in the identification of potential risk-reduction measures. Risk assessment integrated into the development planning process can identify actions that both meet development needs and reduce risk. Identified risk-reduction actions can be incorporated into development policies and legal arrangements. For example, policies and associated laws and regulations to reduce the risk of flash floods can require or encourage construction of spurs or embankments as part of road or water resources projects.

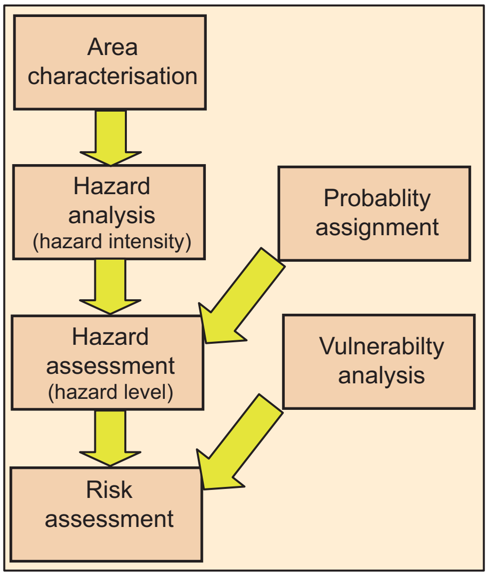


Figure 23: Procedural diagram for flash flood risk analysis

Risk assessment is an essential part of the flash flood risk management decision-making process. A number of methods have been developed to assess the risk of natural disasters. Here, we have adopted the method developed by Colombo et al. (2002), and Gouldby and Samuals (2005), after appropriate modification (Figure 23). Risk assessment steps include:

1. characterising the area
2. assessing hazard or determining hazard level and intensity
3. assessing vulnerability
4. assessing risk

4.3 Characterisation of the Risk-prone Area

This process comprises three main topics: the information to be collected on the area prone to flash floods; the tools to be used for collection, processing, and archiving the information; and the format for documentation.

Information to be collected

The information to be collected to characterise a flash flood-prone area must fulfil two main tasks: it must provide scientific data for hazard, vulnerability, and risk analysis, and it must assist decision-makers during the subsequent planning process. Characterising the area is important for both hazard and vulnerability assessment. For this, the following information should be collected.

- **Geography (physical and social):** for example, the length of river sections, communities/provinces involved, peculiarities of the area, and population and population distribution
- **Geology and geomorphology:** the properties of rocks and soil in the area, river courses or pathways
- **Hydrology and hydraulics:** the properties of the rivers and waterways in the area such as flow amount, cross-sections, and slope
- **Hydrometeorology:** for example, air temperature, annual precipitation, months of maximum and minimum precipitation, values of precipitation extremes

- **Vegetation:** types of plants and trees that grow in the area
- **Land use:** land use types such as agricultural land, forest and other wooded land, built-up and related land, wet open land, dry open land with special vegetation cover, open land with or without significant vegetation cover
- **Existing counter-measures:** for example, check dams and bioengineering work
- **Historical analysis of local flood events:** for example, floods that have happened in the past; sources of information include local memory, damaged environment, national and local databanks, newspapers, and interviews with victims

Tools for collecting, processing and archiving information

Three main tools are useful in characterising the area subject to flash floods:
1. database for storing general information
2. a geographic information system (GIS) for graphical representation of maps and spatial analysis
3. a set of computer programs for data processing (e.g., hydrological and hydraulic models)

Format for documentation

Flash floods in the HKH region are generally spatially limited and often occur in remote and isolated locations, frequently going undocumented. Even documented events often lack information vital for risk analysis. Thus, it is extremely useful to develop a comprehensive standardised format to facilitate further analysis of data. Such a format will enhance information sharing among institutions, communities, and countries in the region. Event documentation should include the following information:
- **Location of the event:** geographic coordinates of settlements in the vicinity of the source, as well as the impacted areas
- **Basin details:** description of the drainage system, the river/stream where the event occurred, the major river basin that the river/stream drains into
- **Cause of event:** heavy rainfall, GLOF, LDOF, etc.
- **Hydrometeorological details:**
  - amount and duration of rainfall including peak hourly intensities
  - amount of water released by LDOF or GLOF
  - duration of flood
  - peak flood discharge
- **Extent of damage:**
  - dead
  - injured
  - missing
  - agriculture
  - infrastructure
  - homesteads
  - businesses
  - cattle
  - affected area, people, families
- **Damage in monetary terms**

4.4 Hazard Analysis

This process includes defining flash flood hazard intensity (the strength of the flash flood), and describing alternative scenarios in their catchments. Determining hazard intensity is a step towards determining hazard levels. It is common to present hazard scenarios in the form of hazard maps. Modern technology has advanced hazard mapping and the prediction of future events considerably through techniques such as geological mapping and satellite imagery, production of high resolution maps, and computer modelling. New geographic information system (GIS) mapping techniques, in particular, are revolutionising the capacity to prepare hazard maps. It is, however, essential to verify the maps through field observation. Often hazard maps can be prepared with community involvement, and the best results can be achieved by combining the technical hazard maps with others prepared by the community. This process includes defining flash flood hazard intensity and possible scenarios in their catchments. A simple way of assigning flash flood hazard intensity is shown in Table 3, although in reality determining hazard intensity is much more complicated. Alternatively, hazard intensity can be determined by the level of anticipated flooding. Figure 24 shows an example of a flood hazard map.

Table 3: **A simple way of assigning hazard intensity**

Hazard intensity	Danger to population close to the stream	Danger to population in settlement (about 500m from the stream)	Danger to population 1 km away from the stream	Danger to population more than 1 km away from the stream
High	yes	yes	yes	yes
Moderate	yes	yes	yes	no
Moderately Low	yes	yes	no	no
Low	yes	no	no	no

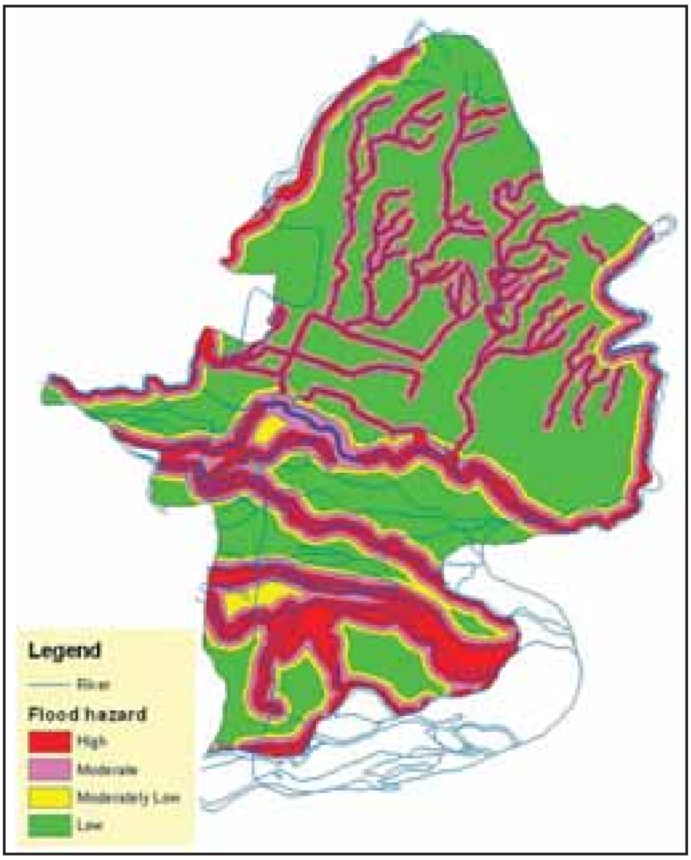
Assigning probability to a hazard scenario

The hazard scenario should be assigned probability levels. In the case of intense rainfall floods, the return period or frequency of the rainfall events, or the return period or frequency of flooding caused by these events, can be used to give probability levels as shown in Table 4.

It is difficult to assign probability levels to other types of flash floods such as LDOF and GLOF, as they often occur only once. In such cases it is customary to use probability levels based on the characteristics of the lake, dam, or surrounding environment, as shown in Table 5.

4.5 Hazard Assessment

Hazard assessment includes determining the hazard level scale by combining the hazard intensity based on the hazard intensity scenario and the hazard probability level. Figure 25 shows an example of a hazard level scale. The hazard probability has four levels and the hazard intensity level has four degrees (high, moderate, moderately low, low). The resulting 16-cell hazard level scale identifies four different levels (very high, high, moderate, and low).



Source: ICIMOD

Figure 24: A simple flood hazard map of Bhandara Village Development Committee area, Chitwan, Nepal

Table 4: Probability level of a hazard scenario

Probability level	Frequency
High	at least once in 10 years
Moderate	once in 10 to 30 years
Moderately Low	once in 30 to 100 years
Low	less frequent than once in 100 years

Table 5: Probability level for LDOF and GLOF

Indicator	Characteristic	Qualitative probability
Type of dam	ice	high
	moraine	medium high
	bedrock	low
Freeboard relative to dam	low	high
	medium	medium
	high	low
Dam height to width ratio	large	high
	medium	medium
	small	low
Impact waves by ice/rock falls reaching the lake	frequent	high
	sporadic	medium
	unlikely	low
Extreme meteorological events (high temperature/ precipitation)	frequent	high
	sporadic	medium
	unlikely	low

Source: RGSL (2003)

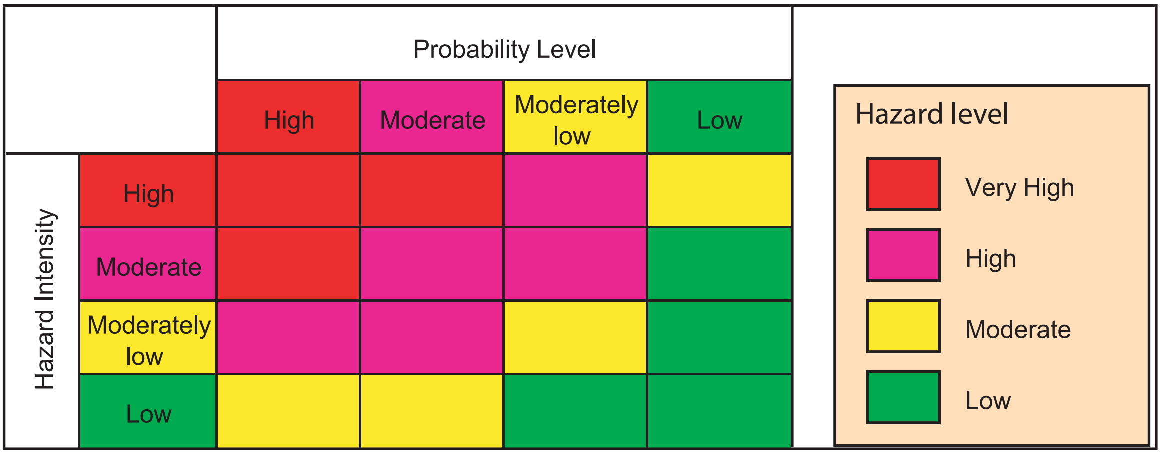


Figure 25: Hazard level scale

4.6 Vulnerability Assessment

The next step in risk analysis is the vulnerability assessment. There are three schools of thought on vulnerability analysis. The first focuses on exposure to biophysical hazards, including analysis of the distribution of hazardous conditions, human occupancy of hazardous zones, degree of loss due to hazardous events, and analysis of the characteristics and impacts of hazardous events (Heyman et al. 1991; Alexander 1993; Messner and Meyer 2005). The second looks at the social context of hazards and relates social vulnerability to coping responses of communities, including societal resistance and resilience to hazards

(Blakie et al. 1994; Watts and Bohle 1993; Messner and Meyer 2005). The third combines both approaches and defines vulnerability as a hazard of place, which encompasses biophysical risks as well as social response and action (Cutter 1996; Weichselgartner 2001; Messner and Meyer 2005). The third school has become increasingly significant in the scientific community in recent years and this manual is based on this approach.

Physical vulnerability assessment

Physical vulnerability is expressed as a vulnerability index that is a function of susceptibility and exposure.

Susceptibility

Susceptibility is the state of being easily influenced by flash flood hazards. Those elements susceptible to flash flood hazard are called elements at flash flood risk. Susceptibility can be expressed in terms of a vulnerability index, which can be in monetary or non-monetary units. Generally, high-value elements are given a higher vulnerability index. It is difficult to quantify some elements at risk, including human lives, ecological species, and landscapes; thus, a vulnerability index must be based on qualitative categories. Table 6 gives a general guideline for assigning vulnerability levels to different land use categories.

Table 6: **Vulnerability level scale as a function of land use categories**

Category	Vulnerability level
Natural areas (e.g., natural water courses, unproductive areas, and so on)	Low
Agriculture and forestry (e.g., meadows, pastures, forests)	Moderately low
Special agriculture (e.g., fields, orchards)	Moderately low
Local infrastructure (e.g., trails, secondary roads, tertiary canals)	Moderately low
Trade and industry	High
National infrastruture (e.g., main roads, railway lines, main canals)	High
Settlements	High
Special objects (e.g., power stations, cultural heritage sites, strategic facilities)	High

Source: RGSL (2003)

Exposure

The vulnerability index also depends on the exposure of the element at flash flood risk. Exposure refers to the type, extent, and magnitude of susceptible elements likely to be affected when a flash flood occurs. The exposure indicator depends on the proximity of the susceptible element to the river, river morphology, geology of the location, elevation, return period of the flood, flow velocity, and so on. Exposure can be evaluated in monetary terms and expressed in qualitative categories (e.g., high, moderately high, moderate, low, etc.).

Socioeconomic vulnerability assessment

Socioeconomic vulnerability is a function of the society's adaptive capacity in a physically vulnerable zone. This adaptive capacity is a function of social and economic processes. New settlements along riverbanks or flash flood debris fans are examples of processes that increase vulnerability to flash flood. Poverty and limited availability of land are governing factors behind this. Areas with access to communications, financial institutions, and markets, and having diversified income sources have a stronger adaptive capacity and are, hence, less vulnerable. Adaptive capacity can be expressed quantitatively or qualitatively. Some quantitative and qualitative indicators are listed in Table 7. The quantitative indicators have to be converted to qualitative categories so that they can be combined with qualitative indicators to derive the socioeconomic vulnerability of the area of interest.

Physical and socioeconomic vulnerability are combined to obtain the total vulnerability, which might again be presented as qualitative categories (high, moderate, moderately low, low, and so on).

Table 7: **Quantitative and qualitative indicators**

Parameter	**Quantitative indicators**
Accessibility	Road density (m/km²)
Health	Number of health institutions/1000 population
Communications	Number of telephones/1000 population
Institutions	Number of GOs and NGOs/1000 population
Economic	Number of financial institutions/1000 population
Loss-sharing measures	Value of revolving fund (disaster fund)
Economic diversity	Percentage of families with a number of income sources
Qualitative indicators	
Emergency facilities	
Warning system	
Loss reduction measures	
Awareness and attitude	
Source: Shrestha (2005)	

4.7 Risk Assessment

A risk-level scale is a combination of hazard level and total vulnerability (both physical and socioeconomic). The scale is obtained by subjective judgment, similar to the hazard-level scale. Figure 26 shows a risk-level scale that can be used to assess flash flood risk. Four levels of hazard and four levels of total vulnerability (high, moderate, moderately low, and low) are considered. The resulting risk-level scale consists of 16 cells and may be classified into five different risk levels: very high, high, moderate, moderately low, and low.

The methodology presented in this section is one of many available in the literature or, rather, it is a combination of several methodologies. It may be modified or simplified according to need, resources available, and data available. Annex 1[6] provides an exercise on hazard vulnerability and risk assessment. The ILWIS[7] 3.2 based exercise uses multiple hazards instead of a single hazard. In reality, communities are exposed to different types of hazards and stresses.

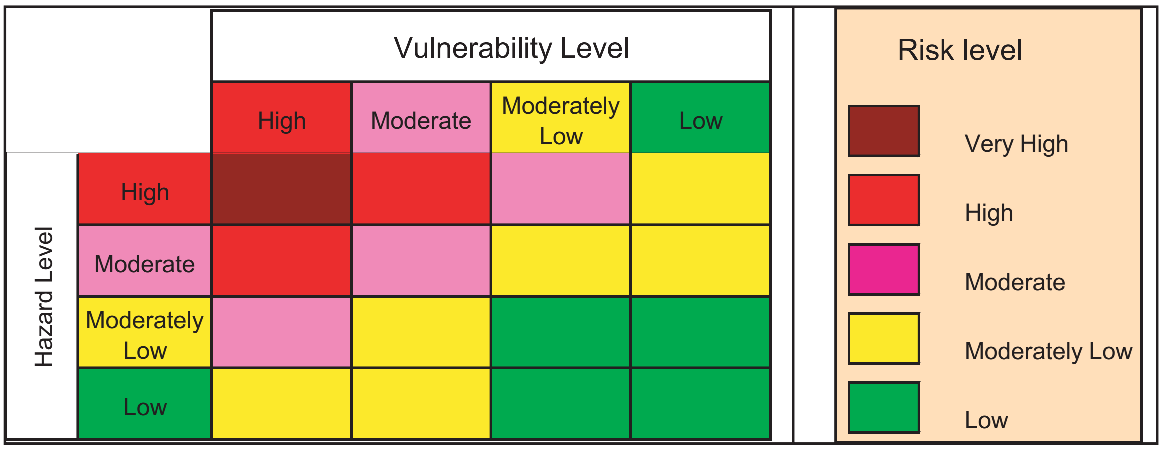


Figure 26: Classification of risk level

[6] The exercise was provided by C.J. van Westen, International Institute for Geo-Information Science and Earth Observation (ITC) and is available from <http://www.itc.nl/ilwis/applications/application01.asp> (Accessed October 2007).
[7] An open source version, ILWIS 3.4 Open, can also be used. It is freely downloadable from <http://52north.org/index.php?option=com_projects&task=showProject&id=30&Itemid=127>.

Chapter 5
Flash Flood Risk Management

Flash flood risk management can include structural and non-structural measures. A common strategy to cope with floods has been to construct civil works such as floodwalls, transversal protection works, embankments, conduits, and reservoirs to protect the environment up to an acceptable risk threshold. Structural measures tend to consider mainly the hydrological and hydraulic implications of flooding, which are generally solved by choosing the alternative that maximises the expected net benefit. In addition, such measures can have a substantial impact on the riverine environment and ecology. Furthermore, while structural solutions contribute to flood reduction and protection, they also have hidden ‘piggy-back’ liabilities associated with them, such as the issue of their long-term value, the false sense of security they may provide, their possible environmental impact, and costs related to their operation and maintenance.

In contrast, non-structural measures (see below) offer a variety of possibilities, ranging from land use planning and construction and structure management codes, through soil management and acquisition policies, insurance, and perception and awareness, to public information actions, emergency systems, and post-catastrophe recovery, all of which contribute towards the mitigation of flood-related problems. The advantage of non-structural measures is that, generally, they are sustainable and less expensive. Table 8 gives some examples of structural and non-structural measures. Non-structural measures are often the most effective in managing flash floods. However, they can only be efficient with the participation of a responsive population and an organised institutional network. A combination of structural and non-structural measures can be the best. This manual deals explicitly with the non-structural measures for flash flood risk management.

Table 8: **Structural and non-structural measures for flash flood risk management**

Structural measures			Catchment-wide interventions (agriculture and forestry actions and water control works)
			River training interventions
			Other flood control interventions (passive control, water retention basins and river corridor enhancement, rehabilitation and restoration)
Non-structural measures	Risk acceptance	Tolerence strategies	Toleration
			Emergency response system
			Insurance
	Risk reduction	Prevention strategies	Watershed management
			Delimitation of flood areas and securing flood plains
			Implementation of flood area regulations
			Application of financial measures
		Mitigation strategies	Reduction of discharge through natural retention
			Forecasting and early warning
			Emergency action based on monitoring, warning, and response systems (MWRS)
			Public information and education

Source: Colombo et al. (2002)

5.1 Non-structural Measures

The need for non-structural measures becomes very important when dealing with settled areas, as they allow control of the vulnerability component of flood risk (see Chapter 4).

Non-structural measures are particularly important for the HKH region for several reasons:

- the high cost and short lifetime of structural measures
- lack of capacity to build and operate structural measures
- low involvement of local community, lack of feeling of ownership
- other environmental impacts of structural measures

Non-structural measures tend to be more sustainable because they include the active involvement of the community. National and regional policy should favour non-structural alternatives due to their low cost and reduced number environmental side effects, and implement structural measures only as a last resort.

Non-structural measures can be grouped into two categories: risk acceptance and risk reduction measures.

Risk acceptance

Acceptable risk is the level of loss a society or community considers acceptable given existing social, economic, political, cultural, technical, and environmental conditions (UN/ISDER terminology[8]).

Risk acceptance implies that the government or community accepts a degree of human and material loss due to a flash flood that could impact the area in the short-, medium-, and long-term. There are mainly three types of risk acceptance strategies: toleration, emergency response system, and insurance.

Toleration

Toleration of risk implies that a competent authority (local, regional, or national) accepts that flash floods occur. Generally, proactive initiatives will not be carried out other than, perhaps, a risk analysis (see example in Annex 1). In this case, it is very likely that the competent authority will accept the results of the risk assessment and not promote any complementary activities. Although risk analysis is gradually gaining ground with competent authority routines, it still needs to become common practice.

Emergency response systems

The use of emergency response systems implies that the local, regional, or national competent authority is aware that their area of jurisdiction is prone to flash floods. Risk assessment and modelling, coupled with mapping, is probably carried out, but flash floods will mainly be dealt with via the elaboration of emergency plans and using already existing structures.

All emergency plans (regional, district, local) should be based on a national emergency plan in order to carry out the same doctrine of civil protection emergency operations within a particular country in a concerted manner. In general, the various public authorities taking part in the emergency plan will play roles related to their day-to-day responsibilities. They must prepare themselves according to the mission statement established in the emergency plan. To achieve this, each competent authority (regional, district, local) must have its own emergency plan, accompanied by an operations manual. Furthermore, each collaborative unit (police, fire brigade, hospital, and so on) should also have its own emergency plan and operations manual.

Insurance

Insurance against flash flood damage should be an integral part of risk acceptance. However, many countries in the HKH region still do not use flood insurance due to its high cost. Existing solutions to flood coverage are

[8] UN/ISDR terminology of disaster risk reduction (http://www.unisdr.org/eng/library/lib_terminology_eng%20home.htm; Accessed June 2007).

quite diverse, mainly due to the technical difficulties involved in providing insurance cover against flooding, differing views on the role of the state in managing flood risk, and last but not least, diverging perceptions of the dangers posed by flooding. The solutions in place range from unrestricted private insurance coverage to state aid for flood victims.

Insurance companies have various instruments available to cover the risk. Some examples are given below.

- **In combination with other natural perils:** Flood risk is usually covered in combination with other natural perils in order to appeal to as many customers as possible, achieve maximum market penetration, and minimise the risk of selection bias.
- **Grouping of several insurance portfolios in a pool:** Flood risk is spread among other insurance portfolios and is offered as a package. This also decreases the risk to the insurer.
- **Resilient reinstatement:** Flood insurance is made available only to floodplain residents who make an effort to make their houses more resistant to flooding (e.g., use of flood-resistant products and techniques when repairing a flood-damaged property, installing electrical sockets one metre above the floor instead of just above the skirting board).

Generally there is difficulty in dividing the risk fairly among the parties involved (i.e., the property owner, (re) insurer, and the state). This is mainly due to the very different hazard potentials in play and the differences in perception of these hazards. Furthermore, the system of insurance policies applied only on a local level is far too expensive both for insurance companies and for private and public entities. The following recommendations may help overcome these problems:

- A mandatory national or regional (e.g. South Asian Association for Regional Cooperation [SAARC], HKH) insurance fund against natural hazards should be established, so as to spread costs. This would follow the concept of joint sharing of burdens and would reduce the costs of expensive disaster-relief payments.
- The development of risk-oriented models for determining the implications of a flood hazard should be promoted and funded. This would require an external source of funds additional to insurance, which could raise data-protection problems.

5.2 Risk Reduction

Success in managing flood areas depends on selecting suitable measures based on flood characteristics, physical and morphological characteristics of flood areas, economic and social conditions, political and environmental conditioning, or flood-control works planning. Structural measures cannot reach these objectives if they are used alone; non-structural measures such as land use control and planning can be tools not only to reduce flood risk, but also to develop a sustainable approach to flood management. Risk reduction is one of the main goals in flash flood management. It can be dealt with in two ways: prevention strategies and mitigation strategies. The following section describes different approaches, tools, and activities for flash flood risk reduction.

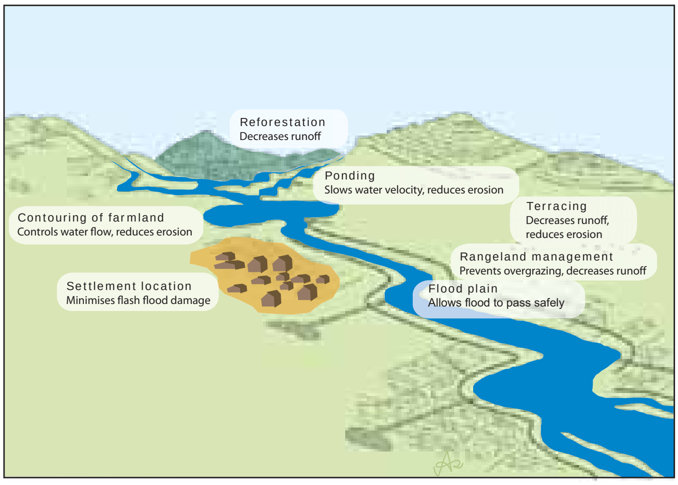
Watershed management[9]

Watershed management has both structural and non-structural components. Non-structural components can be important measures in reducing flash flood risk. Watershed management is a cross-cutting exercise closely related to socioeconomy and development. Watershed management should consider a number of basic principles related to runoff and erosion including soil, topography, land cover and use, and farming practices.

[9] This section includes contributions from Keshar Man Sthapit, ICIMOD.

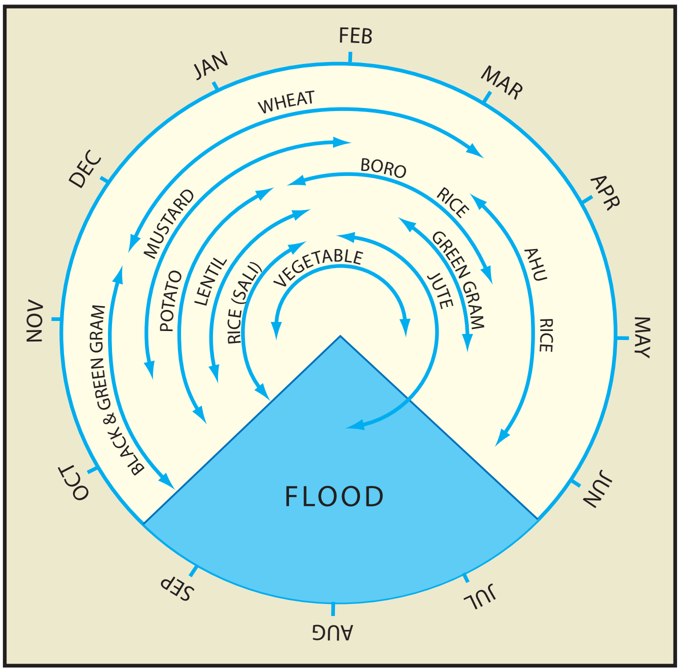
The following measures in a watershed can significantly reduce the risk of flash floods (Figure 27):

- **Agricultural measures:** Agricultural activities should minimise the generation of runoff and sediment. Contouring and terracing of upland farms is a good measure to ensure this. Crops should be selected to ensure longer coverage, especially in rainy periods. Conversion into arable land should be avoided where slopes exceed 25%. Agricultural practices that increase organic matter in the soil should be favoured.
- **Remodelling of agriculture:** Agriculture in flood-prone areas should be conducted in ways that minimise the flood damage to crops. Assam, where floods occur regularly, provides a good example of what can be done. The successive waves of floods from the Bhrahmaputra and Barak rivers and their tributaries cause extensive damage to agriculture (Figure 28):
  - The ahu crop (rice) is damaged before the harvest.
  - The sali or main crop of rice cannot be transplanted in time as the seedlings are damaged either in the nursery or after transplanting, sometimes even destroyed in the field.
  - The jute crop is damaged or quality is adversely affected, and so on.



Source: Modified from DMTP 1997

Figure 27: Some aspects of watershed management



Source: Modified from Swaminathan 1980

Figure 28: Modification of cropping pattern to suit flooding period

Various strategies are used related to remodelling of land use to minimise the adverse effects of recurrent floods (Swaminathan 1980):

- **Multiple cropping:** Cropping of medium tall ahu rice with deep-water rice in low-lying areas as an insurance so that if the ahu rice is damaged, there will be some production from the deep-water rice.
- **Restructuring of the cropping pattern:** The safest way to assure crop production in flood-prone areas is to use the flood-free period for growing crops. Figure 28 shows the flood-free period and the potential for growing crops in this period.
- **Forestry:** Reforestation can be a good measure to decrease runoff. Tree species that do not prohibit undergrowth should be selected. Logging should be carried out during non-rainy seasons. Plan for log-skidding tracks, as they might trigger flash floods. Favour mixed, uneven aged, and autochthonous woods by selective thinning and coppicing.
- **Rangeland management:** Pasture renewal through fire should be avoided as this reduces soil organic matter. Grazing should be regulated through the correct assessment of optimum livestock numbers. A more homogeneous distribution of livestock and use of rotation grazing methods should be encouraged.

- **Floodplain management:**
  - Floodplain management includes flash flood hazard mapping, which shows the areas that will be impacted by a flood of a particular return period and enables delimitation of flood areas. Flood hazard mapping can be conducted to different degrees of detail. A very simple flood hazard map shows the area of inundation. In addition, the depth of inundation, the velocity of flood water at a given location, elements at risk, and others can be provided. A simple exercise on GIS-based flood hazard mapping is provided in Annex 2[10].
  - One important activity is the delimitation of flood areas and securing of flood plains. Based on the technical study on flash flood hazard mapping, streams should have adequate buffer areas to safely cater for flood waves. The floodplain can be divided into: 1) critical zone (waterway); 2) restrictive zone; 3) regulatory zone; and 4) warning zone (Figure 29). Zone 1 is the waterway/river channel that gets flooded every year and where any human interference should be prohibited. Where a river has right of way, humans should stay out of its way. Zone 2 gets flooded every three to five years, and construction should be restricted and only agriculture permitted. Every 3-5 years one crop will be lost due to flood and there will be harvests in flood-free years. In Zone 3, construction should have adequate protection measures such as embankments, flood proofing, and so on. Zone 4 experiences flooding more rarely, averaging once every 25 years. Construction in the area should have tolerance against flash floods. Flood warning plays an important role here.
  - Natural ponds in the watershed retain the runoff and dampen the peak discharges in the stream. The ponds should be maintained properly and filling the depressions for development purposes should be avoided.
  - Incentive policies should be created and promulgated to achieve better control of building in flash flood-prone areas. Examples of such an incentive policy would be granting building permits that are linked to runoff conditions, and relocation grants to move houses from the floodplain.
  - Watershed committees. Legislation should incorporate flash flood related issues within the framework of watershed committees. This is important because of the interdisciplinary implications of flash flood management.

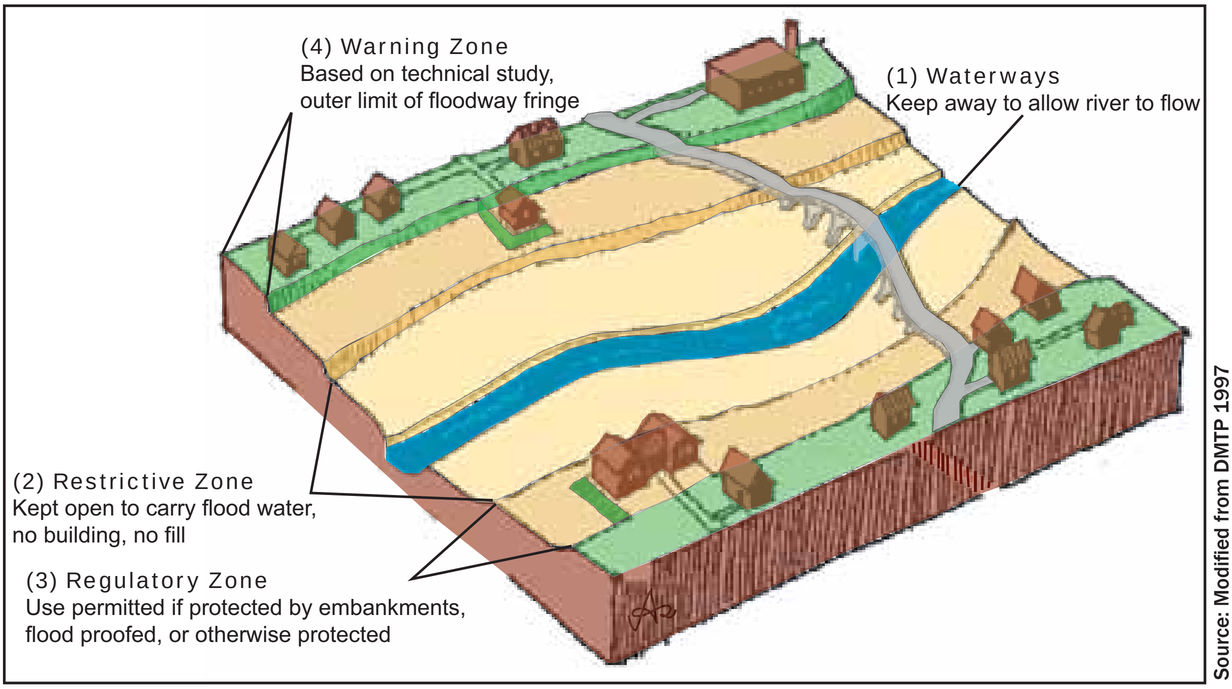


Figure 29: An example of floodplain zoning

[10] The exercise was developed by the Asian Disaster Preparedness Center (ADPC) based on a case study from Sri Lanka. The exercise is based on ILWIS software. An open source version, ILWIS 3.4 Open, can also be used. It is freely downloadable from <http://52north.org/index.php?option=com_projects&task=showProject&i d=30&Itemid=127>.

- **Land use control:** Land use control has much in common with floodplain management; it should also be implemented in conjunction with a technical study on flash flood hazard mapping. Land use regulation is designed to reduce danger to life, property, and development when flash floods occur. The following elements should be addressed while implementing land use control in a watershed. Many of the elements mentioned here are directly related to planning and policy makers, although flash flood managers should also have a good understanding of these issues.
  - Reduction of densities: In flash flood prone areas, the number of casualties is directly related to the population density of the neighbourhood at risk. If an area is still in the planning stage, regulation of densities may be built into the plan. For already settled areas, especially squatter settlements, regulation of density can be a sensitive issue and has to address the socioeconomic implications of resettlement. Unfortunately, many situations exist where dense unplanned settlements are located on floodplains. Planners must incorporate measures to improve sites and reduce vulnerability.
  - Prohibiting development in areas of high risk: No major development should be permitted in areas subject to flooding once every 10 years on average. Areas of high risk can be used for functions with a lower risk potential such as nature reserves, sports facilities, and parks. Functions with high damage potential such as hospitals should be permitted in safe areas only.
  - Relocation of elements that block the flood passage: In addition to the obvious danger of being damaged or washed away, buildings and other structures blocking the floodway may cause damage by trapping floodwaters which then overflow into formerly flood-free zones.
  - Implementation of a building code: The design of buildings and choice of building materials should consider the probability and severity of flash floods.
  - Provision of escape routes: Land use plans should have clear escape routes and provide refuge areas on higher ground.

Integrated flash flood management

Paradigm change in flood management

Flood management has traditionally been problem driven, with more activities implemented after a severe flood. Actions generally have included structural and non-structural, physical and institutional flash flood management interventions implemented before, during, and after the flash flood or other event. Often flood management has involved conflict with other sectors such as building, agriculture, and water resource management. Flood has been treated as a negative phenomenon and its positive aspects largely ignored, although the ecosystem services provided by floods are very important. Some flood management interventions even adversely impact on riverine ecosystems.

Climate change projections suggest there will be an increased frequency and an increase in magnitude of flash floods, and a wider distribution of these events. The traditional methods of flash flood management may not be effective under changed circumstances, as present standard practices regarding infrastructure may become invalid. Conventionally, the risk of flooding is expressed in terms of the excedence probability of a flood of a given magnitude on a particular stretch of river. In recent times, emphasis has been placed on analysing the sequence of events and associated probabilities that result in flash floods – based on meteorological events themselves and the antecedent conditions (e.g., basin shape, solid moisture condition, and vegetation). The new convention on flood management emphasises risk management. It is now more accepted that there is a need to find ways of making life sustainable even in flash flood prone areas and floodplains, even if there is considerable risk to life and property. This can be approached through the integrated management of floods.

Integrated water resources management

According to the Global Water Partnership (GWP), integrated water resources management (IWRM) is a process that promotes the coordinated development and management of water, land, and related resources to maximise the resultant economic and social welfare equitably without compromising the sustainability of vital ecosystems (Figure 30).

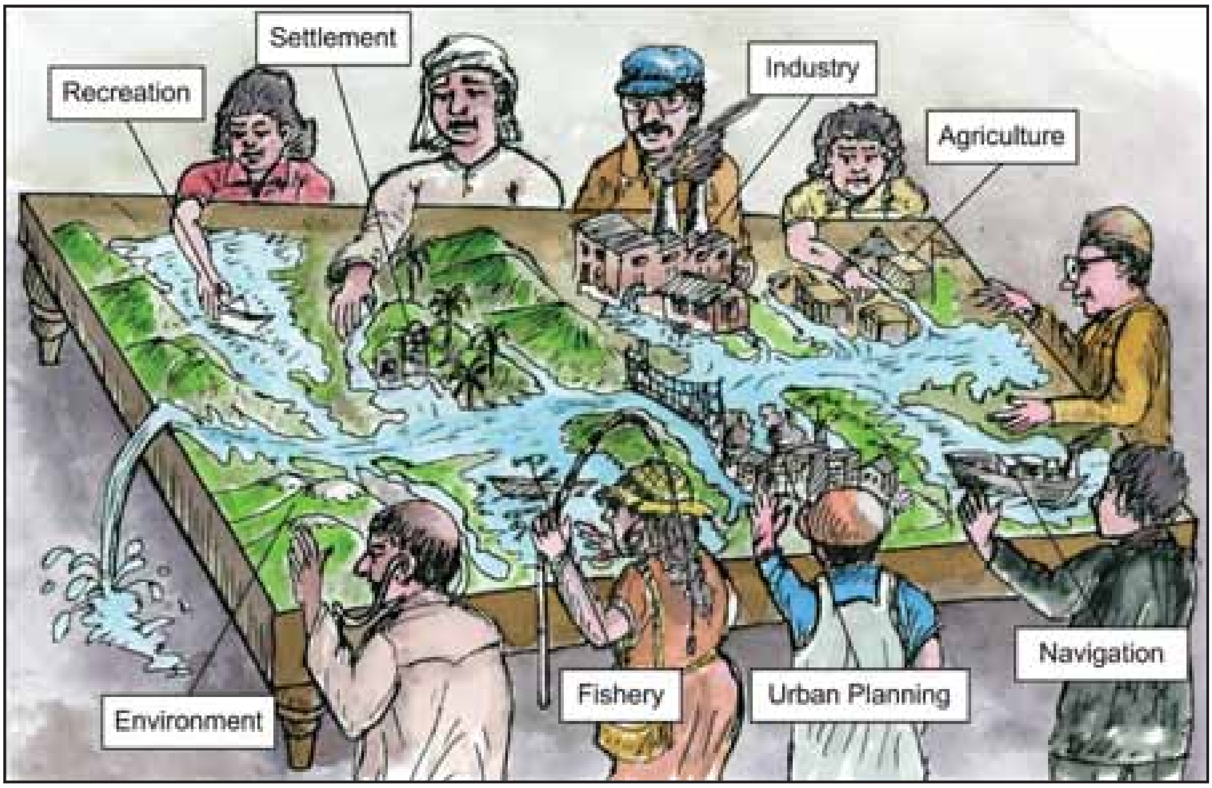


Figure 30: Integrated water resources management

Sustainable and effective management of water resources demands a holistic approach, linking social and economic development with the protection of natural ecosystems and appropriate management links between land and water uses. Therefore, water-related disasters such as floods and droughts, which play an important part in determining sustainable development, also need to be integrated within water resources management.

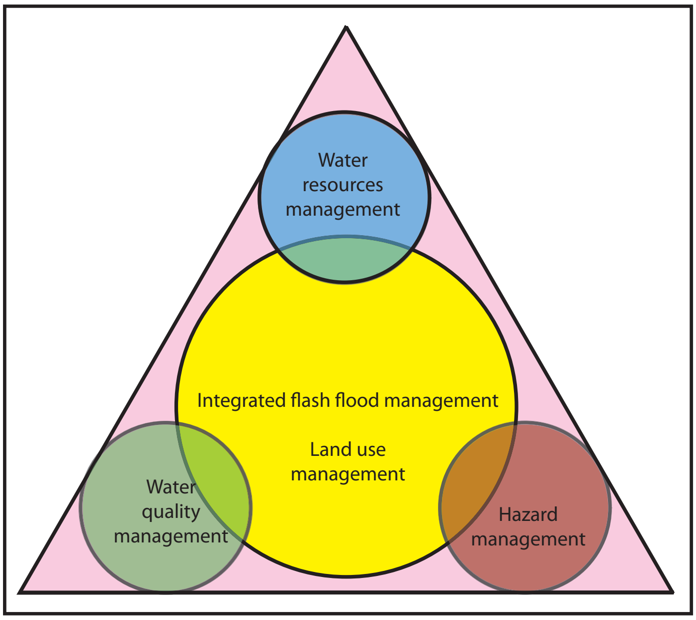


Figure 31: Integrated flash flood management model

Integrated flash flood management

Integrated flash flood management (IFFM) is a process promoting an integrated rather than fragmented approach to flash flood management. It integrates land and water resources development in a river basin within the context of IWRM, and aims at maximising the net benefits from floodplains and minimising loss to life from flooding. IFFM includes four major components: water resources management, water quality management; hazard management; and land use management (Figure 31).

> ***Water is a finite and vulnerable resource; differentiation between water resources management, flood management, and drought management needs to be circumvented.***
>
> **APFM (2004)**

Integrated flash flood management recognises the river basin as a dynamic system in which there are many interactions and fluxes between land and water bodies. In IFFM the starting point is a vision of what the river basin should be. Incorporating a sustainable livelihood perspective means looking for ways of identifying opportunities to enhance the performance of the system as a whole. IFFM is not only used to reduce the losses from floods but also to maximise the efficient use of floodplains – particularly where land resources are limited. While reducing loss of life should remain the top priority, the objective of flood loss reduction should be secondary to the overall goal of optimum use of floodplains. In turn, increases in flood losses can be consistent with an increase in the efficient use of floodplains, in particular, and the basin, in general, (Brilly 2001).

An integrated flash flood management plan should address the following five key elements that would seem to follow logically for managing floods in the context of an IWRM approach:

- **Manage the water cycle as a whole:** Flood management plans should be intertwined with drought management through the effective use of floodwater and maximising the positive aspects of floods. Flood management should also be linked with groundwater management. As they are linked resources, the role of floodplains on groundwater recharge should be considered.
- **Integrate land and water management:** Land use planning and water management planning have to be combined in one synthesised plan through coordination between land management and water management authorities to achieve consistency in planning. Upstream changes in land use can drastically enhance flash floods and cause deterioration of water quality downstream of the basin. In fact, the three main elements of river basin management – water quantity, water quality, and the process of erosion and deposition – are inherently linked and are the primary reasons for adopting a river basin-based approach to IFFM.
- **Adopt a best mix of strategies:** Adoption of a strategy depends on the hydrological and hydraulic characteristics of the river system and the watershed. Three linked factors determine which strategy or combination of strategies is likely to be appropriate in a particular river basin: the climate, the basin characteristics, and the socioeconomic conditions in the region. Quite different strategies are likely to be appropriate in different situations and different countries. However, the strategies often involve a combination of complementary options – a layered approach. In many cases structural and non-structural measures can confer only partial safety. In such cases the strategy could be to reduce the vulnerability through disaster preparedness and flood emergency planning. Often good planning emphasises the long term. However, in the incidence of severe flash floods, short-term interventions are necessary. Therefore, the need is to include both long-term and short-term interventions in the overall plan.
- **Ensure a participatory approach:** IFFM should be based on a participatory approach, involving stakeholders, planners, and policy makers at all levels. The approach needs to be open, transparent, inclusive and communicative, requiring decentralisation of decision-making with public consultation and involvement of stakeholders in planning and implementation. A bottom-up approach is often considered best. However, an extreme bottom-up approach risks fragmentation rather than integration. On the other hand, top-down approaches involve a great deal of effort, subverting the intentions of the responsible institutions. It is important to use the strength of both approaches by using an appropriate mix.
- **Institutional synergy:** All institutions necessarily have geographical and functional boundaries. It is necessary to bring all the sectoral views and interests to the decision-making process. The challenge is to promote cooperation and coordination across functional and administrative boundaries.

Adopt integrated hazard management approaches

Communities are exposed to various natural and human-made hazards and risks. A wide range of activities and agencies are involved in the successful implementation of disaster-management strategies. IFFM should be integrated into a wider risk management system. This helps in structured information exchange and the formation of effective organisational relationships. Effective early warnings for all forms of natural hazards are best received by communities if they emanate from a single, officially designated authority with a legally assigned responsibility.

Financial measures

Financial support is provided after the occurrence of flash flood disasters to aid communities. In such cases, national and regional administrations should promulgate specific regulations to govern economic contributions in order to at least partially cover losses due to flash floods. Financial measures can be either an economic contribution or waiver of financial burdens, such as taxes, loan interest, or liquidation of a loan itself. Depending on the political structure and existing legislation of a country, there are many ways of providing financial support to individuals and local communities.

Financial support for planning, constructing, and maintaining structural interventions can be shared among national, provincial, and local administrative levels, with the total amount divided among them. The financial burden can be shared in two ways: burden sharing during planning and building, and burden sharing during maintenance. In general, the burden share increases progressively from local to provincial to national levels.

Another approach to financial support is to categorise interventions on river courses according to level of importance, which can also be used to regulate funding of hydraulic works of public interest. This categorisation defines who is to provide funds for the interventions and who must maintain them. The categorisation should be carried out on a case-by-case basis, according to the existing regulations of the country.

Financial measures can also be used to subsidise actions targeted towards reducing flash flood risks. The policy of subsidy should be operated in the context of IWRM and IFFM. Subsidies can incorporate forests, pasture, and rangeland management, and protection of water bodies. This can involve subsidies to community forestry user groups and other user groups or committees. Such financial measures can also target farmers to encourage environmentally friendly farming practices that reduce the risk of flash floods, such as contour farming, strip cropping, limited fallow land use, crops adapted to slopes, and terrace cultivation. This may also entice other farmers to farm in a sustainable manner.

5.3 Mitigation Strategies

The following sections provide some examples of non-structural measures that can be used to reduce the intensity, frequency, and impacts of flash floods.

Reducing discharge through natural retention

Studies on water flow have identified the early securing of areas for flood control purposes, so as to have them available in emergency situations, as a crucial aspect (Colombo et al. 2002). To this end, the following measures should be provided.

- Areas particularly suitable for water retention or that are needed to build earth dams or dikes should be singled out and marked as 'devoted to special purposes', which should also be reflected in land-use plans. If these areas fall within the private property of farmers, subsidies for loss due to deprived farming can be arranged.
- Advice from hydraulic engineering experts on passive flood control should be incorporated into regional development programmes and construction plans so that retention basins can be more easily identified and used for flash flood mitigation.
- Natural retention areas should be identified and improved, although this is in contrast with the desire to use them for industrial, economic, agricultural, settlement, and transport purposes. Hence, specific regulations should be made to avoid exploitation conflicts that may arise.
- To facilitate flood control measures or any other intervention entailing reduction of the retention surface of a floodplain, compensation measures can be adopted and subsidies introduced.

Monitoring, warning, and response system (MWRS)

Actions based on monitoring, warning, and response systems (MWRSs) can be a very effective form of non-structural flash flood management (IDNDR 1997; ISDR 2005). MWRSs include many components, all of

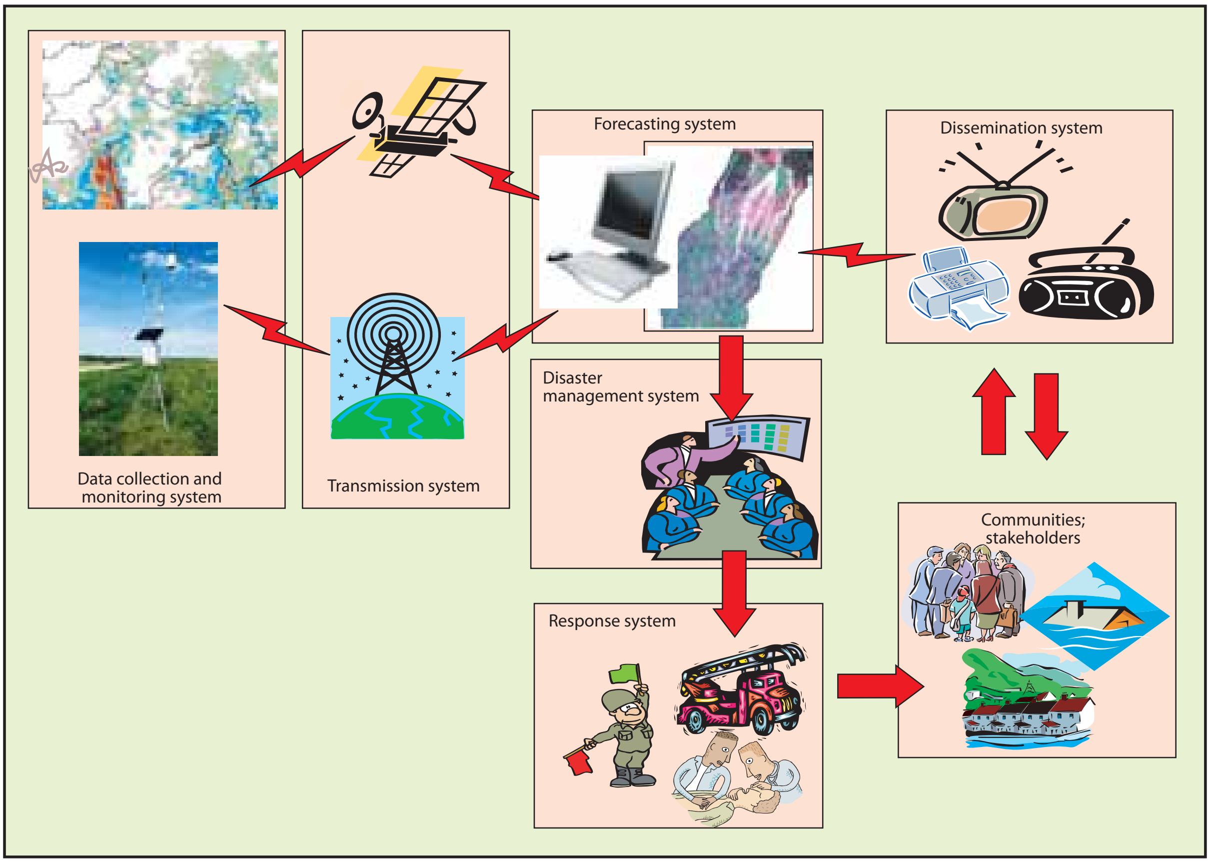


Figure 32: Scheme of a possible monitoring, warning, and response system (MWRS)

which contribute towards the mitigation of flash floods. MWRS is often referred to as an end-to-end flash flood mitigation system (Figure 32). Each component in the system is explained below. Failure of any of these components to function can hamper the effectiveness of the whole system.

Data collection and monitoring system

Monitoring extreme hydrometeorological events is the first step towards understanding what could happen in the future and choosing from possible alternatives. Collection of hydrometeorological data, such as rainfall, temperature, and streamflow, is essential for simulating the natural phenomena. Ground observation networks are commonly used to collect rainfall and other meteorological data. However, in many countries, satellite-based precipitation estimation may be the only source of rainfall data due to scarcity of hydrometeorological networks, long delays in data transmission, and lack of data sharing in many transboundary river basins. A ground-based network seldom has the density sufficient to reflect the natural spatial variability of precipitation, particularly in mountainous terrain as in the HKH region. Satellite estimation can be a valuable complement in such cases. On the other hand, satellite estimates are sometimes biased due to different limitations such as orographic effects and warm cloud processes. Thus, it is not possible to rely on satellite rainfall estimates alone. A combined satellite and surface-based rainfall estimate provides the best input for flash flood forecasting and early warning systems.

Data transmission system

An efficient data transmission system is necessary for timely data transfer from the monitoring site to the centre where the data are analysed. After analysis, the forecasts and warning messages should be relayed to end users in a timely manner. A wide range of data transmission systems are available. In some countries, transmission of manually read data by gauge readers using VHF radio or telegraph is still practised; this can result in errors in data reading and transmission. Automatic transmission of data from the gauge to the centre through different digital media such as terrestrial telephone, GSM, or satellite connections is more reliable, although the high cost of such systems can be a limitation. In Bangladesh, gauges for flood forecasting purposes are equipped with a special data collection unit with a punching device. The unit is brought to the radio room and connected to a high frequency (HF) radio, which transmits the data to the forecasting and warning centre. This system eliminates errors in data reading and transmission.

Forecasting system

Forecasting systems can also vary in complexity. Normally, a forecasting system consists of models (hydrological, hydraulic, and so on) that predict scenarios of potential flash flood events and closely follow the evolution of key parameters that could trigger them. The model may be complicated and can result in very accurate forecasting, but may be of no use if the computation takes so long that it does not provide sufficient lead time before the flood event. Flash floods are rapid processes and often lead time is very small. Further, lack of sufficient data regarding land characteristics hinders the application of sophisticated models. Flash flood managers should consider all these aspects while selecting models for flash flood forecasting. More simplistic models, such as flash flood guidance tables, may be preferable.

Warning system

The general public may not be able to interpret quantitative flash flood forecasts, in which case qualitative warnings have to be issued. Floods are classified into different categories of warnings, which communities and stakeholders should be able to interpret in terms of impact on them. The flash flood warning system for Central America established by USAID/OFDA in collaboration with National Weather Services (NWS) USA uses the concept of a flash flood guidance system (Georgakakos 2004; Figure 33). Flash flood guidance is the volume of rainfall in a given duration (e.g., 1 to 6 hours) over a given small catchment that is just enough to cause minor flooding at the outlet of the draining stream. Any rainfall in excess of the flash flood guidance is considered a flash flood threat.

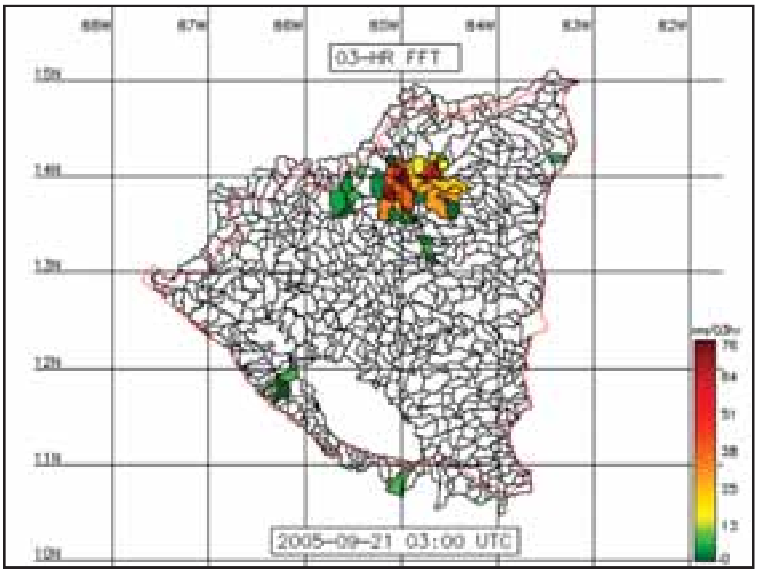


Figure 33: Example of Central America Flash Flood Guidance System product

> ***"More effective prevention strategies would save not only tens of billions of dollars, but save tens of thousands of lives. Funds currently spent on intervention and relief could be devoted to enhancing equitable and sustainable development instead, which would further reduce the risk for war and disaster. Building a culture of prevention is not easy. While the costs of prevention have to be paid in the present, its benefits lie in a distant future. Moreover, the benefits are not tangible; they are the disasters that did NOT happen."***
>
> Kofi Annan,
> "Facing the Humanitarian Challenge:
> Towards a Culture of Prevention"

Dissemination system

After a flood forecast and warning are prepared, they must be disseminated effectively. In the majority of cases, good forecasts fail to prevent damage and loss of life due to poor dissemination systems. The tsunami of December 2004 is a classic example. The forecasts and warnings should reach agencies related to the disaster management system in a timely and understandable manner. These agencies should issue forecasts and warnings by appropriate media such as radio and television and to different levels of disaster management units down to the lowest level. The warning should be clear and concise to be understandable by communities and should use language that will not cause unnecessary panic. The warning may be in text or use diagrams and maps. It is necessary to conduct community awareness raising programmes to help people understand the warnings. In some countries, small inexpensive radios are distributed to the communities in risk areas so that they have access to warnings.

Disaster Management System

Even where there is accurate and timely issue of forecasts and warnings, flash flood damage can happen. A disaster management system should be well-prepared for such events. The disaster management system should have an overall vision of the crisis situation. It is the task of the system to alert key action groups, which is part of the response system.

Response System

A response system consists of actions by groups such as

- police and fire brigade (e.g., assisting vulnerable groups such as the elderly and the handicapped in flood-proofing their houses, evacuation procedures, and so on)
- civil protection authorities (e.g., dissemination of targeted information)
- voluntary groups (e.g., assisting the injured, allocating resources)
- military (e.g., preparing sandbags, constructing temporary structures)
- media (dissemination of information).

Monitoring, warning and response systems (MWRSs) can differ in complexity. The system can be a simple manual with a community-managed system, or an advanced, state-managed system with high automation. MWRSs can be local, national, or regional. Integrating MWRSs into relevant policies is emphasised by the Guiding Principles for Effective Early Warnings (IDNDR 1997; Annex 3). Several groups must contribute to ensure the effective functioning of a MWRS, beginning with **members of vulnerable populations**, who should be aware of the hazards. Local communities should be sufficiently familiar with the hazards to which they are exposed and understand the advisory information received. **National governments** should exercise their sovereign responsibility to prepare and issue hazard warnings for their national territory in a timely and effective manner. **Regional institutions** have a role to play when the hazard and the MWRS are of a regional nature. Such institutions should provide specialised knowledge, advice, or the benefit of experience in support of national efforts to develop or sustain operational capabilities related to hazard risks. **International bodies** should provide means for the sharing and exchange of data and relevant knowledge among themselves to ensure the development and operational capabilities of national authorities.

Four case studies

Case 1: Tsho Rolpa GLOF early warning system

Tsho Rolpa lake is located in the Rolwaling valley of Nepal at an elevation of 4500 masl. The lake is 3.5 km long and 0.5 km wide, and in 2002 occupied 1.76 km^2 surface area and contained 92.4 million m^3 water (Shrestha et al. 2004). The lake is considered one of the most dangerous glacial lakes in Nepal (Reynolds 1999). The Department of Hydrology and Meteorology, Government of Nepal, commissioned an early warning system (EWS) downstream of Tsho Rolpa lake. The system was designed and installed by BC Hydro International, Canada and Metero Communication Corp, USA. The major components of the system are described below.

GLOF sensing system: Six water-level sensors are installed immediately downstream of the lake outlet. The system monitors the outburst flood itself and provides warning downstream that an outburst has occurred. The sensing system is fully redundant to mitigate issuance of false alarm, and multiple sensor failures would have to occur before the system failed to detect an outburst.

Communication system: The signal of an outburst is relayed to the warning stations by the communication system. The warning system relies on extended line of sight very high frequency (VHF) radio technology. A second component of the communication system is the meteor burst communication system. A meteor burst system uses ionized trails of meteors to extend the range of the transmitted radio signals to over 1700 km. For this, a meteor burst master station is located in Dhangadi, western Nepal. The VHF and meteor burst system together are totally redundant to communications failure.

Figure 34: Automated early warning system for Tsho Rolpa, Nepal

GLOF warning system: The EWS consists of 19 warning stations located in 17 villages along the Rolwaling and Tamakoshi rivers (Figure 34). The warning stations consist of an audible horn operated by a charged air cylinder. The horn is activated as soon as the outburst signal is received by the station via the communication system. The 80 dB air horn is audible up to 150m away under the most adverse conditions. As a backup, an electric horn is also installed. The warning stations are powered by a 12 V battery charged by solar panels. The warning station also acts as a relay station for the VHF system, which relays the signals to downstream stations.

The Tsho Rolpa EWS is a highly sophisticated and reliable system. The system functioned satisfactorily for several years. Later, due to security problems, regular maintenance of the components became impossible. Local vandalism of equipment and burglary has left many of the warning stations out of function.

Case 2. Earlier stage of Tsho Rolpa early warning system

Prior to the establishment of the automated EWS, army camps were set up at the lake site and in the villages of Naa and Beding, the first two villages downstream of the lake. The army camps were equipped with HF radio transceivers and were in contact with their headquarters in Kathmandu twice daily to inform the Disaster Cell at the Ministry of Home Affairs of the status of the lake. In addition to the HF sets, the camps were equipped with two satellite phones. In the event of a GLOF from Tsho Rolpa, Radio Nepal, the national radio service, would broadcast a warning message. As the broadcast is received at most of the locations along the valley, the people would be warned of the GLOF. This arrangement was in place until the automatic EWS was established.

Case 3: Bhotekoshi early warning system

The Bhotekoshi EWS was commissioned by Bhotekoshi Power Company Pvt. Ltd. The system is analogous to the Tsho Rolpa EWS and was designed and installed by BC Hydro International, Canada, and Metero Communication Corp, USA, although the number of warning stations are significantly less than those in the Tsho Rolpa EWS. There have been three GLOF events in this river basin in the past (1935, 1969 and 1981), and there are 139 glacial lakes in the basin, of which nine are potentially dangerous (Mool et al. 2005). The EWS's six sensors (two sets of three) are located at the Friendship Bridge at the boundary between Nepal and China. There are two warning stations at the intake site and two at the power house site. One more warning station has been added at the village slightly downstream of the powerhouse. It has been estimated that the travel time for a GLOF from the Friendship Bridge to the intake site is five minutes.

Case 4. Community-based early warning system

Practical Action Nepal has established a community-based EWS in Chitwan, Nepal. The system consists of a watchtower equipped with an alarm (Figure 35). A watchman monitors the river water level during the rainy season and turns on the alarm when the water level crosses the critical flood level.

G. Gurung, Practical Action, Nepal

Figure 35: Community-based early warning system in Chitwan, Nepal

The mountain communities of Pakistan have an old tradition of flash flood warning by burning a fire at strategic locations, often hilltops (Iturrizaga 1997; 2005b; Xu et al. 2006). Shepherds herding sheep in high altitude pastures sensed the occurrence of flash floods much sooner than villagers located in the valley and could provide warnings. This system has disappeared due to the decline in traditional community organisations and the decline in sheep herding in those communities. In some communities, the fire signal has been replaced by modern communication systems such as telephones and mobile phones.

Chapter 6
Hazard-specific Flash Flood Management Measures

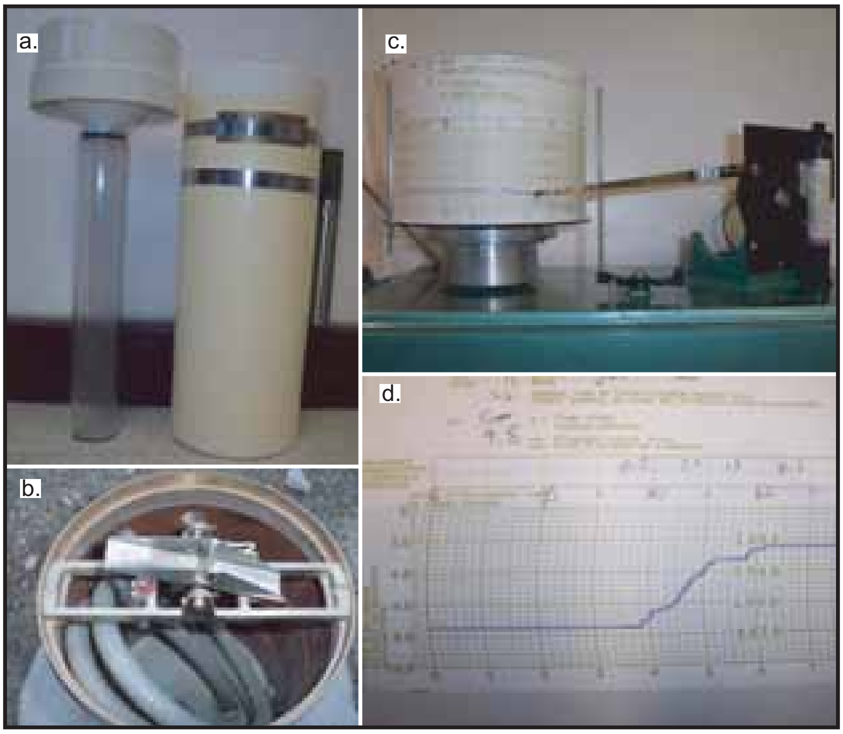
Chapter 5 outlined general, non-structural measures of risk management that are applicable to any type of flash flood. However, proper management of flash flood risks requires implementing some hazard-specific analytical tools and measures. This chapter provides some tools and measures specific to intense rainfall floods, landslide dam outburst floods, and glacial lake outburst floods.

6.1 Intense Rainfall Flood

Rainfall measurement

Rainfall is liquid water of a sufficient mass falling on the earth. It is one of the main sources of water supply. Other forms of precipitation include snow, hail, sleet, mist, dew, and fog. It is important to measure rainfall to forecast and prepare for flash floods. In the case of riverine floods, the total amount of rainfall over a period of time is important. The total amount of precipitation can be measured using simple rain gauges. The amount of rain collected in the gauge is measured at regular intervals to find the total amount of rainfall between two intervals. The measurement intervals can be hours, several hours, or a day. Generally, two measurements are taken, one in the morning and one in the evening. For flash floods, the total amount is less important than the intensity of rainfall, as even a short period of high-intensity rainfall measured in minutes can cause a flash flood. The intensity of rainfall cannot easily be determined by manual rain gauges (Figure 36a). Recording-type rain gauges such as a tipping bucket (Figure 36 b-d) or siphon-type guages are necessary. The recording-type gauges give a continuous record of rainfall and can be resolved into desired time intervals (Figure 36d).

A rain gauge gives a point measurement at that particular location. Intense rainfall is also spatially variable, particularly in mountainous terrain. A dense network of rain gauges is needed to get a reliable spatial representation of rainfall in a catchment. It is not always feasible to have such a network, particularly in the HKH region where resources are limited. It is important to identify key locations in the catchment that can provide important information for flash flood management.



Source: http://commons.wikipedia.org/wiki/User:CambridgeBayWeather (Accessed June 2007)

Figure 36: a. Manual rain gauge; b. tipping bucket of a semi-automatic rain gauge; c. recording chart inside a tipping bucket rain gauge; and d. detailed view of rainfall record made by a tipping bucket rain gauge

Catchment rainfall

For flash flood management measures such as forecasting or modelling, point data from rain gauges alone are not adequate. The data must be transformed into spatial data or area-average data for the catchment. There are several methods to calculate area average. The simplest is to calculate the arithmetic average of rainfall in each rain gauge. Table 9 shows an arithmetic average rainfall calculation for rainfall using nine rain gauges in the Jhikhu Khola watershed in Nepal (Figure 37). However, this method cannot capture spatial variability and is seldom used.

The other simple method is the Theissen polygon method, which uses a weighted average based on the assumption that a gauge best represents the rainfall in the area nearest it. The procedure consists of first locating the station on a map. Straight lines are then drawn on the map to connect each section. Perpendicular bisectors are drawn on each line, and the respective areas and weighing factors are defined. The resulting polygons represent the area closest to each gauge. Figure 38 shows the Theissen polygons prepared for the Jhikhu Khola catchment, and Table 10 the calculation of catchment mean rainfall using this method. The average rainfall derived from the Theissen polygon method is remarkably similar to the arithmetic average in this case, but generally these two methods give different results.

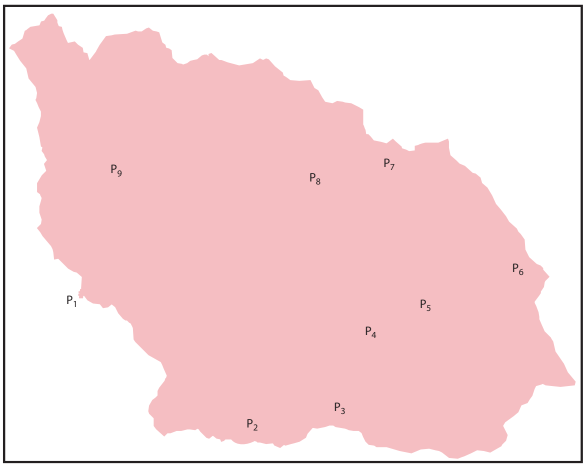


Figure 37: Map of Jhikhu Khola catchment, Nepal showing locations of rainfall stations

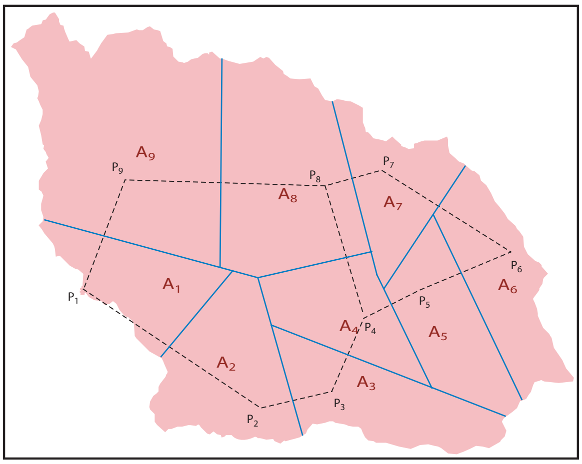


Figure 38: Map of Jhikhu Khola catchment showing the Theissen polygons

Table 9: Arithmetic mean method

Station	Rainfall (mm)
P1	14.4
P2	11.6
P3	9.8
P4	9.0
P5	12.2
P6	17.2
P7	18.6
P8	13.6
P9	14.8
Arithmetic Average	13.5

$$P_{av} = \frac{\sum P}{N}$$

Table 10: Theissen polygon method

Station	Rainfall (mm)	Polygon	Area (km²)	AxP
	P		A	
P1	14.4	A1	9.99	143.9
P2	11.6	A2	11.1	128.8
P3	9.8	A3	12.21	119.7
P4	9.0	A4	9.99	89.9
P5	12.2	A5	12.21	149.0
P6	17.2	A6	9.99	171.8
P7	18.6	A7	8.88	165.2
P8	13.6	A8	16.65	226.4
P9	14.8	A9	19.98	295.7
		Total (Σ)	111.0	1490.3

$$P = \frac{\sum (A \times P)}{\sum A} = \frac{1490.3}{111.0} = 13.4 \text{ mm}$$

A more accurate method for calculating catchment rainfall is the isohyetal method. In this method isohyets, or lines of equal rainfall, are drawn in the same way that contour lines are drawn on an elevation map. Various computer software provides sophisticated algorithms to generate isohyets. Some can incorporate terrain characteristics in generating the map. Further to the generation of isohyets, raster maps of rainfall distribution over an area can be generated. Raster maps represent continuous rainfall fields over the area of interest. Average rainfall at different spatial scales can be calculated from the raster map.

Figure 39a shows an isohyetal map of the Jhikhu Khola catchment based on the same rainfall data discussed above. The isohyetal map is used to generate the raster rainfall map (Figure 39b), which is further transposed over the sub-catchments to give the sub-catchment average rainfall (Figure 39c). Table 11 shows the catchment average rainfall calculated by this method. In this case, the method gives a significantly lower catchment average rainfall compared to the previous two methods.

Table 11: **Isohyetal method**

Sub-catchment	Sub-catchment precipitation (mm)	Area (km²)	AxP
	P	A	
A1	1.0	16.5	16.5
A2	4.0	5.9	23.5
A3	2.0	15.7	31.4
A4	7.0	12.2	85.3
A5	3.0	13.5	40.6
A6	10.0	2.8	28.4
A7	6.0	5.2	31.0
A8	9.0	11.7	104.9
A9	11.0	5.3	58.4
A10	8.0	7.7	61.6
A11	12.0	7.2	86.6
A12	13.0	7.2	94.2
	Σ	111.0	662.4

$$P = \frac{\sum (A \times P)}{\sum A} = \frac{662.4}{111.0} = 5.9 \text{ mm}$$

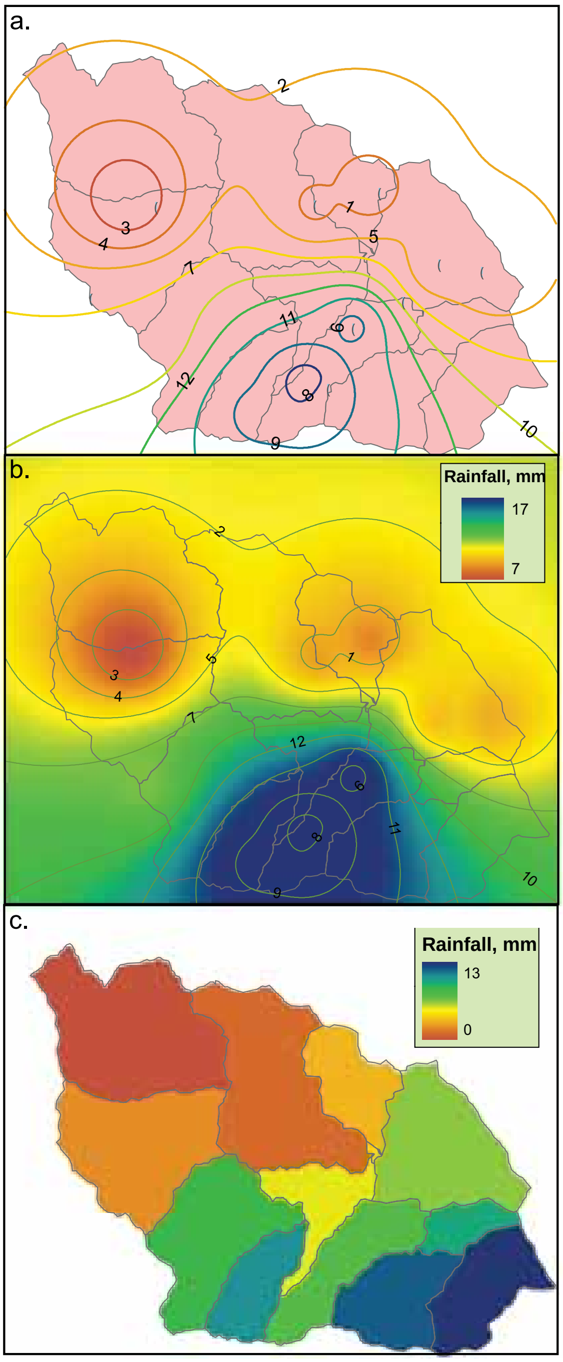


Figure 39: a. Isohyetal map; b. raster rainfall map; and c. sub-catchment average map

Runoff

The rainfall occurring in a catchment contributes to surface storage and soil moisture storage; part of the rainfall is lost by evaporation and transpiration. Only a part of the rainfall, known as excess rainfall or effective rainfall, contributes to the runoff from the catchment. After flowing across the catchment, excess rainfall becomes direct runoff at the catchment outlet. In order to estimate the flood generated by some amount of rainfall, the runoff generated by the rainfall must be calculated. Runoff from a catchment is affected by two major groups of factors: climatic factors and physiographic factors. Climatic factors exhibit seasonal variations in accordance with the climatic environment. Physiographic factors may be further classified into two kinds: basin and channel characteristics (Table 12).

Table 12: **Factors affecting catchment runoff**		
Climatic	**Physiographic**	
	Basin Characteristics	**Channel Characteristics**
Forms of precipitation (e.g., rain, snow, frost)	Geometric factors (size, shape, slope, orientation, elevation, stream density)	Carrying capacity (size and shape of cross section, slope, roughness, length, tributaries)
Types of precipitation (e.g., intensity, duration, aerial distribution)		
Interception (depends on vegetation species, composition, age and density of stands, season, storm size, and others)		
Evaporation (depends on temperature, wind, atmospheric pressure, nature and shape of catchment, and others)	Physical factors (land use and cover, surface infiltration condition, soil type, geological conditions such as permeability, topographic conditions such as lakes, swamps, artificial drainage, and so on)	Storage capacity (backwater effects)
Transpiration (e.g., temperature, solar-radiation, wind, humidity, soil moisture, type of vegetation)		
Source: Chow 1984		

Rational method

Many methods exist for estimating peak runoff rates, including several sophisticated computer models. Here we describe the so-called rational method[11], which is based on empirical and semi-empirical formulas. This formula is based on a number of assumptions and its simplicity has won it popularity. As the method was developed in the United States, the units are in the English system.

This rather simple model estimates peak runoff rates using the formula:

$$Q = C\,i\,A$$

Where:

Q = peak runoff rate in cubic feet per second (ft^3/s)
C = runoff coefficient
i = rainfall intensity in inches per hour
A = area in acres

The rationale of this method is that (1) units agree: 1 cfs = 1 in/hr x 1 acre, and (2) C (a dimensionless quantity) varies from 0 to 1 and can be thought of as the percentage of rainfall that becomes runoff.

Assumptions for the rational formula are related to the intensity term and to quantifying C. They include that:

1. rainfall occurs uniformly over the entire watershed
2. rainfall occurs with a uniform intensity for a duration equal to the time of concentration[12] for the watershed
3. the runoff coefficient C is dependent upon the physical characteristics of the watershed (e.g., soil type)

The values of C are given in Annex 4.

[11] The rational method is more suitable for small catchments.
[12] The time of concentration is the time it takes for the water to travel from the hydrologically most distant point in the catchment to the point of interest.

Rational method

Example:

Find peak runoff for a catchment with
Drainage area = 200 acres
Graded area = 120 acres
Woodland = 80 acres
Rainfall = 8.0 in/hr

Solution:

The total area of the catchment = 80+120 = 200 acres.

Use the weighted average method to calculate C.
Graded: 120 x 0.45 = 54
Woodland: 80 x 0.15 = 12
Average: 66/200 = 0.33

Q = CiA = 0.33x8.0x200 = 528 cfs.
= 15 m^3/s

The other popular method is the SCS curve number method developed by US Soil Conservation Service (now Natural Resources Conservation Service). This method predicts peak discharge for a 24-hour storm event, but can also be applied to shorter and longer duration storms.

These methods require a lot of data, often absent in remote mountain catchments. Peak flood estimation in remote catchments needs to be based on simple equations. Some of the widely-used equations are presented here.

WECS/DHM method

The Water and Energy Commission Secretariat (Department of Hydrology and Meteorology) method developed for catchments in Nepal (WECS/DHM 1990) is set out below.

Step 1: Determine the return period of the flood you want to consider (return period is discussed later in this chapter).

Step 2: Determine the standard deviation of the natural logarithms of annual floods (σ_{lnQF}) from the following equation:

$$\sigma_{\ln QF} = \frac{\ln(Q_{100}/Q_2)}{2.326}$$

Here Q_{100} and Q_2 are 100-year and 2-year return-period floods. These values can be determined using the following equations:

$$Q_{100} = 14.630\,(A_{<3000} + 1)^{0.7342}$$

$$Q_2 = 1.8767\,(A_{<3000} + 1)^{0.8783}$$

Where $A_{<3000}$ is the area of the catchment below 3000m elevation in km^2.

Step 3: Derive the standardised normal variate for a particular return period (S) from Table 13.

Step 4: Determine the peak flood discharge Q using the following equation:

$$Q = e^{(\ln Q_2 + S\sigma_{\ln QF})}$$

Although this method seems lengthy it is quite simple and the only datum required is the area in the catchment below 3000 masl elevation.

WECS/DHM method

Example:
Area of catchment is 300 km², of which area below 3000m is 200 km². Calculate the 50-year return period peak flood.

Solution:
Step 1: The return period, T= 50-years
Step 2:

$$Q_{100} = 14.630\,(200 + 1)^{0.7342}$$
$$= 718.2\ m^3/s$$
$$Q_2 = 1.8767\,(200 + 1)^{0.8783}$$
$$= 197.8\ m^3/s$$
$$\sigma_{\ln QF} = \ln(Q_{100}/Q_2)/2.326$$
$$= \ln(718.2/197)/2.326 = 0.556$$

Step 3: The value of S for T=50 from Table 13 is 2.054
Step 4: The peak flood discharge

$$Q = e^{(\ln Q_2 + S\sigma_{\ln QF})}$$
$$= e^{(\ln[197] + 2.054\ .\ 0.556)}$$
$$= 617.9\ m^3/s$$

There are several more complicated computer models available that can compute runoff and flood magnitude based on rainfall and other data. ICIMOD has developed a manual on rainfall-runoff modelling using the HEC HMS[13] model developed by the US Army Corps of Engineers, Hydrologic Engineering Centre (USACE/HEC), which is provided in Annex 5. The data[14] from the Jhikhu Khola watershed in Nepal, necessary for conducting the exercise is contained in the CD-ROM that accompanies this manual.

Discharge

The quantity of water flowing though a channel (natural or artificial) is known as discharge, sometimes also referred to as streamflow. Discharge is measured in m³/s in the metric system and sometimes denoted as cumecs. In the English system discharge is typically measured in ft³/s or cusecs. The discharge at a given location in the stream is a function of the process occurring in the watershed upstream of that location. In fact, the runoff generated in the upstream area determines the discharge at a particular location. The discharge and the nature of the channel (e.g., cross-section area, slope, roughness of the channel) determine the extent of flooding in the particular location. The graph representing discharge against time is called a discharge hydrograph or streamflow hydrograph. The hydrograph can be an annual hydrograph or an event hydrograph. Annual hydrographs plot discharge fluctuation over a year while event or storm hydrographs represent peak discharges during a particular storm event.

Table 13: **Values of standard normal variate for various return periods**

Return period, T (years)	Standard normal variate, S
2	0
5	0.842
10	1.282
20	1.645
50	2.054
100	2.326
200	2.576
500	2.878
1000	3.090
5000	3.540
10000	3.719

Source: WECS/DHM 1990

[13] HEC GeoHMS and HEC HMS are software produced by the Hydrologic Engineering Center, United States Army Corps of Engineers, USA. The software is freely available from the website: http://www.hec.usace.army.mil/software/.
[14] The data were collected by the People and Resource Dynamics Project (PARDYP), ICIMOD.

Rating curve

Although a hydrograph gives continuous discharge values, continuous measurement of discharge in the river is rarely carried out. Generally, the water level at the gauging site is recorded on a continuous basis using an automatic recorder or manual gauge reading. The water-level data are converted to discharge using a discharge: water level relationship known as a rating curve. A rating curve is developed for each gauging site using a set of discharge measurements (Figure 40).

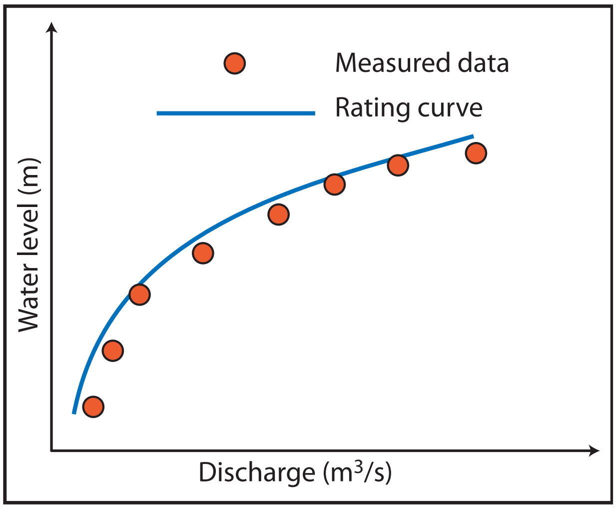


Figure 40: Rating curve

Measurement of discharge

There are many different methods for measuring discharge.

Velocity area method

The velocity area method is the most common method used. The cross-section of the river is divided into several vertical sections and the velocity of the water flow is measured at fixed depths in each section. A current meter is used to measure velocity. Generally, the velocity is measured at 0.2 and 0.8 of the river's depth. The velocity can be measured from a cable car, or if the depth is low, a wading technique can be used (Figure 41). The average of the two velocity measurements gives the average velocity of that section. The velocity of each section is multiplied by the area of the section, and the products for each section are summed to derive the discharge of the whole cross-section.

$$Q = \sum_{i=1}^{n} A_i \cdot V_i$$

Where Q = discharge
A = area of section i
V = velocity of section i

Float method

The velocity can also be calculated by a simpler method if the depth is shallow and high accuracy is not required. Two markers are fixed on the stream bank at the same distance upstream and downstream from the cross-section where discharge measurement is being conducted. The distance between the markers is measured and the cross-section area of the stream at the point of interest is measured. A floating object such as a cork or wooden block is released at the centre of the stream. The time when the float crosses the first and the second marker is noted.

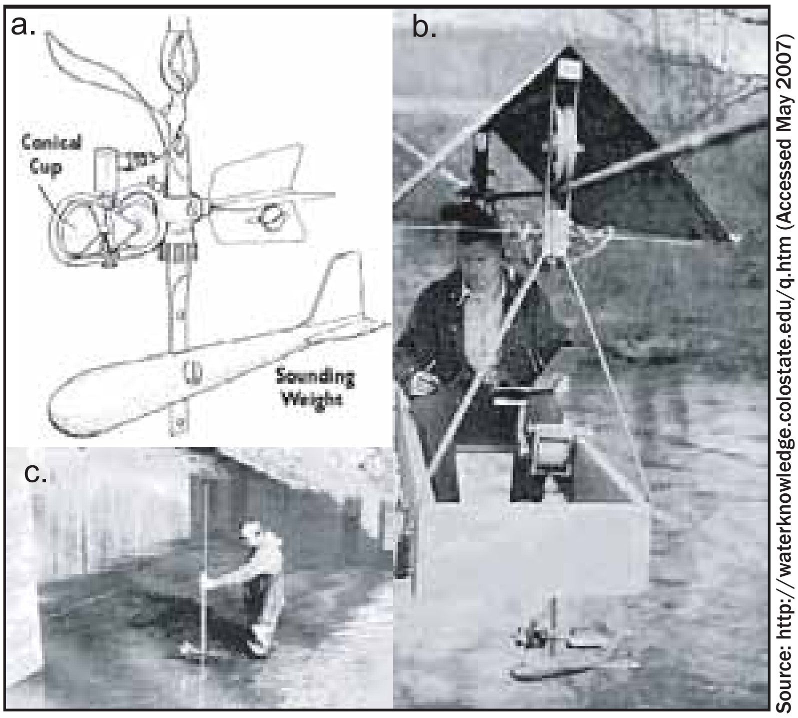


Figure 41: a. Current meter; b. velocity measurement from a cable car; and c. velocity measurement using the wading technique

The velocity of the river is given by:

$$v = \frac{d}{T_2 - T_1}$$

Where T_1 and T_2 are the times recorded at markers 1 and 2, respectively, and d is the distance between the two markers.

Such float measurements are conducted several times and the mean velocity, V_m is calculated.

The discharge at the cross-section of interest is given by:

$$Q = A \, . \, V_m$$

Where A is the cross-section area.

Dilution method

This method is particularly appropriate for mountainous streams where due to high gradient the turbulence is high and current-meter measurements are not possible. A tracer of known concentration is put in the upstream end of the specified reach and its concentration is monitored in the downstream reach. The distance should be adequate to ensure thorough mixing of the tracer in the water and there should not be an inlet, outflow, or stagnant water zone within the reach. The tracer can be common salt or a fluorescent dye, which is not readily adsorbed by the bed materials of the stream and the suspended sediment. The tracer can be injected into the stream instantaneously or in a continuous manner at a constant rate. For continuous injection a special apparatus called a Mariotte bottle is used (Figure 42a). The concentration at the downstream end is determined by collecting a water sample (Figure 42b) and analysing it using appropriate techniques. If a salt tracer is used, a conductivity meter is used to derive the concentration, while for a dye tracer, a fluorimeter is used (Figure 42c). The discharge Q can be calculated using following equation:

$$Q = q \cdot \frac{C_1 - C_2}{C_2 - C_0}$$

Where q is the injection rate of the tracer and C_1, C_2 and C_0 are the concentration of the tracer during injection, at the downstream end (sampling point), and in the background concentration of the stream water respectively. The method is described in detail in Merz (2007).

Slope area method

This method is particularly suitable for post-flood investigations to estimate the peak discharge of a flash flood after the flood has passed. This is an indirect method of obtaining discharge in streams, in which velocity is not measured but instead calculated using the Manning uniform flow equation. To compute velocity, the area, the wetted perimeter, the channel slope, and the roughness of the reach where the discharge is going to be determined must be known (Figure 43). The area, the perimeter, and the slope are measured and the roughness coefficient is estimated as accurately as possible. The Manning equation[15] is:

$$V = \frac{1}{n} \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}$$

Where, n is the Manning coefficient, R is the hydraulic radius, and S is the longitudinal slope (see Figure 43).

[15] This form of the Manning equation is only valid for metric units.

Figure 42: Discharge measurement using the dilution method: a. dye tracer injection using a Mariotte bottle; b. sample collection; and c. laboratory analysis of tracer concentration

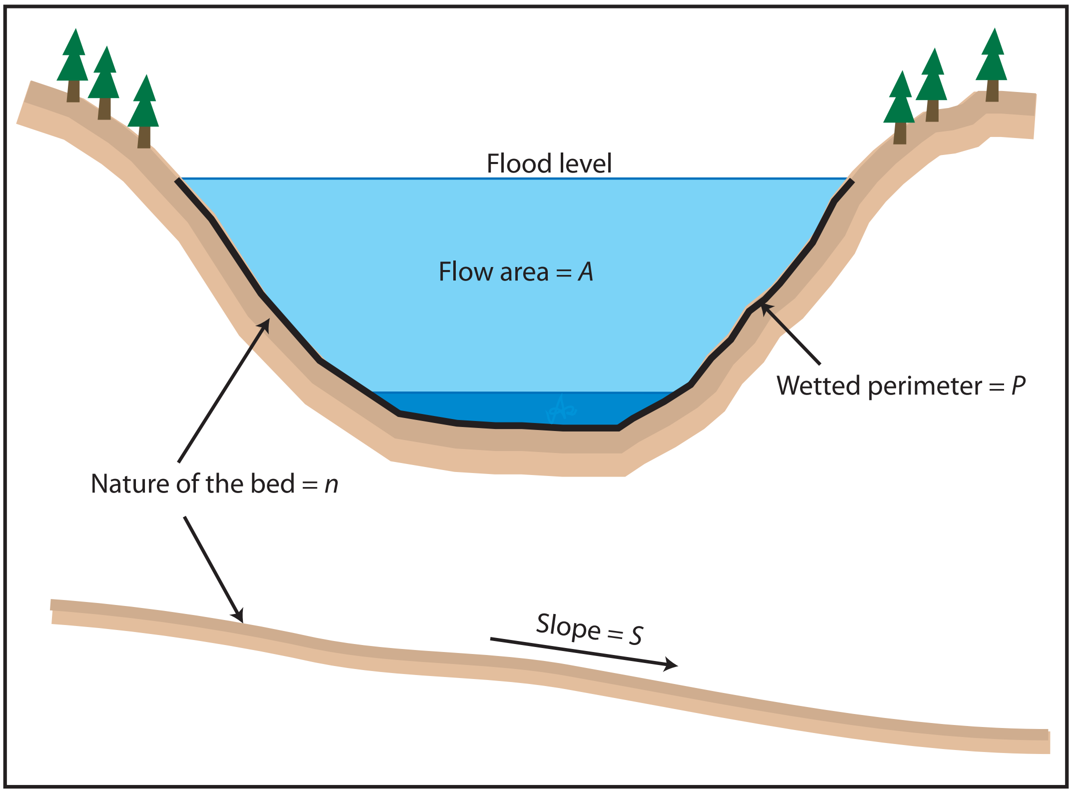


Figure 43: Slope area method

The steps for estimating discharge using the slope area method are as follows:

Step 1: A straight river with as uniform a slope, cross-section, and roughness as possible is selected.

Step 2: A detailed survey of the river reach is conducted and the Manning roughness coefficient, n, for the river reach estimated. The Manning coefficient can be taken from Table 14. The highest flood mark should also be recorded.

Step 3: The survey data are used to calculate the flow area A and determine the wetted perimeter P. The longitudinal slope also needs to be taken into account. The hydraulic radius, R, is calculated using:

$$R = \frac{A}{P}$$

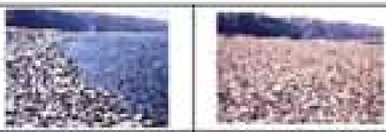
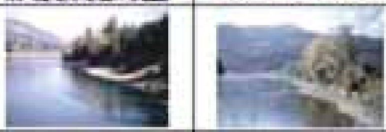
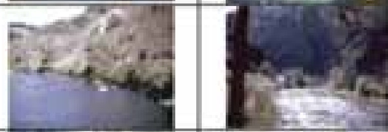
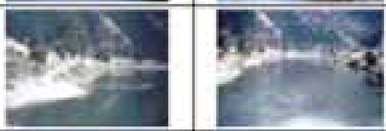
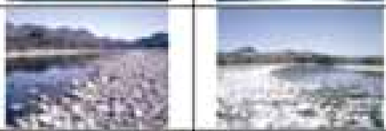
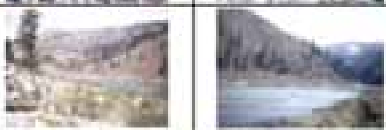
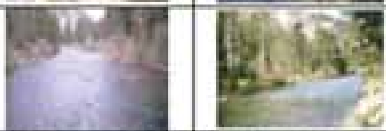
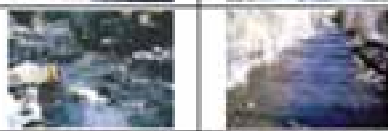
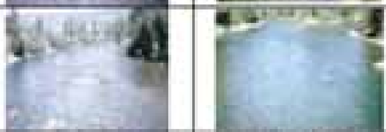
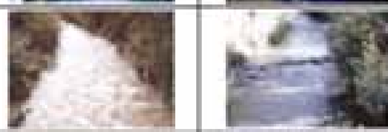
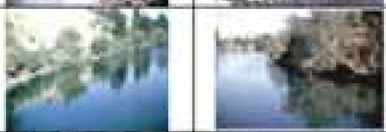
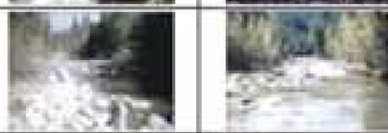
The values thus obtained are used to calculate the flow velocity during the flash flood using the Manning equation. Then the discharge, Q, is calculated from Q = A x V.

Flood routing

Flood routing is a procedure to determine the time and magnitude of flow at a point on a water course from a known or assumed flood at one or more points upstream. Methods to determine runoff from a catchment due to a rainfall event are described above. The runoff will produce a certain level of flooding at the outlet of the catchment. It is also necessary to understand the impact of such a flood at the locations of different communities and settlements downstream of the catchment outlet. Flood routing can provide such information; it is a highly technical procedure and several computer software programs are available to conduct complicated flood routing. Here we describe a simple method with examples.

The basic principle of flood routing is the continuity of flow expressed by the continuity equation. There are several methods of flood routing including modified plus, kinematic wave, Muskingum, Muskingum-Cunge, and dynamic (Chow et al. 1988). Here we limit our discussion to the Muskingum method, a commonly used hydrological flood routing method that models the storage volume of flooding in a stream channel by a combination of wedge and prism storage (Figure 44).

Table 14: **Table for estimation of Manning's coefficient, n**

Manning n-value	Typical appearance	Manning n-value	Typical appearance
0.024		0.043	
0.028		0.043	
0.030		0.045; 0.073	
0.032		0.050	
0.033		0.051	
0.036		0.053; 0.079	
0.037		0.057	
0.038		0.060	
0.038		0.065	
0.041		0.073	
0.043		0.075	

Source: USGS (http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/indirects/nvalues/ Accessed May 2007)

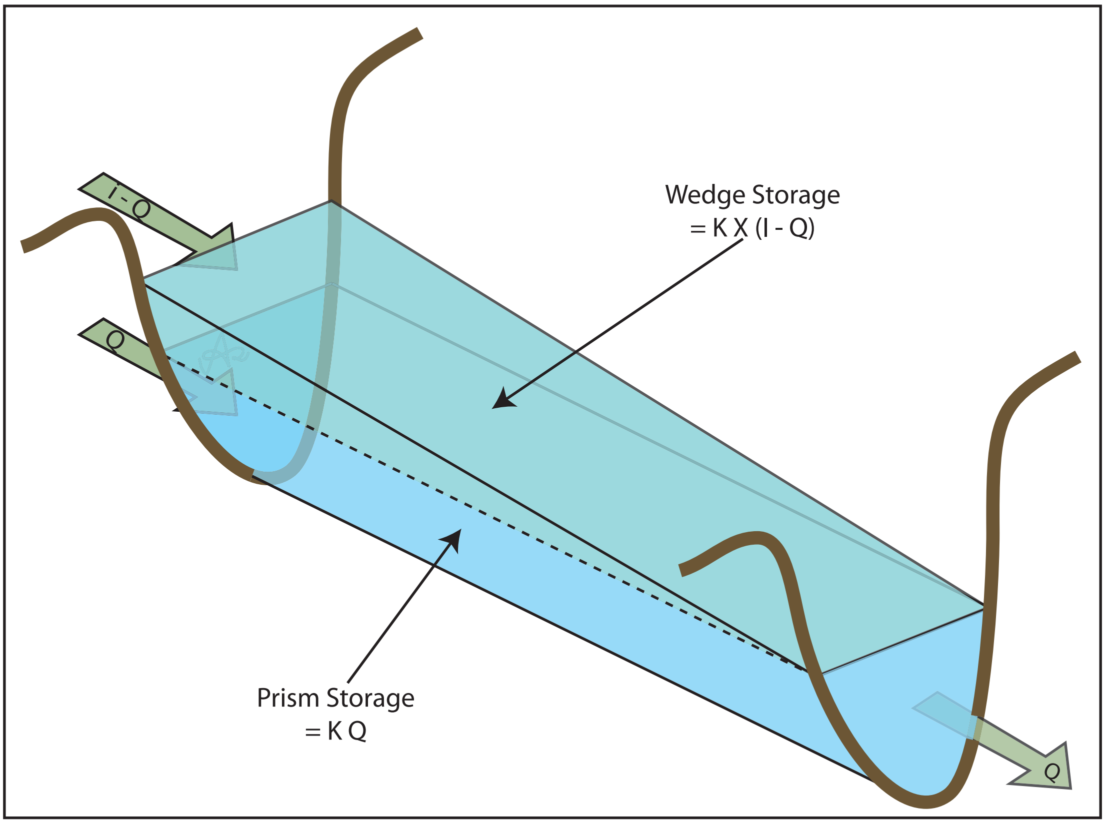


Figure 44: Prism and wedge storage in a channel reach

During the advance of a flood wave, inflow exceeds outflow, producing a wedge of storage. During the recession of a flood, outflow exceeds inflow, producing a negative wedge shape. In addition, there is a prism of storage which is formed by a volume of constant cross-section along the length of a prismatic channel.

The prism storage $S_p = K\,Q$

Where K is the proportionality coefficient and Q is the constant discharge equal to the outflow at the beginning.

The wedge storage $S_w = K\,(I - Q)\,X$

Where I is the total inflow due to flood and X is a weighting factor with a range of $0 \leq X \leq 0.5$.
The total storage $S = S_p + S_w = KQ + K\,(I - Q)\,X = K[X\,I + (1\text{-}X)\,Q]$.

The storage at times j and j +1 can be written as:

$S_j = K\,[X\,I_j + (1 - X)\,Q_j]$ and

$S_{j+1} = K\,[X\,I_{j+1} + (1 - X)\,Q_{j+1}]$

The difference in storage between these times is

$S_{j+1} - S_j = K\{[X\,I_{j+1} + (1 - X)\,Q_{j+1}] - [X\,I_j + (1 - X)\,Q_j]\}$.

The change in storage is also given by the following equation:

$$S_{j+1} - S_j = \frac{(I_j + I_{j+1})}{2}\Delta t - \frac{(Q_j + Q_{j+1})}{2}\Delta t$$

Combining the two equations we get the routing equation of the Muskingum method:

$$Q_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 Q_j$$

Where

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t}$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t}$$

Note that $C_1+C_2+C_3 = 1$.

In the Muskingum method, K and X are determined graphically from the hydrograph, while in the Musking-Cunge method they can be determined using the following equations:

$$K = \frac{\Delta x}{c_k} \text{ and } X = \frac{1}{2}\left(1 - \frac{Q_{max}}{BS_0 c_k \Delta x}\right)$$

Where C_k is celerity, and B is the width of the water surface.

The method becomes much clearer from the following exercise:

Exercise on flood routing

Example:
The hydrograph at the upstream end of a river is given in the following table. The reach of interest is 18 km long. Using a subreach length Δx of 6km, determine the hydrograph at the end of the reach using the Muskingum-Cunge method. Assume c_k = 2m/s, B = 25.3m, S_0 = 0.001m, and no lateral flow.

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12
Flow (m^3/s)	10	12	18	28.5	50	78	107	134.5	147	150	146	129	105
Time (hr)	13	14	15	16	17	18	19	20	21	22	23	24	
Flow (m^3/s)	78	59	45	33	24	17	12	10	10	10	10	10	

Solution:
Step 1: Determine K

$$K = \frac{\Delta x}{c_k} = \frac{6000}{2} = 3000 \text{ sec}$$

Step 2: Determine X

$$X = \frac{1}{2}\left(1 - \frac{Q_{max}}{BS_0 c_k \Delta x}\right) = \frac{1}{2}\left(1 - \frac{150}{(25.3)(0.001)(2)(6000)}\right) = 0.253$$

Step 3: Determine C_1, C_2 and C_3

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} = \frac{3600 - (2)(3000)(0.253)}{(2)(3000)(1-0.253) + 3600} = 0.26$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} = \frac{3600 + (2)(3000)(0.253)}{(2)(3000)(1-0.253) + 3600} = 0.633$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t} = \frac{(2)(3000)(1-0.253) - 3600}{(2)(3000)(1-0.253) + 3600} = 0.109$$

Here Δt is 1 hour = 3600 sec. If we want our hydrograph to show a 2-hour interval, then we must take Δt = 7200 sec, and so on.

Step 4: Calculate discharge at 6, 12, and 18 km distances.

The results of the calculation are shown in Table 15. The initial flow at 0 hours is taken as 10 m^3/s at all three locations.

The initial flow at 6 km at 0 hours (Q_0^{6km}) is 10 m^3/s.

The flow at 1 hour at 6 km distance (Q_1^{6km} value in blue) is given by

$$Q_1^{6km} = C_1 Q_0^{0km} + C_2 Q_1^{0km} + C_3 Q_0^{6km} = (0.26)(10) + (0.6333)(12) + (0.109)(10) = 11.3\ m^3/s$$

Similarly, the flow at 2 hours at 6 km distance (Q_2^{6km} value in red) is given by

$$Q_2^{6km} = C_1 Q_1^{0km} + C_2 Q_1^{0km} + C_3 Q_1^{6km} = (0.26)(12) + (0.633)(18.0) + (0.109)(18) = 15.7\ m^3/s$$

The calculations can be carried out in a similar manner for the remaining part of the hydrograph at 6 km distance for the remaining times in the table.

The flow at 1 hour at 12 km distance (Q_2^{6km} value in green) is given by

$$Q_1^{12km} = C_1 Q_0^{6km} + C_2 Q_1^{6km} + C_3 Q_0^{12km} = (0.26)(10) + (0.633)(10.9) + (0.109)(10) = 10.8\ m^3/s$$

The calculation can be carried out in a similar way for the remaining part of the hydrographs at 12 and 18km distance (Table 15). The flood hydrographs at all four locations clearly show how the peak discharge decreases and the hydrograph stretches with distance (Figure 45).

Flood frequency

Floods are a recurring phenomena. Small floods occur more frequently and large floods less frequently. Floods at a certain location can be defined by different probability functions. One of the simplest probability functions used to define flood intensity is the return period (T). Return period, also known as a recurrence interval, is an estimate of the likelihood of occurrence of events like flood or river discharge flow of a certain intensity or size. It is a statistical measurement denoting the average recurrence interval over an extended period of time. Return period is an important parameter, and is usually required for risk analysis. Return period can be determined using the following equation:

$$T = \frac{n+1}{m}$$

Where n is the number of years on record, and m is the rank of the flood being considered (in terms of the flood size in m^3/s).

Table 15: **Calculation of flow values at different times and locations**				
	Flow (m³/s)			
Time (hr)	**0 km**	**6 km**	**12 km**	**18 km**
0	10.0	10.0	10.0	10.0
1	12.0	11.3	10.8	10.5
2	18.0	15.7	14.1	12.9
3	28.5	24.4	21.1	18.4
4	50.0	41.7	35.1	29.7
5	78.0	66.9	57.0	48.5
6	107.0	95.3	83.9	73.2
7	134.5	123.3	112.0	100.7
8	147.0	141.5	133.8	124.8
9	150.0	148.6	145.4	140.5
10	146.0	147.6	147.9	146.8
11	129.0	135.7	140.4	143.3
12	105.0	114.8	123.3	130.1
13	78.0	89.2	99.7	109.4
14	59.0	67.3	76.7	86.4
15	45.0	51.2	58.3	66.2
16	33.0	38.2	43.8	50.1
17	24.0	27.9	32.4	37.3
18	17.0	20.0	23.5	27.4
19	12.0	14.2	16.8	19.7
20	10.0	11.0	12.5	14.4
21	10.0	10.1	10.6	11.5
22	10.0	10.0	10.1	10.4
23	10.0	10.0	10.1	10.1
24	10.0	10.0	10.0	10.1

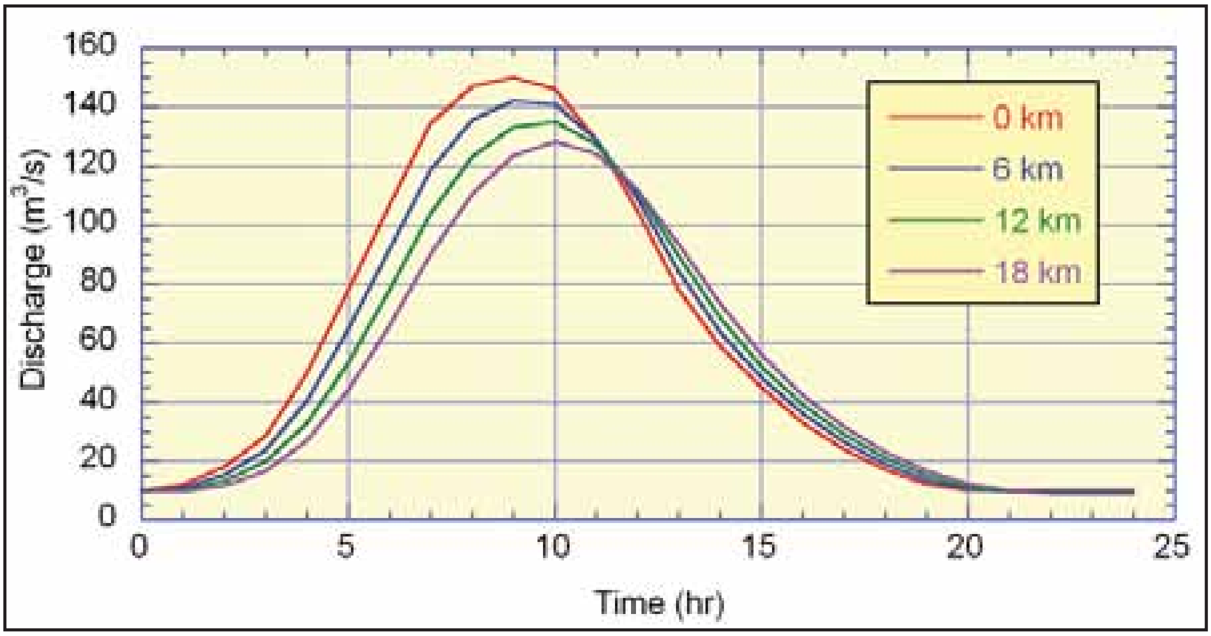


Figure 45: Hydrographs at different locations

Calculation of return period is explained by the following example based on the data given in Table 16.

Step 1: The discharge data is arranged in ascending order as in column 2 of Table 17.
Step 2: Rank the discharge data as in column 3 of Table 17.
Step 3: Determine the return periods from the equation given above.

Table16: **Annual maximum one-day flood data**

Year	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953
Discharge (m^3/s)	14.57	8.44	14.00	22.62	4.82	29.30	24.20	12.45	7.28	6.23	18.30	9.68	6.48	3.68	11.43
Year	**1954**	**1955**	**1956**	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**
discharge (m^3/s)	21.24	8.50	9.72	5.81	19.65	37.30	7.22	20.86	18.70	7.65	6.09	4.39	10.34	12.88	42.50

Table 17: **Calculation of return period**

Year	Annual maximum 1-day flood ($x1000\ m^3/s$)	Rank of the flood	Return Period
	Q	m	T
1952	3.68	1	31.00
1965	4.39	2	15.50
1943	4.82	3	10.33
1957	5.81	4	7.75
1964	6.09	5	6.20
1948	6.23	6	5.17
1951	6.48	7	4.43
1960	7.22	8	3.88
1947	7.28	9	3.44
1963	7.65	10	3.10
1940	8.44	11	2.82
1955	8.50	12	2.58
1950	9.68	13	2.38
1956	9.72	14	2.21
1966	10.34	15	2.07
1953	11.43	16	1.94
1946	12.45	17	1.82
1967	12.88	18	1.72
1941	14.00	19	1.63
1939	14.57	20	1.55
1949	18.30	21	1.48
1962	18.70	22	1.41
1958	19.65	23	1.35
1961	20.86	24	1.29
1954	21.24	25	1.24
1942	22.62	26	1.19
1945	24.20	27	1.15
1944	29.30	28	1.11
1959	37.30	29	1.07
1968	42.50	30	1.03
$\Sigma Q = 426.27$ $n = 30$			

The return period is important in relating extreme discharge to average discharge. The return period has an inverse relationship with the probability (P) that the event will be exceeded in any one year. For example, a 10-year flood has a 0.1 or 10% chance of being exceeded in any one year and a 50-year flood has a 0.02 (2%) chance of being exceeded in any one year.

It is commonly assumed that a 10-year flood will occur, on average, once every 10 years and that a 100-year flood is so large that we expect it to occur only once every 100 years. While this may be statistically true over thousands of years, it is incorrect to think of the return period in this way. The term 'return period' is actually a misnomer. It does not necessarily mean that the design storm of a 10-year return period will return every 10 years. It could, in fact, never occur, or occur twice in a single year. It is still considered a 10-year storm.

Return period is useful for risk analysis (such as natural, inherent, or hydrological risk of failure). When dealing with structural design expectations, the return period is useful in calculating the risk to the structure with respect to a given storm return period given the expected design life. The equation for assessing this risk can be expressed as

$$\bar{R} = 1 - (1 - \frac{1}{T})^n = 1 - (1 - P(X \geq x_T))^n$$

Where $\frac{1}{T} = P(X \geq x_T)$ expresses the probability of the occurrence for the hydrological event in question, and n is the expected life of the structure.

6.2 Landslide Dam Outburst Flood

Understanding the process

Landslides usually occur as secondary effects of heavy storms, earthquakes, and volcanic eruptions. Bedrock or soil (earth and organic matter debris) are the two classes of materials that compose landslides. A landslide may be classified by its type of movement, as shown in Figure 46.

Falls: A fall is a mass of rock or other material that moves downward by falling or bouncing through the air. These are most common along steep road or railroad embankments, steep escarpments, or undercut cliffs (especially in coastal areas). Large individual boulders can cause significant damage. Depending on the type of materials involved, it may be rockfall, earthfall, debris fall, and so on.

Topple: A topple occurs due to overturning forces that cause a rotation of the rock out of its original position. The rock section may have settled at a precarious angle, balancing itself on a pivotal point from which it tilts or rotates forward. A topple may not involve much movement, and does not necessarily trigger a rockfall or rock slide.

Slides: Slides result from shear failure (slippage) along one or several surfaces; the slide material may remain intact or break up. The two major types of slides are **rotational** and **translational** slides. Rotational slides occur on slopes of homogeneous clay of shale and soil slopes, while translational slides are mass movements on a more or less plane surface.

Lateral spreads: A lateral spread occurs when large blocks of soil spread out horizontally after fracturing off the original base. Lateral spreads generally occur on gentle slopes of less than 6%, and typically spread 3m to 5m, but may move from 30m to 50m where conditions are favourable. Lateral spreads usually break up internally and form numerous fissures and scarps. The process can be caused by liquefaction whereby saturated, loose sand or silt assumes a liquefied state. This is usually triggered by ground shaking, as with an earthquake. During the 1964 Alaskan earthquake, more than 200 bridges were damaged or destroyed by lateral spreading of flood plain deposits near river channels.

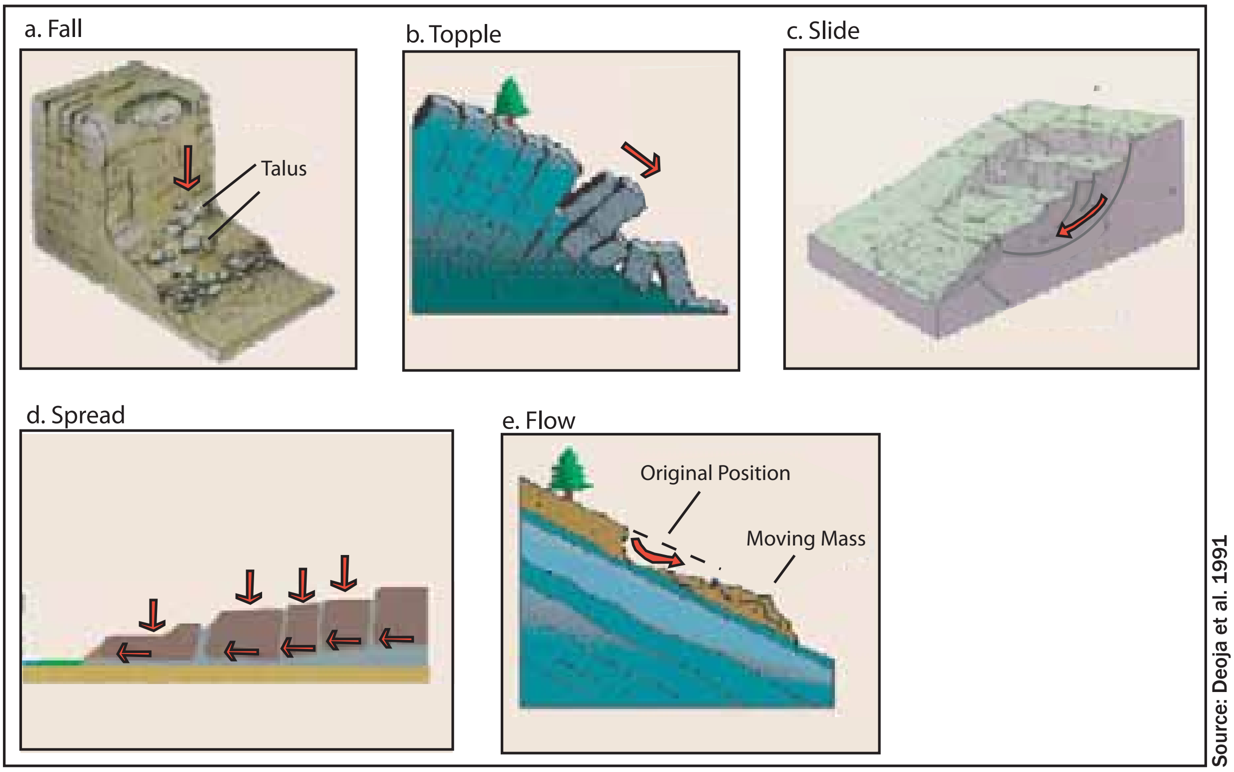


Figure 46: Types of landslides

Flows: Flows move like a viscous fluid, sometimes very rapidly, and can cover several miles. Water is not essential for flows to occur, although most flows form after periods of heavy rainfall. A mudflow contains at least 50% sand, silt, and clay particles. A lahar is a mudflow that originates on the slope of a volcano and may be triggered by rainfall, sudden melting of snow or glaciers, or water flowing from crater lakes. A debris flow is a slurry of soils, rocks, and organic matter combined with air and water. Debris flows usually occur on steep gullies. Very slow, almost imperceptible, flow of soil and bedrock is called creep. Flows can be creep, debris flow, debris avalanche, earth flows, or mud flows.

Where landslides can dam a river

Both natural and anthropogenic factors can initiate dam-forming landslides. The most important natural processes in initiating dam-forming landslides are excessive precipitation (rainfall and snowmelt) and earthquakes (Figure 47).

Figure 47 shows that globally about 50% of dam-forming landslides are caused by rainstorms and snowmelt, about 40% by earthquakes, and only 10% by other factors. As volcanic eruptions are rare in the HKH region, the percentage of landslides causing dam formation due to rainfall, snowmelt, and earthquakes is higher.

Landslide dams form most frequently where narrow steep valleys are bordered by high rugged mountains (Table 18). This setting is common in geologically active areas where earthquakes and glacially steepened slopes occur, which is typical of the HKH region. These areas contain abundant landslide source materials, such as sheared and fractured bed materials, and experience triggering mechanisms which initiate landslides. Steep, narrow valleys require a relatively small volume of material to form dams; thus, even small mass movements present a potential for formation of landslide dams. Such dams are much less common in broad, open valleys. Most landslide dams are caused by falls, slides, and flows. Large landslide dams are often caused by complex landslides that start as slumps of slides and transform into rock or debris avalanches.

Modes of failure of landslide dams

A landslide dam in its natural state differs from a constructed dam in that it is made up of a heterogeneous mass of unconsolidated or poorly consolidated material and has no proper drainage system to prevent piping

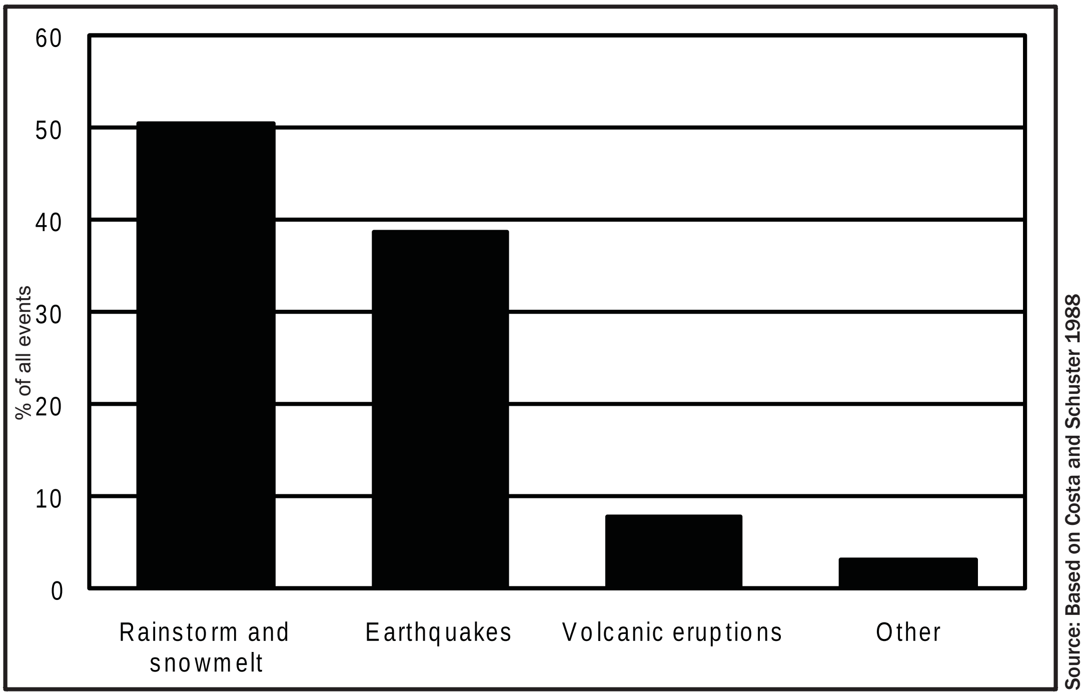


Figure 47: Causes of landslides that have formed dams

Table 18: **Factors causing dam forming landslides**

Natural	Anthropogenic
High relief	Deforestation
Undercutting of river banks	Improper landuse
Weak geology	- agriculture on steep slopes
High weathering	- irrigation of steep slopes
Intensive rainfall	- overgrazing
High snowmelt	- quarrying
Poor sub-surface drainage	Construction activities
Seismic activities	

and control pore pressures. It also has no channelised spillway or other protected outlets; as a result, landslide dams commonly fail by overtopping, followed by breaching following erosion by the overflow water. In most documented cases, the breach has resulted from fluvial erosion of the landslide material, with headcutting originating at the toe of the dam and progressively moving upstream to the lake. When the headcut reaches the lake, breaching occurs. The breach commonly does not erode down to the original river level as many landslide dams contain some coarse material that armours the streambed locally. Smaller lakes can thus remain after dam failure.

Because landslide dams do not undergo systematic compaction, significant porosity and seepage through the dam can cause piping, which can lead to internal structural failure, although failure due to piping and seepage are quite rare compared to failure due to overtopping (Figure 48). In some cases piping and undermining of the dam can cause partial collapse of the dam, followed by overtopping and breaching.

A landslide dam with steep upstream and downstream faces and with high pore-water pressure is susceptible to slope failure. If the dam has a narrow cross-section or the slope failure is progressive, the crest may fail, leading to overtopping and breaching. Nearly all faces of landslide dams are at the angle of repose of the material or less; however, because they are formed dynamically, slope failures are rare. A special type of slope failure involves lateral erosion of the dam by a stream or river.

Main triggers of landslides

Rainfall-induced landslides

Rainfall is an important landslide trigger. There is a direct correlation between the amount of rainfall and the incidence of landslides.

- Cumulative rainfall between 50-100 mm in one day and daily rainfall exceeding 50 mm can cause small-scale and shallow debris landslides.
- Cumulative two-day rainfall of about 150 mm, and daily rainfall of about 100 mm, have a tendency to increase the number of landslides.
- Cumulative two-day rainfall exceeding 250 mm, or an average intensity of more than 8 mm per hour in one day, rapidly increases the number of large landslides.

Earthquake-induced landslides

Earthquakes can cause many large-scale, dam-forming landslides. Seismic accelerations, duration of shock, focal depth, and angle and approach of seismic waves all play a role in inducing landslides, but environmental factors such as geology and landforms play the most important role. This is why small earthquakes can sometimes induce more landslides than large earthquakes.

The type of slope and the slope angle have a great influence upon landslides. Landslides rarely occur on slopes less than 25°. The large majority of landslides occur on slopes with angles ranging from 30° to 50°.

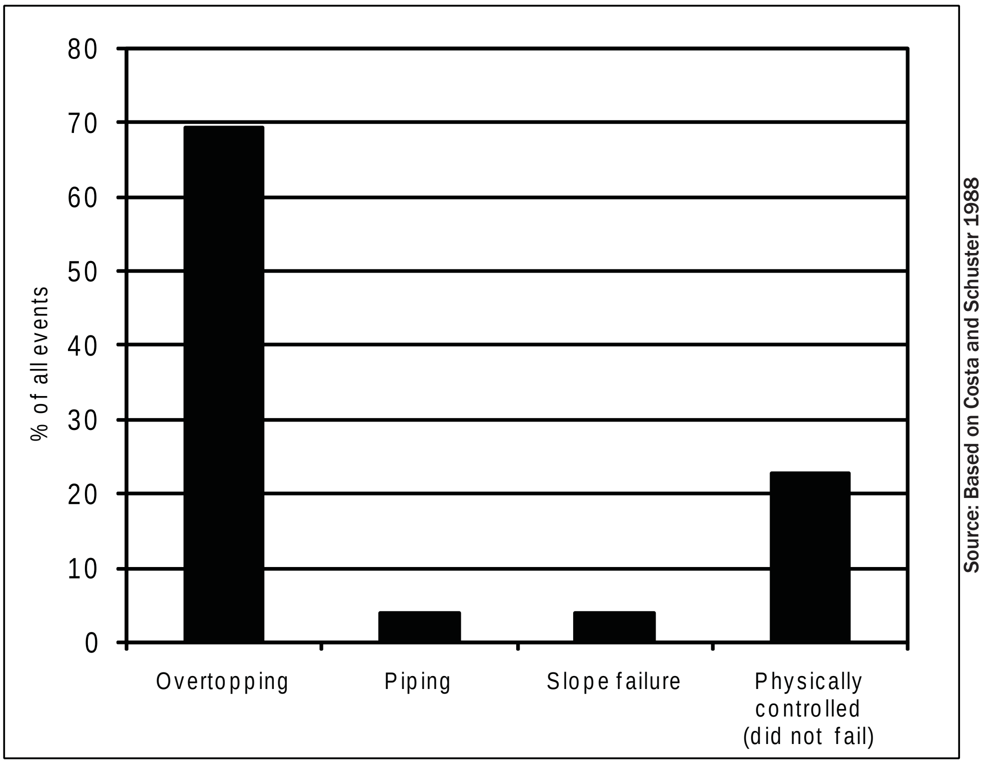


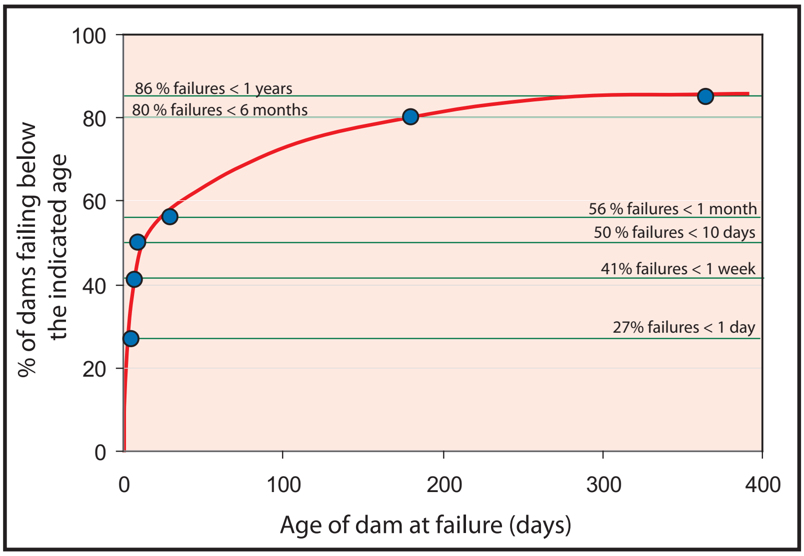
Figure 48: Modes of failure of landslide dams

Longevity of landslide dams

Landslide-dammed lakes may last for several minutes or several thousands of years, depending on many factors, including volume, size, shape, sorting of blockage material, rates of seepage, and so on. External factors can also determine the longevity of landslide dams. For example, high stream inflow, intensive rainfall, or rockfall into the lake can cause rapid collapse of the dam.

There is very little time for action in the case of landslide dam formation. About 40% of landslide dams fail within a week of formation, and 80% fail within 6 months (Figure 49). It is clear that in the majority of cases there is not much time to mitigate the effects of dam failure unless a good local disaster management plan is in place.

Three factors govern the longevity of landslide dams: 1) rate of inflow to the impoundment; 2) size and shape of the dam; and 3) geophysical characteristics of the dam. The life of a dam can be shortened significantly due to the external factors mentioned above. The inflow rate is generally proportional to the upstream catchment area and is significantly greater during monsoon seasons. Landslide dams of predominantly soft, low-density, fine-grained, or easily liquified sediment lack resistance to erosion and are more susceptible to failure. Landslide dams comprised of larger and cohesive material are more resistant to failure. Poorly sorted materials with d_{15}/d_{85} ratios greater than 5 are susceptible to internal erosion by piping (Sherard 1979).



Source: Based on Costa and Schuster 1988

Figure 49: Length of time before failure of landslide dams (based on 73 case studies)

Measures to minimise the risk of LDOF

Control measures, such as the construction of spillways to drain the ponded water, have been attempted in various places around the world. Sometimes these measures have been successful in preventing an LDOF, in others overtopping has occurred before satisfactory control measures could be constructed. In some cases, the attempts themselves triggered floods that caused large-scale casualities. Here we focus on non-structural measures to mitigate LDOFs.

Landslide hazard assessment

The first approach in LDOF mitigation is to identify places where the hazard can occur. This can be accomplished by preparing a landslide hazard map. If a landslide can occur in a narrow valley close to a stream, it could potentially cause a lake-forming dam. Additional analysis may provide an estimate of the volume of the dam, which together with the stream inflow rate can give an indication of the rate of lake level rise.

Hazard and risk mapping is done using 1) a simple qualitative method, which is based on experience and uses an applied geomorphic approach to determine parameters and their weightings, and scores and overlays of parameter maps for pre-feasibility level; 2) a statistical method score for the different parameters determined based on bi-variate and multivariate statistical analysis; 3) a deterministic method based on the properties of materials; and 4) social mapping using information derived from discussions with local people based on their experiences and feelings.

The hazard may be classified as relative (assigning ratings to different factors contributing to hazard), absolute (deterministically derived, e.g., factor of safety), or monitored (actual measurement of effects, e.g., deformation along roads, rocks, and so on).

Relative hazard assessment generally follows these steps

- determination of different factors contributing to slope instability
- development of a rating scheme and scores for hazard probability
- identification of elements at risk and their quantification
- development of a rating scheme and scores for damage potential
- construction of a hazard and risk matrix
- mapping of hazard and risk

Estimation of downstream flooding

Informed estimates about the magnitude of a potential flood are necessary in order to implement mitigation measures in areas downstream of the landslide-dammed lake. This can be done through techniques involving varying degrees of complexity. As, in most cases, the time between the dam formation and outburst is so short, a detailed analysis may not be possible and estimates will have to rely on simple techniques. Costa and Schuster (1988) suggested the following regression equation to estimate peak discharge of a LDOF:

$$Q = 0.0158P_e^{0.41}$$

Where Q is peak discharge in cubic metres per second, and P_e is the potential energy in joules.

P_e is the potential energy of the lake water behind the dam prior to failure and can be calculated using the following equation:

$$P_e = H_d \times V \times \gamma$$

Where H_d is the height of the dam in metres, V is the volume of the stored water, and γ is the specific weight of water (9810 Newton/m^3).

Mizuyama et al. (2006) suggest the following equation for calculating peak discharge:

$$Q = 0.542 \left\{ \frac{(gh^3)^{0.5}}{\tan\theta \cdot q_{in}} \cdot 10^3 \right\}^{0.565} \cdot \frac{q_{in} \cdot B}{10^6}$$

Where Q is the peak discharge in m^3/s; q_{in} the inflow into the lake in cm^3/s; g the gravitation acceleration (about 9.8 m/s^2); h the dam height in metres; and θ the stream-bed gradient.

Figure 50 shows a schematic diagram of the input parameters and an example of calculating peak outflow is given below. The two methods give entirely different results as they include different parameters, the second method including more parameters than the first.

Sophisticated computer models are available to estimate the peak outflow of the LDOF and to route the flood along the river reach downstream of the lake. This will give the area and level of flooding, and can help in making decisions regarding relocating people or implementing structural mitigation measures.

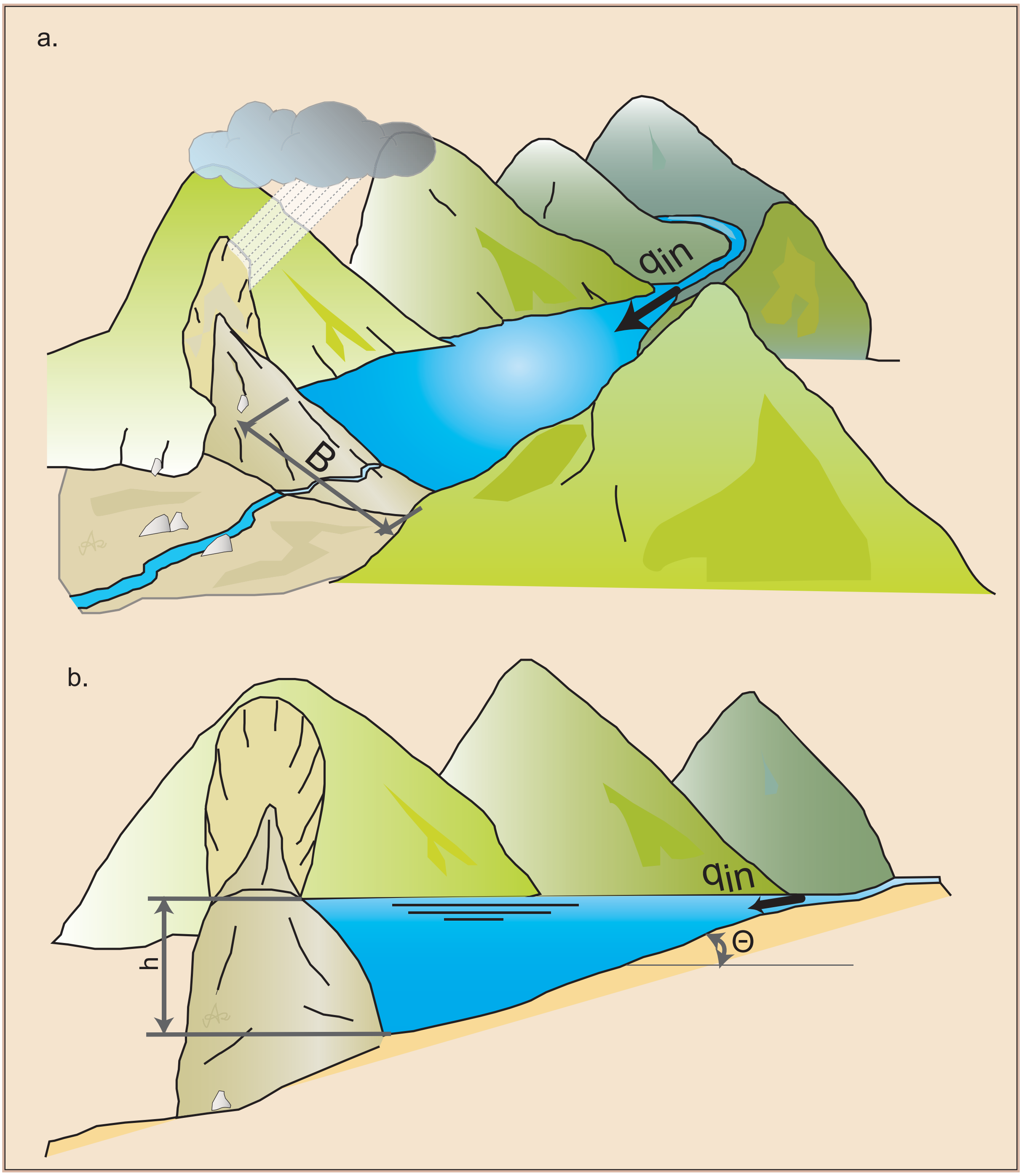


Figure 50: A schematic diagram showing the parameters used in calculating peak outflow discharge: a. isometric view; and b. cross-section.

Estimation of past floods

Estimation of past floods provides an idea of the magnitude of floods that are likely to affect a location. The slope-area method for estimating the magnitude of past floods is described above. Paleohydraulic reconstruction techniques can also provide estimates of past floods. These techniques reconstruct the velocity of the flow, depth, and width of the channel during the flood based on the size of boulders deposited by the flood. Details are given in Costa (1983). These estimates provide a basis for identifying the magnitude of a past flood and for assessing potential future hazard and risk.

Example of LDOF peak outflow calculation

Let us assume the following input parameters
H = 50m; B = 200m; θ = 5°

First we derive the volume of the lake:
V = ½ h x B x L

Where l = h/tan 5° = 50/0.087 = 574m

V = 0.5 x 50m x 200m x 574m = 2,870,000 m^3

$P_e = H_d \times V \times \gamma$, $P_e = 50 \times 2{,}870{,}000 \times 9810$
$= 14 \times 10^{11}$

Substituting into equation $Q = 0.0158\, p_e^{0.41}$

$Q = 0.0158 \times (14 \times 10^{11})^{0.41} = 1511.9\ m^3/s$

Now let us apply equation by Mizuyama to calculate the peak discharge.

Let us assume the inflow q_{in} is 50 m^3/s or 50 x 10^6 cm^3/s

$$Q = 0.542 \left\{ \frac{(9.81 \cdot 50^3)^{0.5}}{\tan 5 \cdot (50 \cdot 10^6)} \cdot 10^3 \right\}^{0.565} \cdot \frac{(50 \cdot 10^6) \cdot 200}{10^6}$$

$$= 0.542 \left\{ \frac{1107.36}{4374433.17} \cdot 10^3 \right\}^{0.565} \cdot 10000$$

$= 0.542 \times 0.46 \times 10000$

$= 2494\ m^3/s$

The following steps are used to reconstruct the flood magnitude:

Step 1: Velocity calculation
Several equations have been developed for calculating the velocity of a past flood based on the size of boulders deposited. Here we present some of the common ones.

(i) Mavis and Laushey (1949)

$$V_b = 0.5 d^{\frac{4}{9}} (S_g - 1)^{\frac{1}{2}}$$

Where V_b is the bed velocity of flow in ft/s, d is the boulder diameter in mm, and S_g is the specific gravity of the boulder.

The mean velocity is calculated as

$$\bar{V} = \frac{1}{3} V_b$$

(ii) Strand (1977)

$$V_b = 0.51d^{\frac{1}{2}}$$

Where V_b is velocity of flow in ft/s and d is the boulder diameter in mm. The mean velocity of flow is derived in the same way as for Mavis and Laushey (1949).

(iii) Williams (1983)

$$\bar{V} = 0.065\, d^{0.5}$$

Where $\bar{V}$ is the mean velocity of flow (m/s) and d is the diameter of the boulder in mm.

Step 2: Depth Calculation
The next step is to calculate the mean depth of the flow. Again several methods are available for calculating the mean depth.

(i) Manning's equation

$$\bar{D} = (\bar{V} \frac{n}{\sqrt{S}})^{1.5}$$

Where $\bar{D}$ is mean depth, n is the roughness coefficient, and S the slope.

(ii) Costa (1983)

In this method, a nomogram developed by Costa (1983; Figure 51) is used to derive the mean depth.

(iii) Sheild (1936)

$$\bar{D} = \theta . d\,(\gamma_S - \gamma_f)/s$$

Where θ is dimensionless shear stress (use 0.02), γ_f = 1070 kg/m^3, and γ_s = 2700 kg/m^3.

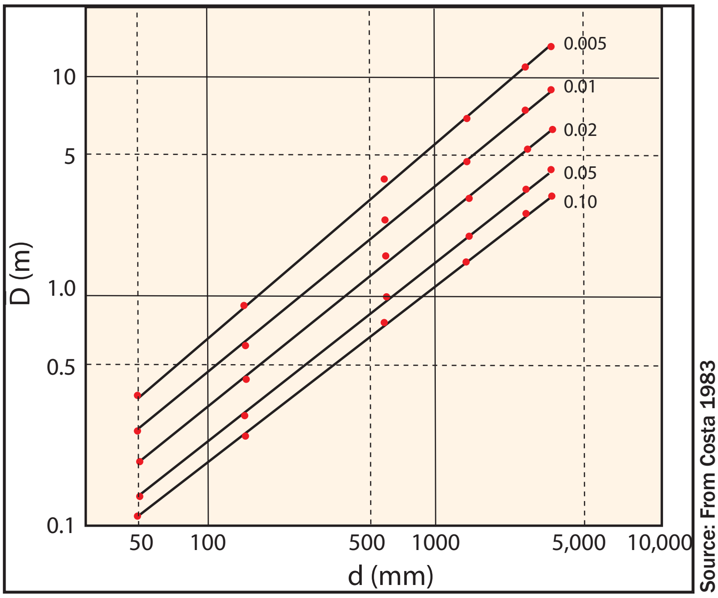


Figure 51: Graph to predict average depth ($\bar{D}$) of past flood from boulder size (d) and channel slope. The numbers beside the lines indicate the channel slopes.

(iv) Williams (1983)

$$\bar{D} = \tau/\gamma_f S$$

$$\tau = 0.17\, d^{1.0}$$

Where τ is shear stress (N/m^2), d is diameter of boulder (mm), and γ is the specific weight of water.

Step 3: Width calculation
The width is determined using an iterative method. A straight reach for cross-section (neither expanding nor contracting) is selected. The site should not be abnormally wide, narrow, steep, or flat. At least one, and preferably both, valley walls should be bedrock. The site should be close to the depositional site. Select at least two cross-sections spaced about one valley-width apart. No major tributaries should enter the main channel between the cross-sections.

Once the cross-sections have been plotted, draw a line to represent the estimated top width of the cross-section (Figure 52). Using a planimeter or a digitiser, calculate the area of the cross-section and divide it by the top width of the cross-section. If the value deviates from the estimated depth from Step 2, draw a new top-width line and repeat the process until the two values agree. Now, calculate the cross-sectional area 'A' for the final top-width.

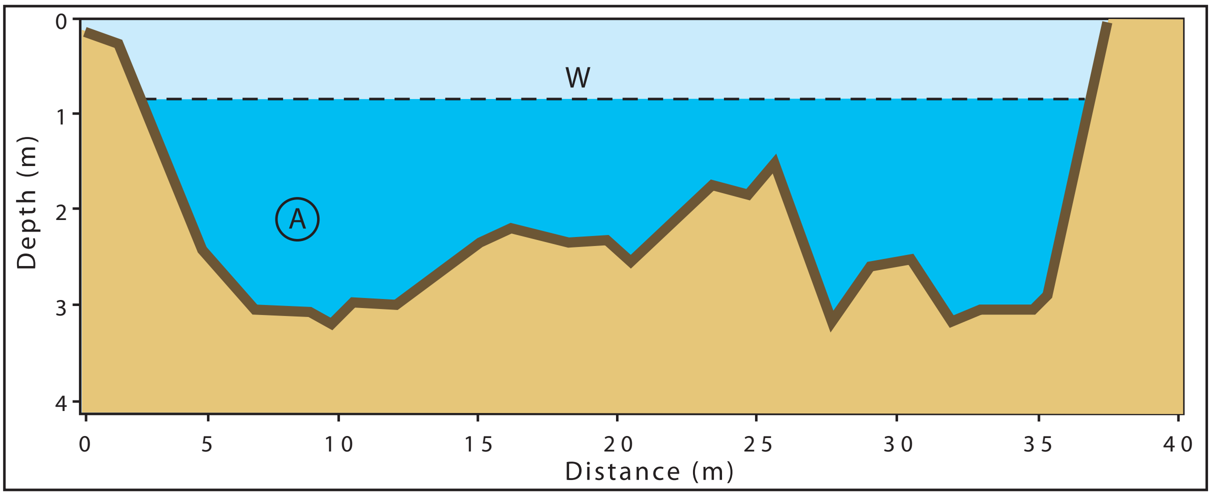


Figure 52: Top-width (W) and cross-section area (A) for calculation of depth by the iterative method

Step 4: Calculation of discharge

Knowing the average velocity from Step 1 and the cross-sectional area from Steps 2 and 3, a single discrete estimate of flood discharge (Q) can be made using the following equation:

$$Q = \bar{V}.A$$

Land use regulation

The increasing hazard and risk of LDOFs are a result of unregulated use of land and investment in flood-prone areas for infrastructure development such as buildings and roads. Public buildings such as schools are being constructed even on small islands between river distributaries, and houses are encroaching on natural river channels. Figures 53 and 54 provide evidence of such practices. In this context, the most effective way to mitigate LDOFs is to avoid activities that can cause landslides, particularly in narrow valleys where landslides can result in lake-forming dams. In such areas, development activities should be located on stable ground and landslide-susceptible areas should be used for open space or for low-intensity activities such as parkland or grazing. Land use controls can prevent hazardous areas from being used for settlements or as sites for important structures. The controls may also involve relocation away from the hazardous area, particularly if alternative sites exist. Restrictions may be placed on the type and amount of building that may take place in high-risk areas. Activities that might activate a landslide should be restricted. Where the need for land is critical, expensive engineering solutions for stabilisation may be justified. Building codes and design standards are also necessary.

Financial measures

Governments may assume responsibility for the cost of repairing damage from LDOFs as well as efforts to prevent them. Insurance programmes may reduce losses from LDOF by spreading the expenses over a larger base and including standards for site selection and construction techniques. Financial measures may be used to relocate people/activities from a landslide-prone area.

N.R. Khanal, TU, Nepal

Figure 53: Damage resulting from the 1998 LDOF in Syangja, central Nepal

Figure 54: A school located on a small island between distributaries of the Bagmati River in Kavre District, Nepal

Early warning systems

Early warning systems (EWSs) can be an effective measure to mitigate the impacts of LDOFs, particularly in saving life and property. Depending on the situation, a variety of early warning systems can be implemented. As the lifetime of landslide dams is often quite short, a sophisticated system may not be possible. In many cases the best option is to implement a community-based EWS. This may consist of placing people at strategic locations starting from the dam site to the distance downstream up to which the LDOF can have an impact. Each location should have visual contact with the person just upstream and downstream. EWSs as part of a monitoring, warning, and response system (MWRS) have been described in Chapter 5.

6.3 Glacial Lake Outburst Flood

Understanding the process

Glaciers

A glacier is a large flowing ice mass. The flow is an essential property in defining a glacier. Usually a glacier develops under conditions of low temperature caused by cold climate, although this in itself is not sufficient to create a glacier. An area in which the total depositing mass of snow exceeds the total mass of snow melting during a year is defined as an accumulation area. Thus, snow layers are piled up year after year because the annual net mass balance is positive. As a result of the overburden pressure due to weight, compression occurs in the deeper snow layers, and the density of the snow layers increases. Snow becomes impermeable to air a critical density of approximately 0.83 g/cm^3. The impermeable snow is called ice. Ice has a density ranging from 0.83 to a pure ice density of 0.917 g/cm^3. Snow has a density range from 0.01 g/cm^3 for fresh layers just after snowfall to ice at a density of 0.83 g/cm^3. Perennial snow with high density is called 'firn'. In the glacier, the snow changes to ice below a certain depth. When the thickness of ice exceeds a certain critical depth, the ice mass starts to flow down along the slope by plastic deformation and slides along the ground driven by its own weight. The lower the altitude, the warmer the climate. Below a critical altitude, the annual mass of deposited snow melts completely, the 'end' of the glacier. Here, snow disappears during the hot season and may not accumulate year after year. This area with a negative annual mass balance is defined as the ablation area. A glacier is divided into two such areas, the accumulation area in the upper apart of the glacier and the ablation area in the lower part. The boundary line between them is defined as the equilibrium line, where the deposited snow mass is equal to the melting mass in a year. Ice mass in the accumulation area flows down into the ablation area and melts away. Such a dynamic mass circulation system is defined as a glacier. There are different types of glaciers, such as ice sheet, ice field, ice cap, outlet glacier, valley glacier, mountain glacier, glacieret and snowfield, ice shelf, and rock glacier.

A glacier can change in size and shape due to the influence of climate change, advancing when the climate changes to a cool summer and heavy snowfall in winter and the monsoon season. As the glacier advances, it expands and the terminus shifts to a lower altitude. A glacier retreats when the climate changes to a warm summer and less snowfall. As the glacier retreats, it shrinks and the terminus climbs up to a higher altitude. Thus, climatic change results in a glacier shifting to another equilibrium size and shape.

Formation of glacial lakes

The formation and growth of glacial lakes is closely related to deglaciation. Shrinkage of glaciers is a widespread phenomenon in the HKH region at present, closely associated with climate change. The world has experienced many episodes of glacial and inter-glacial periods, during which glaciers advanced and retreated dramatically. A globally synchronous re-advance of glaciers occurred during the so-called 'Little Ice Age' (LIA), which prevailed from the middle of the 16th Century to the middle of the 19th Century[16]. The climate has gradually warmed since the end of the LIA, accompanied by the retreat of glaciers. Glacial retreat has accelerated in recent decades, generally attributed to human-induced increase of greenhouse gasses in the atmosphere and resultant overall warming. Valley glaciers generally contain supra-glacial ponds, which grow bigger and merge with a warming climate. This process is accelerated by rapid retreat of glaciers. As glaciers retreat, they leave a large void behind, and meltwater is trapped in the depression previously occupied by glacial ice thus forming a lake. Figure 55 shows the rapid growth of Tsho Rolpa lake in Nepal as an example.

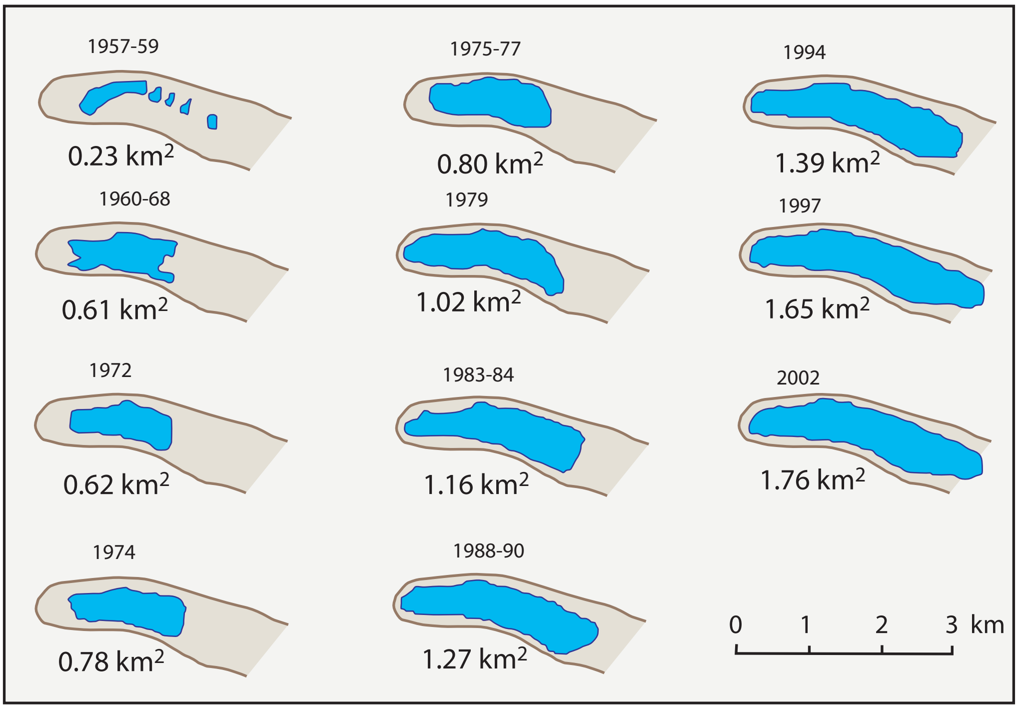


Figure 55: Development of Tsho Rolpa glacial lake, Nepal

[16] It was initially believed that the LIA was a global phenomenon, but recent studies question this. The beginning and end of the LIA is also a matter of debate among the scientific community.

Moraine dams

Glacial lakes are retained by the moraine dams created by the glacier during its advance stage. Debris falling on glaciers due to weathering of surrounding slopes and materials collected from the bottom of the glacier, are dumped loosely at the end of glaciers forming a terminal or end moraine (1 in Figure 56) and at the side of the glaciers forming lateral moraines (2 in Figure 56). These moraine dams are structurally weak and unstable, and undergo constant changes due to slope failure, slumping, and so on. This process can be aggravated; there is a potential for catastrophic failure, causing a glacial lake outburst flood (GLOF).

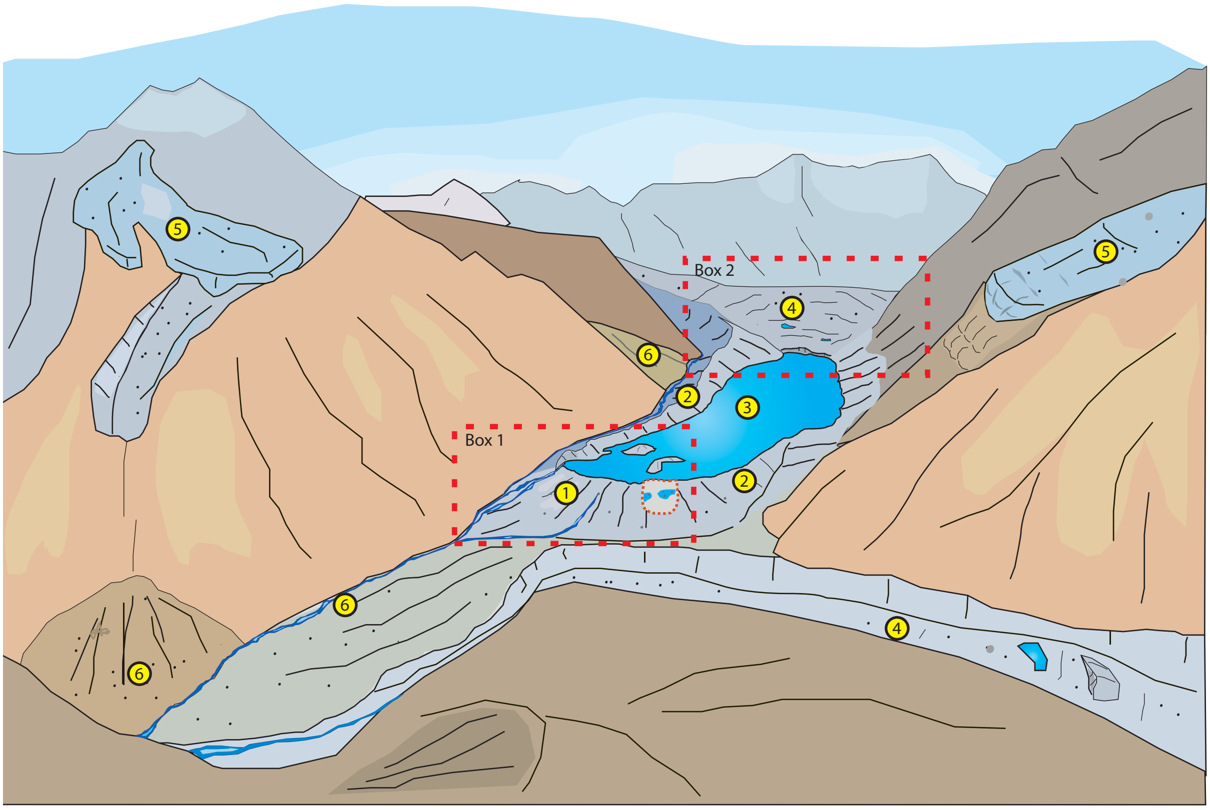


Figure 56: Schematic view of a typical glacial lake in the Himalayas. 1) end moraine; 2) lateral moraine; 3) glacial lake; 4) glacier terminus; 5) hanging glacier; 6) talus slope (rock fall). Details of Boxes 1 and 2 are shown in Figure 57

Causes of failure of moraine dams

A moraine dam may break as the result of the action of some external trigger or by self-destruction. A huge displacement wave generated by a rockslide or snow/ice avalanche from the glacier terminus (Figure 57, bottom) or hanging glaciers (5 in Figure 56) falling into the lake, may cause the water to overtop the moraines, creating a large breach and eventually causing dam failure (Ives 1986). Earthquakes may also trigger a dam break depending upon magnitude, location, and characteristics. Self-destruction is caused by the failure of the dam slope and seepage from the natural drainage network of the dam (Figure 57, top). Richardson and Reynolds (2000) analysed 26 GLOF events in the Himalayas in the 20th Century and concluded that a majority of the moraine dam failures were triggered by overtopping by a displacement wave caused by ice avalanches into the lake from hanging or calving glaciers (Figure 58).

Impacts of GLOFs

A GLOF is characterised by a sudden release of a huge amount of lake water, which in turn rushes downstream along the stream channel in the form of dangerous flood waves. These flood waves are comprised of water mixed with morainic materials and can have devastating consequences for downstream riparian communities, hydropower stations, and other infrastructure. Rushing water erodes both banks of the river and causes landslides from the steep slopes along the river channel. A moraine-dammed lake outburst results in a greater rate of water release than an ice-dammed lake burst, as in the latter case the release of water occurs

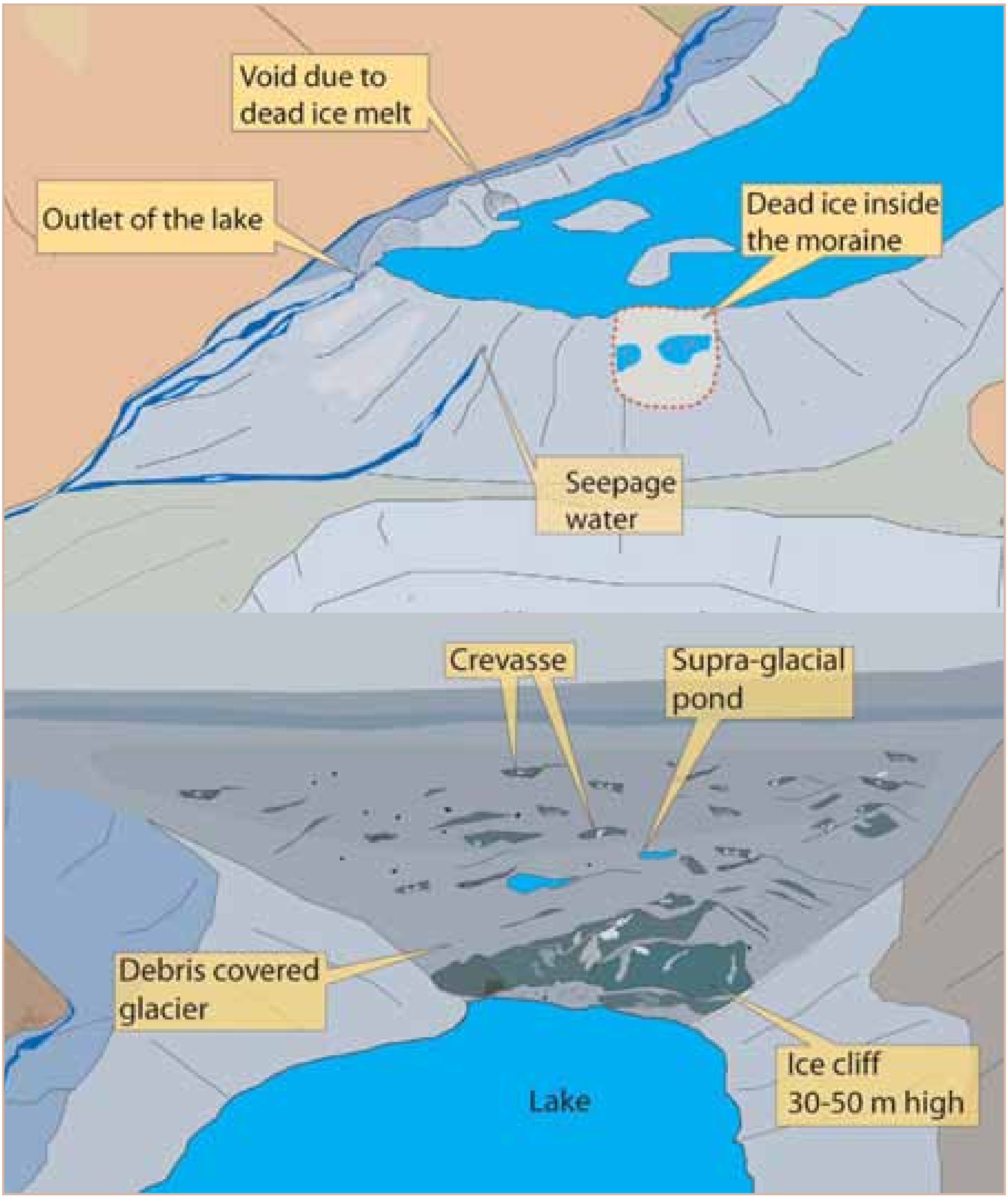


Figure 57: Detailed view of frontal part of the glacial lake, Box 1 in Figure 56 (top), and terminus of the parent glacier, Box 2 in Figure 56 (bottom)

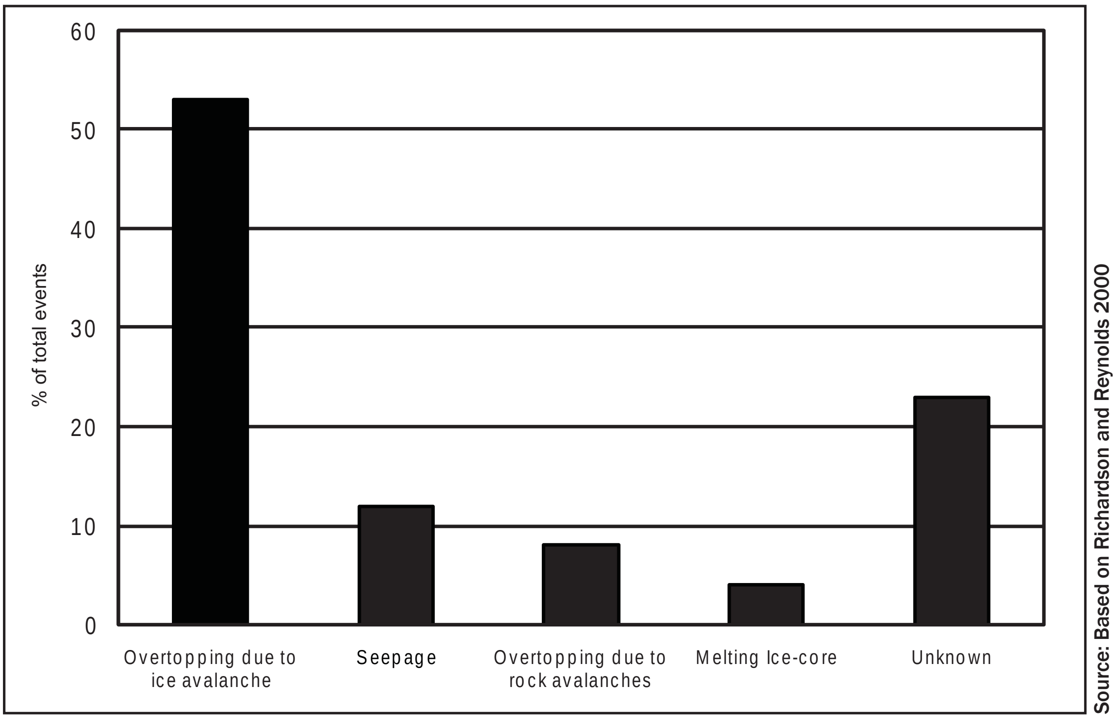


Figure 58: Causes of recorded glacial lake outburst floods in the Himalayas

over a prolonged duration, sometimes days, whereas in the former case the outburst is almost instantaneous, occurring within minutes to hours (Figure 59; Yamada 1998). The magnitude of the GLOF and the corresponding damage depend on the surface area and volume of the lake, release rate of water, and natural features of the river channel. The discharge rates of such floods are typically several thousand cubic metres per second. The peak discharge during the outburst of Zhangzangbo GLOF in 1981 was estimated to be around 16,000 m^3/s (Xu 1985). The peak outflow of the Dig Tsho GLOF was estimated to be 5,610 m^3/s (Shrestha et al. 2006).

Depending on the channel topography and morphology, the peak flood will attenuate along the river channel. Figure 60 shows some examples of attenuation of peak flood discharge with distance along the river channel. While the inundation caused by the GLOF is generally not extensive, it can be quite destructive due to the high velocity of the flood waves. Flood velocities during a GLOF can be as high as 10m/s, which is high

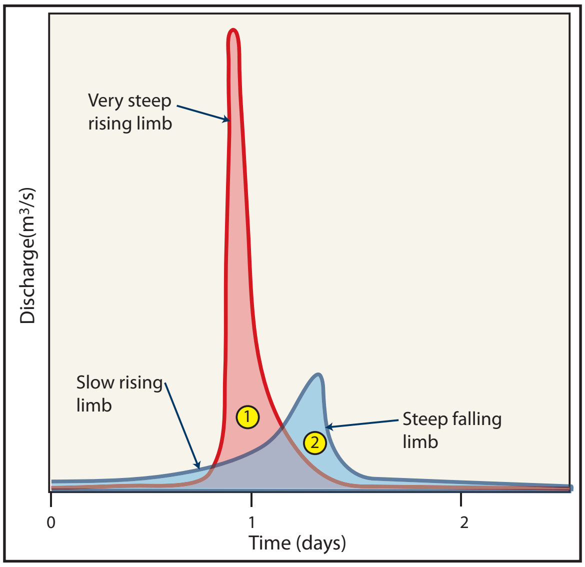


Figure 59: Outburst of moraine-dammed lake (1) and ice-dammed lake (2) (Yamada 1998)

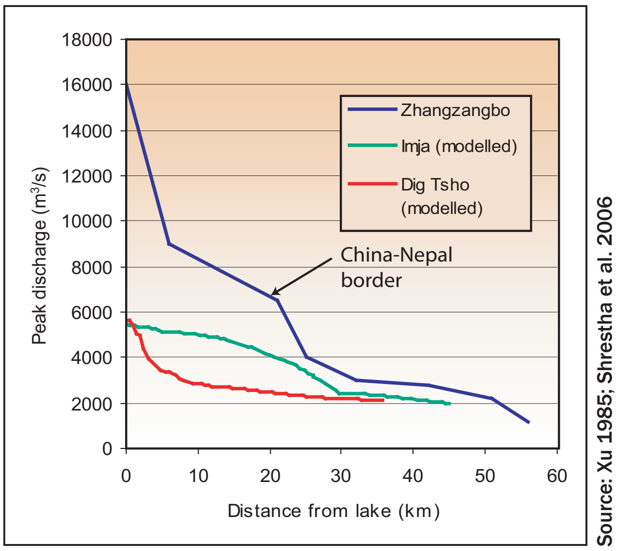
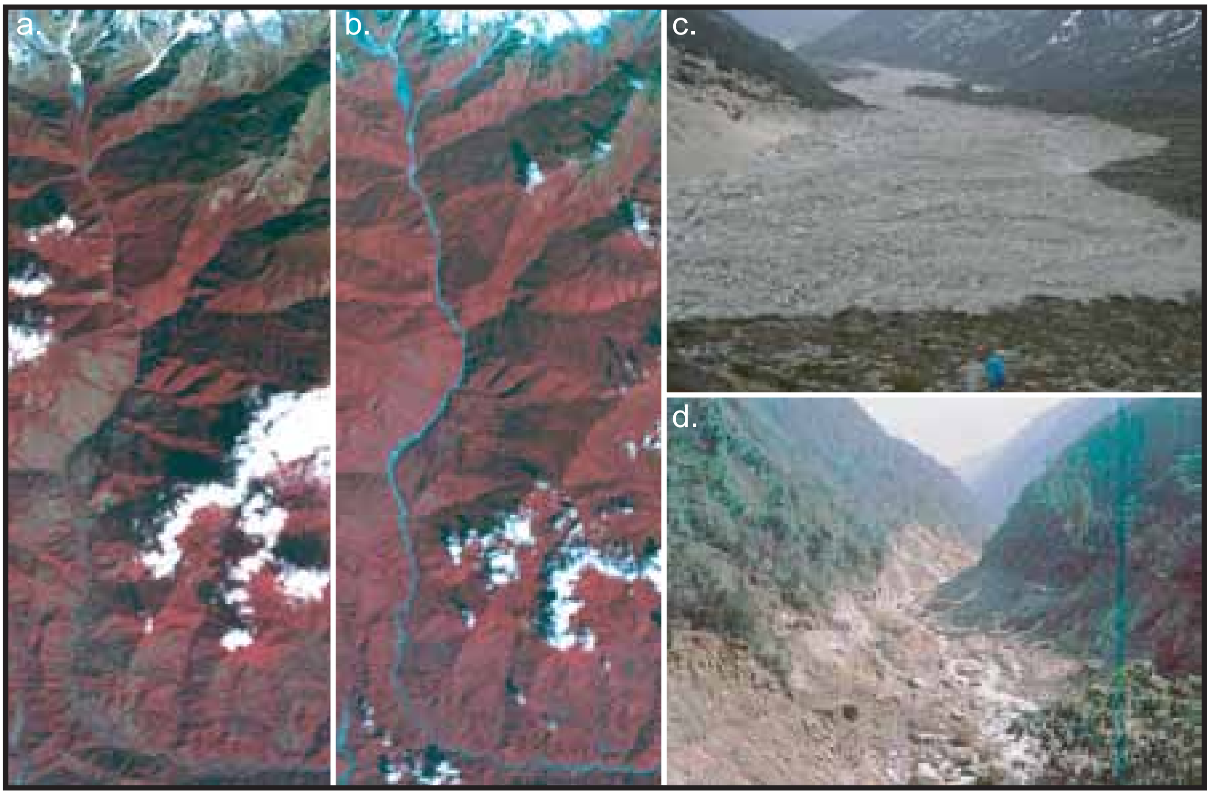


Figure 60: Examples of attenuation of peak flood along the river channel

enough to destroy bridges and settlements and wash away highways and agricultural lands. GLOFs typically contain a large amount of debris mixed with water, which increases the destructive power of the flood. During the recession of the flood, the debris settles on the valley floor, making it useless for agriculture and other uses for a long time (Figure 61).



Source: a. & b. Aster images; c. Arun B. Shrestha; and d. Mool et al. 2001

Figure 61: Impacts of GLOF on the river channel of the Madi River in central Nepal: a. before; and b. after a small GLOF on 15 August 2003; c. deposition of debris in the river channel due to Dig Tsho GLOF of 1985; and d. eroded banks of Tamur River after the Nagma GLOF

Which glacial lakes can burst out?

ICIMOD has identified more than 8,800 glacial lakes in the HKH region (Table 19; ICIMOD 2007). Most of these lakes do not pose any danger of outburst, but a small number do. These are called 'potentially dangerous lakes'. From the study of past GLOFs in the region, it is clear that GLOF events are clustered around the eastern Himalayas in Nepal, Bhutan, and Tibet. For GLOF risk management it is important to know which lakes pose a danger of outburst. Some 20 potentially dangerous lakes were identified in Nepal and 24 in Bhutan.

Methods to determine whether a lake is potentially dangerous can range from simple desk-based to complicated methods, involving many highly specialised field investigations. A potentially dangerous lake can be identified based on the following factors.

Table 19: **Glacial lakes in the Hindu Kush-Himalayan region**

River basins	Glacial lakes	
	Total number	**Area (km²)**
Pakistan		
Indus Basin	2420	126.35
India		
Himachal Pradesh	156	385.22
Uttaranchal	127	2.49
Tista River	266	20.2
Tibet Autonomous Region of the Peoples' Republic of China (sub-basins of Ganges)	824	85.19
Nepal Himalaya	2323	75.7
Bhutan Himalaya	2674	106.87
Total within the study area	8790	799.49

Source: ICIMOD 2007

Volume and rise in lake water level

An outburst of a relatively small lake may not have a significant impact. Lakes smaller than 0.01 km^3 in volume are not considered potentially dangerous. The dynamics of the water level are also important, as increase in water level increases the hydrostatic pressure on the moraine dam and may result in the collapse of the dam.

Activity of glacial lake

The activity of the lake is very important for analysing the potential danger. Rapidly increasing lake size indicates a high possibility of a GLOF. Similarly, a lake boundary and outlet position that is dynamic in nature also indicates a high risk.

Position of lake

Potentially dangerous lakes are generally at the lower part of the ablation area of the glacier near the end moraine. The parent glacier must be sufficiently large to create a dangerous lake environment. Regular monitoring needs to be carried out for such lakes with the help of multi-temporal satellite images and field investigations.

Moraine dam condition

The condition of the moraine damming the lake determines the lake stability. The possibility of outburst due to collapse of the moraine dam increases if:

- the dam has a narrow crest area
- the dam has steep slopes
- the dam is ice cored
- the height above the valley floor is high
- there are instabilities on the slopes of the dam
- there is seepage through the moraine dam

Condition of parent glacier and glaciers on the periphery

The terminus of the parent glacier in contact with the lake experiences calving due to development of thermo-karsts on the lower part of the terminus and exploitation of crevasses on the glacier. A large drop of glacial ice can cause a displacement wave sufficient to travel across the lake and cause overtopping of the moraine dam. A steep parent glacier or glacier on a side valley can cause ice avalanches into the lake. Such ice avalanches also cause displacement waves capable of overtopping moraine dams.

Physical condition of surroundings

Unstable mountain slopes with the possibility of mass movements around the lake, and snow avalanches, can cause displacement waves and overtopping of moraine dams. Smaller lakes located at higher altitudes sometimes pose a danger to a glacial lake of concern. Outbursts of such high-altitude lakes might drain into the glacial lake, causing overtopping and consequent failure of the moraine dam.

Measures to minimise the impacts of GLOFs

Early recognition of risk

The most effective way to minimise the risk of a GLOF is to understand the risk early so that appropriate measures can be taken in a timely and cost-effective manner. This involves investigation of the factors listed above. Many of these can be investigated without field studies by using remote sensing and GIS technologies. The first step is to inventory the glaciers and glacial lakes in the region. While preparing the inventory of glacial lakes, parameters that can be derived remotely can be entered as attributes. Then a logical command in the GIS software can identify potentially dangerous lakes in the area of interest.

Annex 6 describes a methodology[17] for preparing an inventory of glaciers and glacial lakes and automatically identifying those that are potentially dangerous. Annex 6 is based on image processing and the GIS software

[17] The annex is part of an unpublished manual developed by P.K. Mool and S.R. Bajracharya of ICIMOD.

ILWIS[18] 3.2 developed by the International Institute for Geo-Information Science and Earth Observation (ITC), Netherlands. Example data for conducting the exercise accompanies the Annex. Following desk-based identification of the potentially dangerous lakes, field investigations can be conducted on the short-listed lakes.

RGSL (2003) has suggested criteria for defining the GLOF hazard of glacial lakes (Table 20), and a hazard rating based on the score (Table 21). A glacial lake scoring higher than 100 is potentially dangerous and an outburst can occur at any time.

Glacial lakes should be monitored regularly to establish the status of the criteria listed in Table 20. Here we present some guidelines for determining each of the criteria.

Table 20: **Empirical scoring system for moraine-dammed glacial lake outburst hazard (RGSL 2003)**

Criteria affecting hazard/score	0	2	10	50
Volume of lake	N/A	Low	Moderate	Large
Calving risk from ice cliff	N/A	Low	Moderate	Large
Ice/rock avalanche risk	N/A	Low	Moderate	Large
Lake level relative to freeboard	N/A	Low	Moderate	Full
Seepage evident through dam	None	Minimal	Moderate	Large
Ice-cored moraine dam with/without thermokarst features	None	Minimal	Partial	>Moderate
Compound risk present	None	Slight	Moderate	Large
Supra/englacial drainage	None	Low	Moderate	Large

Table 21: **Hazard rating on the basis of the empirical scoring system (RGSL 2003)**

0	50	100	125	150+
Zero	Minimal	Moderate	High	Very High
		An outburst can occur any time		

Volume of lake: The volume of the lake can be established by bathymetric survey; there are two common methods. The first is to directly measure the depth when the lake is frozen. A grid of measurement points is pre-determined and holes are bored through the ice layer, through which depth sounding is done. The measurement points are interpolated to get the total volume of the lake. Another method gaining more popularity is measurement using echo-sounders. Echo-sounders are mounted on a small boat, which travels along pre-established transects on the lake. The positions along the transects are given by an online GPS connected to the echo-sounder (e.g., Shrestha et al. 2004; Figure 62). This method can give a relatively dense measurement in a short time. The volume thus derived can be related to the surface area of the lake and after a number of measurements a volume:area relationship can be established. The surface area can be measured more frequently either by field survey or by remote sensing analysis, and the volume derived from the volume:area relationship.

Calving risk from ice cliff: The status of the parent glacier terminus has to be routinely monitored in the field. The geometry and size of the terminus can give useful information regarding the possibility of large displacement waves. A high and overhanging ice-cliff can be conducive to ice calving, potentially causing large displacement waves. A debris/ice apron in front of the ice-cliff (Figure 57, bottom) reduces the chance of generating a large displacement, even when ice calving occurs. Often ice termini have a series of crevasses (Figure 63). These crevasses are exploited during ice calving, thus monitoring crevasses and the structure of the ice cliff can be useful in predicting the size of future ice calving. The terminus and crevasses can be

[18] An open source version, ILWIS 3.4 Open, can also be used. It is freely downloadable from <http://52north.org/index.php?option=com_projects&task=showProject&id=30&Itemid=127>

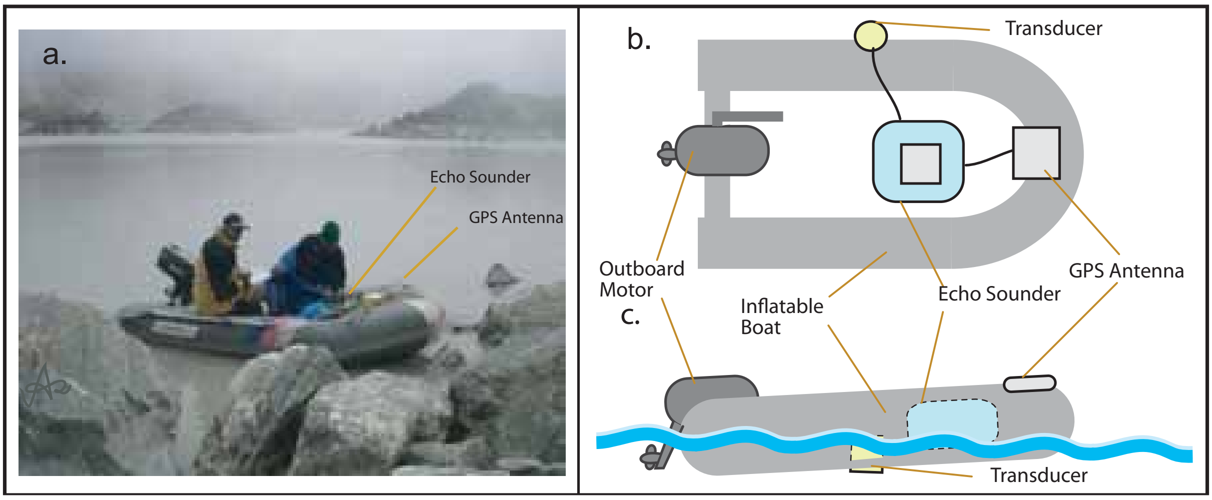


Figure 62: a. Set-up for bathymetric survey; b. schematic set-up diagram, top view; c. schematic setup diagram, side view

monitored by repeat photography. High-resolution satellite imagery can provide some information on the crevasses, and field surveys can provide information on the height of the ice cliff.

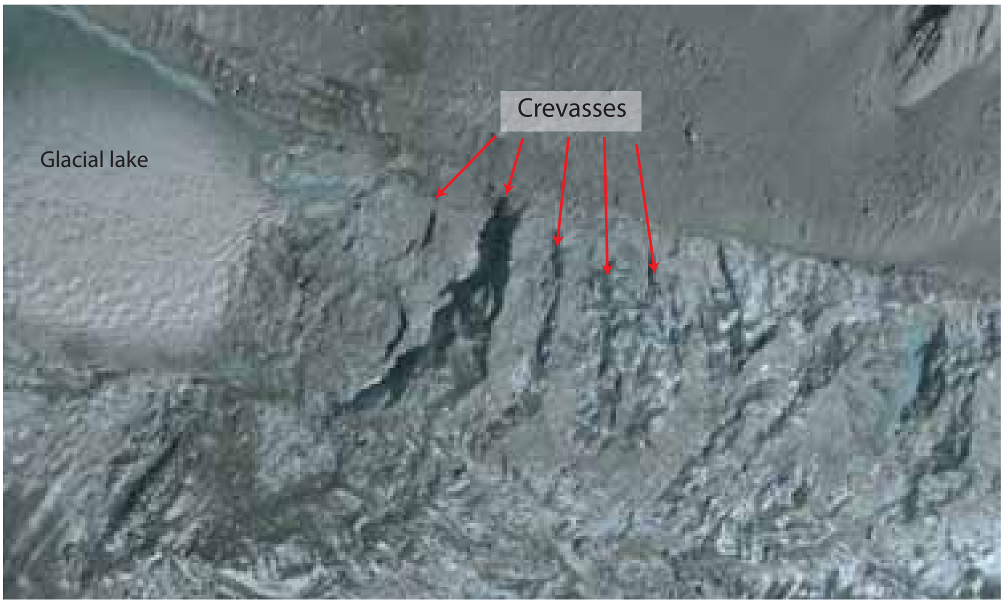
Ice/rock avalanche risk: Ice avalanches from hanging glaciers and rock avalanches from weathered slopes into lakes can cause large displacement waves capable of overtopping moraine dams and causing their failure. Ice and rock avalanche areas have to be monitored regularly for early detection of large avalanches. This can be done through a combination of visual inspection on the ground and high-resolution satellite imagery (Figure 64; 5 in Figure 56).

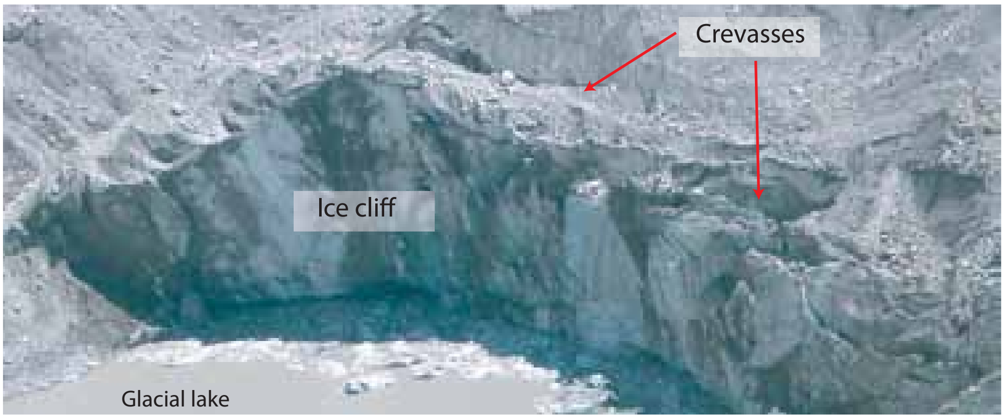
Lake level relative to freeboard: High water level and low freeboard means that even a relatively small displacement wave can overtop the moraine dam. The dynamics of the lake water level have to be observed continually. This can be done by establishing a lake water level measuring station (Figure 65). The station can have a simple level gauge monitored regularly by a gauge reader, or could be an automatic recorder with a water level pressure sensor and data logger. The water level observation can be supplemented by discharge measurements, which will give important information on the outflow of the lake.

Seepage evident through dam: Seepage through a moraine dam may indicate piping inside the dam leading to dam failure. Seepage could also be due to rapid melting of dead ice inside the moraine dam, which can lead to formation of a void inside the dam and consequently its collapse. The height of the seepage outlet and seasonal fluctuation of the seepage quantity have to be monitored. Seepage due to infiltrated precipitation is seasonal and does not pose a serious threat to the integrity of the dam.

Ice-cored moraine dam with/without thermokarst features: Thermokarst refers to voids in the moraine dam caused by rapid melting of buried ice blocks (Figure 56, Box 1). Thermokarsts reduce the structural stability of the moraine dam against the hydrostatic pressure of the lake water. Slumping and subsidence due to collapse of a thermokarst may cause overtopping of a moraine dam, leading to its collapse. Features on the moraine like slumping and subsidence have to be monitored regularly. This can be done visually or by conducting a detailed topographic survey of the area of concern. Specialised techniques such as ground penetrating radar survey or electro-resistivity survey have to be conducted for 3-dimensional mapping of the buried ice.

Supra/englacial drainage: Parent glaciers generally contain several supra-glacial lakes (Figure 56, Box 2; Figure 57, bottom; Figure 66) and englacial channels. Occasionally these ponds drain though the englacial channel into the glacial lake. Similarly, other lakes at higher altitude might suffer outbursts that might drain into the glacial lake. If the volume of the water released is significant, it might cause overtopping of the moraine dam. Supra-glacial ponds and high altitude lakes have to be monitored regularly. Satellite images





Source: Google Earth (top); Arun B. Shrestha (bottom)

Figure 63: Terminus of the Trakarding glacier, the parent glacier of Tsho Rolpa glacial lake, Nepal, showing a series of crevasses in plan view and frontal view

can provide multi-temporal information on the development of supra-glacial ponds and high altitude lakes in the surrounding areas.

Estimation of peak outflow discharge: Sophisticated computer models are available to estimate the peak discharge of a GLOF. Due to limited resources and expertise, it is not always possible to do a detailed modelling exercise. A simple method can also provide a reasonably good estimate of the outburst magnitude.

Costa and Schuster (1988) suggested the following equation for predicting peak outflow discharge from a GLOF:

$$Q = 0.00013(P_e)^{0.60}$$

Where Q is peak discharge in m^3/s, and P_e is potential energy in joules.

P_e is the energy of the lake water behind the dam prior to failure and can be calculated using the equation:

$$P_e = H_d \times V \times \gamma$$

Popov (1991) suggested the following equation for predicting flash flood peak discharge due to glacier outburst:

$$Q = 0.0048 V^{0.896}$$

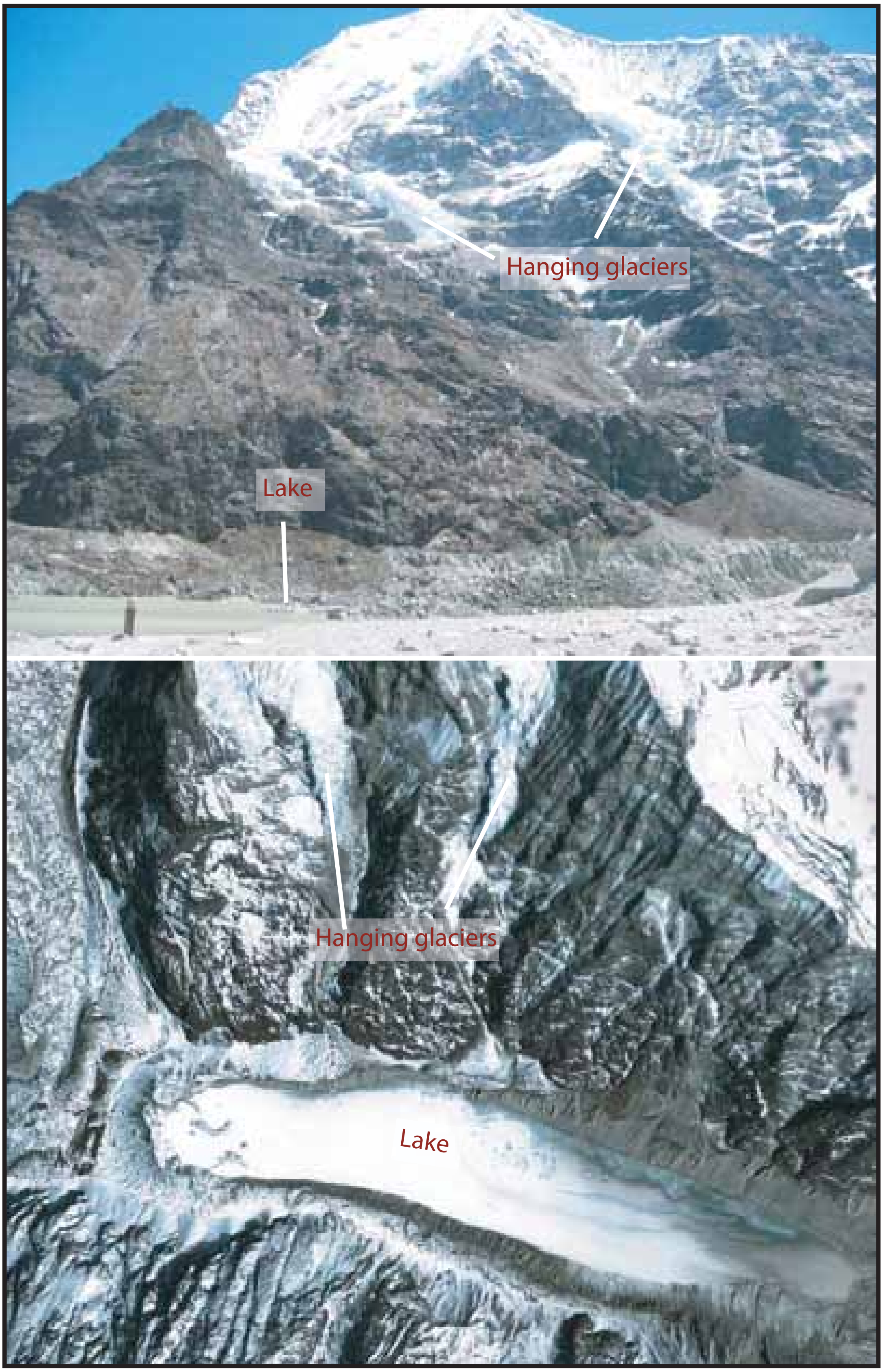


Figure 64: Hanging glaciers near a glacial lake: frontal view (top) and plan view (bottom)

The peak discharge depends on the volume of the glacial lake (V). The lake volume is generally not available unless a detailed bathymetric survey has been conducted. The surface area of the lake, however, can be easily derived from maps of satellite imageries. The volume can then be calculated using the following formula suggested by Huggel et al. (2002):

$$V = 0.104A^{1.42}$$

Peak outburst depends on the nature of the outburst, i.e., the duration of the outburst, the nature of the outburst hydrograph, and the size and geometry of the dam breach. In the simple approach, a triangular breach hydrograph is assumed and the duration of the outburst is assumed as 1000s. Huggel et al. (2002) suggest that most outbursts last between 1000 and 2000 seconds, and the peak discharge is calculated by:

$$Q = \frac{2V}{t}$$

Figure 65: An automatic weather station equipped with a lake water-level recorder, Lirung, Nepal

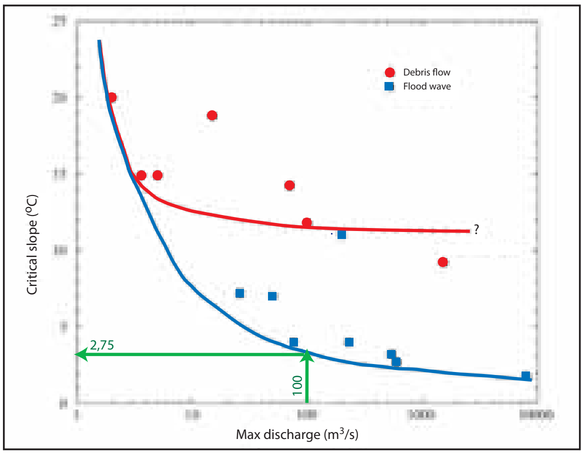
Figure 66: Parent glaciers of Imja Lake, Nepal, showing supra-glacial ponds

Estimation of area that can be impacted by a GLOF

The hazard assessment should include a rough estimate of the area potentially affected by a lake outburst. A worst-case scenario is generally followed for delineating the area that could be affected. The runout (travel) distance of an outburst is related to the amount of debris available to be mobilised. Outburst floods with a higher content of solid material form debris flows and stop abruptly, whereas GLOFs with predominantly water attenuate more gradually.

To roughly estimate the maximum affected area, the peak discharge is used to estimate the overall slope of the outburst flood (the average slope between the starting and the end points of an outburst event). Figure 67 shows the relationship between maximum outflow discharge and critical runout slope. For instance, an outflow discharge of 100 m^3/s gives a critical slope of 2.75.

Figure 68 shows the profile of a river channel. The critical slope of 2.75 means the flood will have an effect up to a distance of 20 km (point 3 in Figure 68).



Source: Based on Huggel et al. 2002; Huggel et al. 2004

Figure 67: Relation between peak discharge and overall slope of runout distance of lake outburst based on data from the Alps

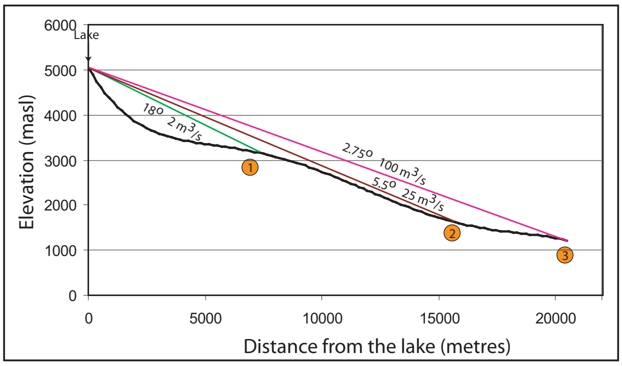


Figure 68: Longitudinal profile of a stream and runout distances for different peak outfow discharges

GLOF risk mapping

GLOF risk mapping is an important tool to understand the areas likely to be impacted by a GLOF and to understand the vulnerability of those areas, and will help in planning mitigation measures. Detailed descriptions of GLOF risk mapping can be found in Shrestha et al. (2006) and Bajracharya et al. (2007 a and b). The process involves estimating the discharge hydrograph at the outlet (breach). This can be done using dam break models or by simple calculation assuming the breach size and the lake drawdown rate. The hydrograph is routed through the river reach to find the peak discharge and flood height at the locations of interest. An inundation map is prepared by overlaying the flood height over the terrain map. Overlaying a socioeconomic vulnerability map based on the information mentioned in Chapter 4 will give the risk map of the area. See Chapter 4 for details on risk assessment.

Terrain Analysis

GLOF is a complex phenomenon involving floods, sediment transport, debris flows, landslides, and others, which cannot be accurately predicted or foreseen. Terrain analysis can be a good indicator of the magnitude of what might happen during a GLOF event. Terrain analysis is a good tool to verify the results of a hazard map. Bajracharya et al. (2007b) provides a detailed description of terrain analysis.

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ISBN 978 92 9115 095 3

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