Day 3

Session/Activity		Activity time (minutes)	Cumulative time of session
Session 10: Non-Structural Measures for Flash Flood Risk Management			
10.1	Measures for flash flood risk management and the importance of non-structural measures	15	15
10.2	Strategies for flash flood risk acceptance	10	25
10.3	Strategies for flash flood risk reduction	35	60
Session 11: Modelling Tools for Flash Flood Management			
11.1	Modelling flash flood scenarios	20	20
11.2	Hazard-specific modelling tools	40	60
Session 12: Integrated Flash Flood and Watershed Management			
12.1	Integrated flash flood management (IFFM)	45	45
12.2	Concept and components of watershed management	15	60
12.3	Watershed management measures	30	90
Session 13: Hazard-Specific Flash Flood Management: Intense Rainfall Floods			
13.1	Rainfall measurement and catchment rainfall	10	10
13.2	Runoff and factors that affect it	10	20
15.3	Discharge and methods of measuring it	10	30
15.4	Flood routing and calculating hydrographs at different locations	15	45
15.5	Flood frequency and return period	15	60
Session 14: Hazard-Specific Flash Flood Management: Landslide Dam Outburst Floods			
14.1	Types of landslides and factors that trigger landslides	15	15
14.2	Process of landslide damming and factors that can cause landslide dams	15	30
14.3	Case studies of landslide dam outburst floods	05	35
14.4	Measures that can reduce the risk of landslide dam outburst floods	25	60

Session 10 Non-Structural Measures for Flash Flood Risk Management

Time: 60 minutes

Objectives

To introduce the various non-structural measures available for flash flood risk management, including:

- Types of flash flood risk management
- The importance of non-structural measures
- Risk acceptance methods
- Risk reduction methods

Activities

Activity 10.1: Measures for flash flood risk management and the importance of non-structural measures

Time: 15 minutes

Step 1 Highlight the different flash flood risk management measures that can be used. Give a PowerPoint presentation explaining the different structural and non-structural measures that are available. Explain that a community can use both small-scale structural measures and non-structural measures. Emphasise that a combination of the two is the best way of achieving a good result.

Step 2 Explain that there are three phases to disaster risk management: pre-flood, during the flood, and post-flood.

Step 3 Explain that while a combination of structural and non-structural measures is best, a community with limited resources can achieve the greatest margin of safety by concentrating efforts on non-structural measures.

Activity 10.2: Strategies for flash flood risk acceptance

Time: 10 minutes

Step 1 Clarify what 'risk acceptance' means.

Step 2 Introduce the three key risk acceptance strategies. Discuss how risk acceptance strategies are implemented in different areas and mention in each case who responds and how they respond during emergencies.

Note to the trainer

Mention that emergency planning is based on government policy and on the existing institutional arrangements for flash flood and disaster risk management. Emergency planning usually has national, sub-national, and local level components complete with operational plans that assign roles and responsibilities.

Activity 10.3: Strategies for flash flood risk reduction

Time: 35 minutes

Step 1 Differentiate between the two types of strategies that can be used to reduce the risks associated with a flash flood: strategies aimed at prevention and strategies aimed at mitigation.

Step 2 Present the various preventive strategies for flash flood management.

Step 3 Clarify the concept of watershed. Discuss the social and natural components of watersheds; note that a watershed can consist of agricultural lands, forests, rangelands, barren lands, and/or floodplains. Draw attention to the fact that better agricultural practices, some rearranging of the agricultural calendar, reforestation, and regulation of grazing are some of the measures that can be used to prevent flash floods. The watershed approach will be discussed in Session 12.

Step 4 Open up a short question and answer session on possible mitigation strategies. Sum up the participants' feedback and present the entire range of possible mitigation strategies.

Note to the trainer

When you discuss mitigation strategies, encourage the participants to share their knowledge and experience in reducing the intensity, frequency, and impact of flash floods in their regions. Present the strategies of discharge reduction, monitoring, warning, forecasting, and response system.

It is important to mention that warnings, forecasts, and the methods used to communicate them to local communities should be easy to understand. Warnings should be issued in the local languages and dialects of the major linguistic groups who live in the flood affected area.

Step 5 Discuss the need for hydrometeorological monitoring, analysis, and forecasting. Explain how a forecasting system works.

Step 6 Discuss how warnings are disseminated. Discuss efficient ways of disseminating information (see Box 9 in RM 10.3).

Step 7 Discuss how flash flood affected communities and individuals can access financial support. Some financial instruments available to cash-strapped flood victims are tax waivers, low interest loans (or waiver of loan interest), and compensation for maintaining structural interventions. Financial support can also be available sector-wise, such as from forest users' or farmers' groups.

Step 8 Discuss how different groups respond to flash floods. Finally, discuss some of the challenges to flash flood risk management (see Box 10 in RM 10.3).

Session 10 Resource Materials

RM 10.1: Measures for flash flood risk management and the importance of non-structural measures

Flash flood risk management includes both structural and non-structural measures. Structural measures tend to deal with the hydraulic and hydrological implications of flooding. Structural measures can include, river training, building embankments, constructing reservoirs and dams and other works aimed at controlling the flow of water to reduce the flood hazard. Non-structural measures work by using a different set of strategies, such as risk tolerance, risk prevention, and risk mitigation. The range of possibilities for these encompasses a wide diversity of measures such as: land use planning, devising and enforcing construction and structure management codes, soil management, land acquisition policies, insurance, sensitising the population through perception and awareness campaigns, disseminating information, as well as putting in place systems for emergency and post-disaster preparedness. A combination of structural and non-structural measures yields the best results. Strategies for flash flood risk management are given in Table 6.

Non-structural measures

Non-structural measures are very important when dealing with settled areas. Compared to structural measures, non-structural measures tend to be more sustainable because they include the active involvement of the community. National and regional policies tend to favour non-structural alternatives since these are low cost and have fewer environmental side effects; expensive structural measures with potentially serious environmental repercussions are considered as only a last resort.

There are two categories of non-structural measures: risk acceptance and risk reduction measures.

Table 6: **Structural and non-structural measures for flash flood risk management**

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

Source: Colombo et al. (2002)

RM 10.2: Various strategies for flash flood risk acceptance

Acceptable risk, as defined in the United Nations International Strategy for Disaster Reduction, is the level of loss that a society or community considers acceptable within the given existing social, economic, political, cultural, technical, and environmental conditions (UNISDR 2009). There are three main types of risk acceptance strategies: toleration, emergency response systems, and insurance.

Toleration

Toleration of risk implies that a competent authority (local, regional, or national) accepts that flash floods can occur. In this case, it is very likely that the competent authority will accept the results of the risk assessment and not promote any activities to reduce the risk.

Emergency response systems

All emergency plans (regional, district, local) should be based on a national emergency plan so that emergency operations within a particular country will be carried out according to the same doctrine of civil protection and in a concerted manner. In general, the various public authorities implicated 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 this end, each competent authority (regional, district, local) should have its own emergency plan, accompanied by an 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 have this practice because of the high costs involved. Insurance companies have various policies that cover risk. Insurance policies that apply only at the local level are far too expensive both for the insurance companies and for the private and public subscribers.

RM 10.3: Various strategies for flash flood risk reduction

Risk reduction is one of the main goals in flash flood management. It can be dealt with in two ways: through prevention strategies and through mitigation strategies.

Prevention strategies

Watershed management. (See also Session 12.) Watershed management has both structural and non-structural components. Watershed management is cross-cutting and closely related both to the socio-economic status of the community and its development. Watershed management takes into consideration a number of basic principles related to runoff and erosion including soil, topography, land cover and use, farming practices, and floodplain zoning. This topic is covered in more detail later in the section on watershed management and the integrated flash flood management approach.

Financial measures. Financial support can be provided after a flash flood occurs in order to aid communities in dealing with the aftermath of the disaster. Usually this aid is administered through national or regional agencies. Financial measures can be

- an economic contribution or the waiver of a financial burden such as: taxes, loan interest, or the liquidation of a loan;
- financial support to individuals and local communities for planning, constructing, and maintaining structural interventions that can be shared among national, provincial, and local administrative levels, with the total amount divided among them (the share of the burden generally increasing progressively from local to provincial to national level);
- support to maintain and regulate hydraulic works of public interest (where the support is given to those who maintain it);

- subsidies targeted at reducing flash flood risks for the protection of forests, pastures, rangelands, and water bodies, including subsidies to community forestry user groups or to targeted farmers to encourage environmentally friendly farming practices.

Mitigation strategies

Mitigation strategies can reduce the intensity, frequency, and impacts of flash floods. These strategies can include the following.

Reducing discharge through natural retention. Various measures can be adopted to promote the natural retention of water.

- Suitable areas for water retention need to be identified based on a land-use plan. If these areas fall within farmers' private properties, the farmers must be compensated for the loss they incur due to reduced farming revenues;
- Passive flood control measures (as advised by hydraulic engineering experts) can be incorporated into regional development programmes and construction plans so that retention basins can be identified and used for flash flood mitigation;
- Natural retention areas need to be identified and improved.

Monitoring, warning, and response systems (MWRSs). MWRSs can contribute to the mitigation of flash floods and can be a very effective non-structural measures (IDNDR 1997; UNISDR 2005). MWRSs include systems for data collection, monitoring, and transmission; forecasting; warning; dissemination; disaster management; and response. When any of these components fails to function, the effectiveness of the whole system can be hampered.

- **Data collection, monitoring, and other associated systems.** Collection and monitoring of hydrometeorological data, such as rainfall, temperature, and stream flow, is essential since these data are used in simulations and forecasting that help planners prepare for future scenarios and choose between possible alternatives. Ground-based observation networks and satellite-based precipitation estimations are both good sources of data. Ground-based networks are a tried and true means of collecting rainfall and other meteorological data. Where ground-based observation networks are not available, satellite-based estimates of precipitation may be the only source of rainfall data. Combined satellite and ground-based rainfall estimates provide the best input for flash flood forecasting and early warning systems.

  It is important that data be transmitted efficiently from the site to the centre where the data are analysed. The centre can then issue forecasts and warning messages to end users in a timely manner. A wide range of data transmission systems are available; these can include, for example, automated gauge readers that use VHF radio or telegraph to transmit data digitally to the centre.
- **Forecasting systems.** A forecasting system consists of models (e.g., hydrological, hydraulic) that can predict potential flash flood events; these models are used to closely follow the evolution of key parameters that could trigger a flood event. Forecasting can be very accurate, but if the computation time is too long they are not relvant. Flash floods, as their name implies, are rapid processes and typically the lead time is very short. Since time is of the essence, it is sometimes preferable to forego elaborate (and time consuming) forecasting models in favour of simpler models, such as flash flood guidance tables, which can give immediate results.
- **Warning systems.** It is often difficult for the general public to grasp the meaning of quantitative flash flood forecasts; for general dissemination, qualitative warnings are much more useful (Box 9). An example of such a qualitative warning is the flash flood guidance; this is the volume of rainfall during a given time (e.g., 1 to 6 hours) over a given small catchment area. Even the general public can easily interpret this number knowing that rainfall in excess of the flash flood guidance number is considered a flash flood threat.
- **Dissemination systems.** Flood forecasting and warning information needs to be disseminated effectively. In the majority of cases, even good forecasts fail to prevent damage and loss of life because they are poorly

disseminated. The South Asian tsunami of December 2004 is a classic example. The forecasts and warnings need to be communicated to the disaster management agencies in a timely and understandable manner. These agencies can then issue warnings to the different disaster management units down to the lowest level using the appropriate media (e.g., radio, television). The warning should be clear and concise so that they can easily be understood by communities. Those issuing the warnings should make sure to use language that will not cause unnecessary panic. The warnings can be issued in the form written text and can also contain useful diagrams and maps as needed.

- **Disaster management systems.** Even when forecasts and warnings are issued in a timely manner, flash floods can still cause damage. A disaster management system should be well prepared for such events. The system should alert key action groups, which are part of the response system.
- **Response systems.** A response system consists of intervention by groups such as:
  - police and fire brigade;
  - civil protection authorities (e.g., to disseminate targeted information);
  - volunteer groups (e.g., to assist the injured, to allocate resources);
  - military (e.g., to prepare sandbags, to construct temporary structures);
  - media (to disseminate information).

Box 9: How effective is the warning system?

The effectiveness of warnings hinges on many factors, including:

- The quality of the data, how they are shared, and the methods used to communicate the information
- The extent of political commitment: to what extent are warnings part of the overall government plan and how well are they coordinated?
- The efficacy of the communication and dissemination system

Warnings are much more effective if the population has been previously advised (through community awareness and education sessions) on how to interpret them and how to respond to them.

Local communities should be sufficiently aware in advance of the hazards to which they are exposed so that they can understand the advisory warnings. The responsible authorities at different levels should prepare and issue the hazard warning. International bodies can provide the means for sharing and exchanging data and relevant knowledge to ensure the development and operational capabilities of national authorities.

Challenges

The main challenges for flash flood risk management are listed in Box 10.

Box 10: Challenges to flash flood risk management

Poverty: Poverty challenges sustainable livelihoods and affects resource extraction patterns and environmental conservation.

Climate change: The various impacts of climate change, such as increased frequency of GLOF events and changes in agricultural cropping patterns, are a challenge to the security and resilience of flood prone communities.

Poor hydrometeorological data and information: Lack of reliable information hinders the ability to forecast extreme events, intensity, and magnitude of rainfall and runoff.

Transboundary nature of rivers: Insufficient data sharing, differing institutional structures, lack of collaborative political will, and differing management priorities of countries sharing a river put people on both sides at risk.

Differential access and control over resources: Some groups (e.g., women, children, the elderly, and the disabled) have unequal access to resources, information, and decision making; this makes them particularly vulnerable during disasters.

Policy and institutional gap: Many levels of government lack policies for flash flood risk management, institutional mechanisms to deal with flood disasters, and/or coordination among stakeholders.

Session 11 Modelling Tools for Flash Flood Management

Time: 60 minutes

Objectives

To introduce modelling tools for flash flood management, including:

- Tools that can be used to understand different flash flood scenarios
- Hazard-specific modelling tools

Activities

Activity 11.1: Modelling flash flood scenarios

Time: 20 minutes

Engage the class in a short question and answer session to see how familiar they are with the various types of software and modelling tools that are available for flash flood modelling.

Give a quick introduction to the two types of flash flood models, i.e., rainfall-runoff models and runoff routing (to the catchment) outlet models.

Activity 11.2: Hazard-specific modelling tools

Time: 40 minutes

Step 1 Discuss satellite rainfall estimation and how it is helpful in hydrological modelling.

Step 2 Discuss computer software models that can be used to understand the various intense flash flood scenarios.

Step 3 Discuss the computer software models used to simulate dam failures.

Session 11 Resource Materials

RM 11.1: Modelling flash flood scenarios

There are two basic components to modelling flash flood scenarios. The first component is to convert rainfall into run-off and the second is to determine how that run-off will route to the catchment outlet.

Rainfall runoff model

Rainfall runoff models simulate the behaviour of watersheds, channels, and other water-control structures. They can help to predict runoff volumes, peak flows, and the timing of flows by simulating the behaviour of watersheds, channels, and reservoirs.

Flood routing model

Flood routing models compute the progressive time and shape of flood waves at successive points along a river. Flood routing is also called storage routing or stream-flow routing. Flood routing models are numerical methods used to estimate the movement of flood waves along a channel reach. They are based on knowing the discharge hydrograph at the upstream end and on knowing the hydraulic characteristics of the reach; they typically assume that there is no perturbation coming from the downstream.

RM 11.2: Hazard specific modelling tools for flash flood management

Satellite rainfall estimation

Precipitation is a crucial part of the hydrological cycle. The spatial and temporal variations of precipitation are enormous. An accurate global coverage of rainfall records is necessary to improve weather and climate predictions. Rain gauge data are available only from stations that are on land (where they are located mainly in densely populated areas), and little offshore information exists.

Rainfall can be estimated remotely, either from ground-based weather radars or from space-based satellites. The use of satellite-based rainfall estimates in the HKH region will enable a more thorough, accurate, and timely analysis of weather and climate-related phenomenon by providing accurate rainfall estimates. The use of satellite data can help to improve the analysis of precipitation which is currently interpolated solely from sparse rain gauge data. Satellite data can also be useful in agricultural and hydrological applications such as crop monitoring and stream flow modelling. Mitigation measures for weather-related disasters can always use more accurate and timely information in the decision-making process.

Why satellite rainfall estimation?

It has been a constant challenge to represent the spatial distribution and quantity of precipitation at the small scale throughout the region since only a sparse rain gauge network has been available. When rain gauge data are not available or sufficient, satellite data can be used to derive quantitative estimates of precipitation that are then fed into hydrological models which can forecast discharge. This is one way to overcome the problem of data scarcity in the HKH region.

Computer-based modelling tools and their capabilities

Geographic information systems (GIS). A GIS captures, stores, analyses, manages, and presents data that are linked to location. In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology. GIS systems are used in many disciplines, such as geography, hydrology, climatology, land surveying, utility management, natural resource management, photogrammetry, urban planning, emergency management, navigation, and most importantly, flash flood modelling and mapping, hazard mapping, and flash flood risk management.

HEC-GeoHMS. HEC-GeoHMS was developed by the United States Army Corps of Engineers' Hydrologic Engineering Center (USACE/HEC) as a geo-spatial hydrology toolkit for engineers and hydrologists with limited GIS experience. The program allows users to visualise spatial information, document watershed characteristics, perform spatial analysis, delineate sub-basins and streams, construct inputs to hydrologic models, and it also assists them with report preparation. It creates hydrological inputs that can be used directly with the Hydrologic Modelling System, HEC-HMS.

HEC-GeoRAS. HEC-GeoRAS is an extension to be used with Arc View GIS (a general purpose geographic information system software program developed and copyrighted by the Environmental Systems Research Institute, Inc., (ESRI) Redlands, California. HEC-GeoRAS processes geospatial data for use with USACE/HEC's River Analysis system (HEC-RAS, see below). The extension allows users to create HEC-RAS import files that contain geometric attribute data from existing digital terrain models (DTMs) and to process results obtained from HEC-GeoRAS.

HEC-HMS. HEC-HMS was developed by USACE/HEC and is capable of simulating the precipitation-runoff in dendritic watershed systems. It was designed to be applied in a wide range of geographic areas and to solve the widest possible range of problems, from large river basin water supplies and flood hydrology to small urban or natural watershed runoff. Hydrographs produced by this program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanisation impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operations.

The program is a generalised modelling system that is capable of representing many different watersheds. A model of the watershed is constructed by separating the hydrologic cycle into manageable pieces and constructing boundaries around the watershed of interest. Any mass or energy flux in the cycle is simulated by a mathematical model. In most cases, the user can choose between several available models for each flux. Each mathematical model included in the program is tailored to a given set of environmental conditions. Choosing the correct model requires having both prior knowledge of the watershed and knowing what the goals of the hydrologic study are, as well as engineering judgment. The program features a completely integrated work environment including a database, data entry utilities, computation engine, and tools for reporting results. A graphical user interface allows the user seamless movement between the different parts of the program. Program functionality and appearance are the same across all supported platforms.

NWS Breach. The NWS Breach program was developed, in 1988, by Professor DL Fread, Senior Hydrologist with the Hydrologic Research Laboratory, United States National Weather Service. This program mathematically models the breaching of an earthen dam either by overtopping or by a piping failure. The program predicts the dam-breach characteristics, such as size, shape, and time of formation, and graphs the breach outflow hydrograph.

BOSS DAMBRK. BOSS DAMBRK is an enhanced version of the NWS DAMBRK model. This software can be used to analyse dam and bridge failures, storage effects, and floodplain overbank flow and flood wave attenuation. It is used for one-dimensional hydrodynamic flood routing, dam safety analysis, and reservoir spillway analysis. The program can take into account reservoir inflow, breach formation, spillway and turbine flow, downstream tail water elevations, valley storage, frictional resistance and lateral inflows and outflows. It estimates flood wave travel time, time to flood stage, time to peak elevation, and the corresponding water surface elevations.

HEC-RAS. HEC-RAS was developed by USACE/HEC and is capable of performing one-dimensional steady and unsteady flow water surface profile calculations.

Geospatial Stream Flow Model (GeoSFM). GeoSFM is a semi-distributed hydrological model for wide-area hydrology analysis. It uses globally available terrain, soil and land cover data, and satellite derived estimates of daily rainfall. The model outputs include stream flow and flood hazard maps.

Session 12 Integrated Flash Flood and Watershed Management

Time: 90 minutes

Objectives

To introduce the concepts of integrated flash flood and watershed management, including:

- An integrated approach to flash flood management
- The major components of watershed management
- Watershed management measures

Activities

Activity 12.1: Integrated flash flood management (IFFM)

Time: 45 minutes

Step 1 Discuss the traditional approaches to flash flood management.

Step 2 Discuss the shifting paradigm in flood management.

Step 3 Discuss the concept and objectives of IFFM.

Step 4 Discuss the key elements of IFFM in the context of integrated water resource management (see Box 11 in RM 12.1)

Note to the trainer

Engage the class in a quick question and answer session to help you assess how much they have understood about IFFM and what it aims to achieve.

Reiterate that IFFM aims to:

- support sustainable development by balancing development needs and flood risk;
- support livelihood security and reduce vulnerability by ensuring that different activities of poverty alleviation are incorporated into the planning;
- use environmental preservation as a means of flood prevention;
- reduce the number of lives lost.

Also reiterate that IFFM is an attempt to integrate:

- land and water management;
- upstream and downstream concerns;
- structural and non-structural measures;
- short-term and long-term strategies;
- local- and basin-level measures;
- top-down and bottom-up decision making;
- development needs with ecological and economic concerns;
- institutions with different functions.

Activity 12.2: Concept and components of watershed management

Time: 15 minutes

Step 1 Define what a watershed is. Show the map of a water basin and point out the major rivers, the minor rivers, and the contour lines. Alternatively, clarify the concept of a watershed by drawing a map on the board. Remember to include major rivers, minor rivers, and contour lines. On either map, draw a line around the basin boundary and indicate the different watersheds and sub watersheds. Explain that a major water basin can have several watersheds.

Step 2 Present the major components of a watershed.

Step 3 Present the benefits of watershed management:

- Improved water availability
- Improved water quality
- Reduced risks of natural disasters
- Higher crop yields
- Increased biomass cover
- Improved soil quality
- Increased possibilities for income generating activities
- Improved habitats for flora and fauna and, therefore, improved biodiversity

Activity 12.3: Watershed management measures

Time: 30 minutes

Step 1 Present the major watershed management measures, such as land-use management, agricultural remodelling, watercourse maintenance, and bioengineering.

Step 2 Discuss the major activities of land-use management and how they apply in different land types (e.g., agricultural land, forests, pastureland, and settlements).

Step 3 Discuss the various methods of agricultural remodelling such as multiple cropping and modified cropping patterns. Inform participants that information on the extent and timing of floods in a given area can be collected using various participatory rural appraisal (PRA) tools. The information gathered can be used to generate an agricultural 'calendar'. With this information in hand, farmers can be advised on how to time their cultivation calendar so as to avoid the major flood periods. They can also be advised on what other suitable crops can be planted in the flood-free period.

Step 4 Discuss watercourse maintenance and floodplain management that includes flood hazard mapping with zoning areas on both sides of rivers. Mention that it shows the different zones with various levels of flood hazard to support management intervention: watercourse maintenance can also be done using social hazard mapping technique with the support of GIS.

Step 5 Explain the role of bioengineering in helping to stabilise and protect slopes and minimise runoff. Discuss how trees, grass, shrubs, and other vegetation can be used alone or in combination with small-scale structural measures.

Note to the trainer

Local people usually know most of the watershed management measures since these are based on local knowledge and common practices. Some of this knowledge and these practices can be shared with and replicated in other places if they are sustainable. In addition to local knowledge, simple scientific techniques such as bioengineering, techniques of jute netting, and small structural measures can be implemented. Watershed management should consist of both structural and non-structural measures.

Session 12 Resource Materials

RM 12.1: Integrated flash flood management

Even though floods provide important ecosystem services, they have traditionally been viewed as negative phenomena and their positive attributes have been largely ignored. Accordingly, flood management has largely been problem driven, with most activities implemented after a severe flood. Different structural, non-structural, physical, and institutional interventions are possible at different phases, i.e., before, during, and after the disaster. Flood management often conflicts with activities of other sectors, such as construction, agriculture, and water resource management. Traditional approaches to flood management have focused mainly on reducing runoff by controlling water at the source, storing runoff, enhancing the capacity of the river, putting adequate separation between the river and the population, emergency management, and flood recovery. The emphasis has been on control rather than on management. Flood control measures have usually been planned in isolation from other development, they have commonly been reactive rather than proactive, they have focused on structural measures, sought solutions from mono-disciplines, and integrated flood management policies have been neglected (for details see WMO 2009).

Climate change projections suggest that in future there will be an increase in the frequency and magnitude of flash floods, and that there will be a wider distribution of flood events. A new concept of flood management emphasises the need to find ways of making life sustainable even in flash flood prone areas and floodplains, even when there is considerable risk to life and property. The IFFM approach integrates water resource management, land-use management, and hazard management; it changes the flood management paradigm from defensive to pro-active, from ad-hoc to integrated flood management. It focus on managing and living with floods, balancing floods for sustainable development, and approaching the decision-making process differently by learning to manage risk (WMO 2009).

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 (Global Water Partnership Technical Advisory Committee 2000, cited in WMO 2009). 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.

Integrated flash flood management (IFFM) promotes an integrated approach (Box 11); it advocates the integrated development of land and water resources in a river basin within the context of IWRM, and it aims at maximising the benefits of using floodplains and minimising loss of life from flooding. Furthermore, it focuses on environmental conservation and sustainable development.

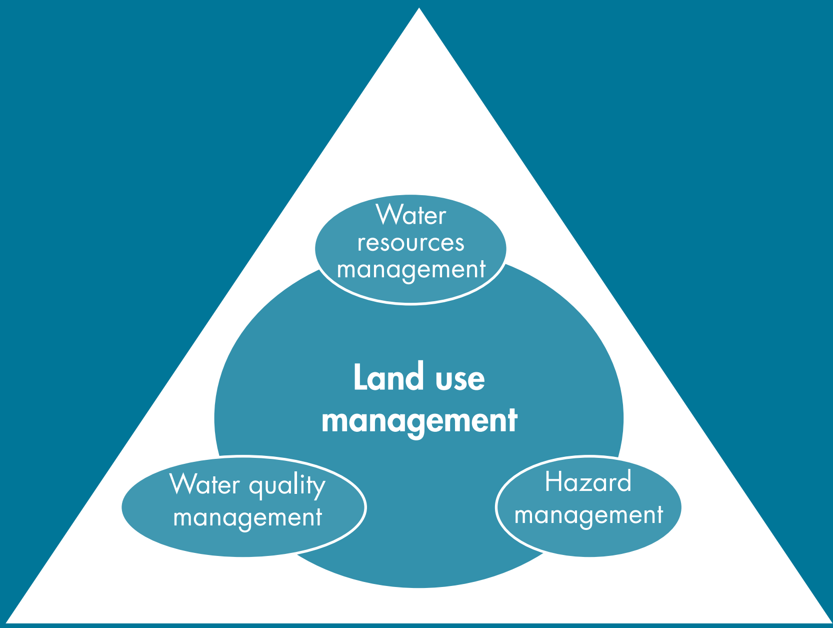
IFFM has four major components: water resources management, water quality management, hazard management, and land use management (Figure 13). Integrated flash flood management recognises the river basin as a dynamic system in which there are many interactions and fluxes between land and water bodies. In IFFM the starting point is a vision of what the river basin should be. Incorporating a sustainable livelihood

Box 11: Major elements of IFFM

- Managing risk
- Seeing floods are part of the water cycle
- Taking a multi-hazard approach; flash floods give rise to ancillary hazards
- Using the river basin as a planning unit
- Looking at all aspects - interdisciplinary
- A participatory approach involving the whole community

perspective means looking for ways of identifying opportunities to enhance the performance of the system as a whole. IFFM does not only reduce the losses from floods but also maximises 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 optimising the use of floodplains. Increases in flood losses can be consistent with an increase in the efficient use of floodplains, in particular, and the basin as a whole, in general (Brilly 2001).

Figure 13: **Integrated Flash Flood Management Model**



An integrated flash flood management scheme involves integrated strategies for both structural and non-structural measures and for living with floods, as well as both short- and long-term, and local- and basin-level measures. It aims to balance development with a focus on environmental conservation. It includes several aspects of flood management such as, scientific and engineering, social, environmental, economic, legal and institutional.

Key elements of IFFM, following from flood management in the context of IWRM

Managing the water cycle as a whole. Flood management plans need to be integrated with drought management plans in order to make effective use of floodwaters and to maximise the positive aspects of floods. Flood and drought management should also be linked with groundwater management, as the role that floodplains play in recharging groundwater cannot be neglected; and with urban flood management and urban water management, particularly drinking water supply, sewerage, and wastewater and surface runoff disposal.

Integrate land and water management. The water quantity, water quality, and the process of erosion and deposition within a river basin are all linked. The type and density of the vegetative cover and the area's land-use characteristics are all important in understanding how the catchment responds to rainfall. Thus, integrated planning of land and water, both upstream and downstream, is essential and is advocated in IFFM.

Manage risk and uncertainty. People often choose to live in flood prone areas where risk to property and life is high, such as floodplains, because these areas provide livelihood opportunities and resources. Therefore, policy should consider risk at the individual, household, and community levels, and in the context of livelihoods, poverty alleviation, and socioeconomic development. Importantly, flood risk is associated with uncertainties, especially regarding hydrometeorological processes. Social, economic, and political uncertainties also affect the choice of management strategies.

Ensure a participatory approach. IFFM should be based on a participatory approach; it needs to be open, transparent, inclusive, and communicative, and the decision making needs to be decentralised. A bottom-up approach is often considered the best; however, an extreme bottom-up approach can entail a risk of fragmentation rather than integration. On the other hand, top-down approaches can require greater effort and can undermine the intentions of the responsible local institutions. It is important to use an appropriate mix to benefit from the strengths of both approaches.

Institutional synergy. Institutions all have their own geographical and functional boundaries, but for an optimal outcome it is necessary to fold all diverse views and opinions into the decision-making process. The activities of local, regional, and national development agencies, including private agencies working in agriculture, urban and watershed development, mining, poverty alleviation, environmental conservation, and forestry, should be coordinated at the appropriate levels. The challenge is to promote cooperation and coordination across functional and administrative boundaries.

Adopt the best mix of strategies. The optimal strategy for a given area will depend 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 of the region. Quite different strategies are likely to be appropriate in different situations and different countries. The strategies often involve a combination of complementary options in a layered approach (Table 7). IFFM discards isolated perspectives. Successful IFFM entails looking at the situation as a whole, comparing the available options, and selecting the strategy or combination of strategies, both structural and non-structural, that is most appropriate to the particular situation.

Table 7: **Strategies and options for flood management**

Strategy	Options
Reducing flooding	Dams and reservoirs
	Dike, levees and flood embankments
	High flow diversion
	Catchment management
Reducing Susceptibility to damage	Floodplain regulation
	Development and redevelopment policies
	Design and location of facilities
	Housing and building codes
	Flood proofing
	Flood forecasting and warning
Mitigating the impacts of flooding	Disaster preparedness
	Past flood recovery
	Flood insurance
Preserving the natural resources of flood plain	Flood plain zoning and regulation

Source: WMO (2009)

Integrated hazard management approaches. Communities are exposed to various natural and human-made hazards and risks. IFFM should be integrated into a wider risk management system. Since hazards such as landslides or GLOFs upstream have the potential to generate or modify the flood risk downstream, a holistic approach is essential. This type of approach can lead to structured information exchange and the formation of effective organisational relationships. The advantage of a holistic approach is that it brings together many different disciplines to speak with a single voice. This is beneficial in dealing with communities because effective early warnings for all forms of natural hazards are best accepted if they emanate from a single, officially designated authority with a legally assigned responsibility.

RM 12.2: Concept and components of watershed management

Simply put, a watershed is a land area from which a river receives its water supply. Small rivers have small catchment areas; large river systems cover a large area consisting of several small rivers. The components of a watershed are social (e.g., population, settlements), environmental (e.g., agricultural lands, forests, water, rangelands), and physical (e.g., slopes, ridges, valleys). People use the environmental components or resources to meet their livelihood and other needs. The sustainable use of these resources is very important to control runoff and erosion and to help manage the flash floods. The community also manages the floods using non-structural measures.

Watershed management is a holistic approach to natural resource management in which communities try to maintain watersheds and improve soil fertility and biomass coverage since these provide key resources for their livelihoods. Watershed management has three phases: the identification of users and the preparation of a watershed management plan; putting the plan into practice; and long-term implementation of the plan.

RM 12.3: Measures of watershed management

Watershed management is basically the proper use of land. It involves the use of both structural and non-structural measures for controlling runoff and erosion. Land-use management (Box 12), modification of cropping, watercourse maintenance, and bioengineering are primary management interventions for which community participation is very important.

Box 12: Some land-use management measures

- Terracing, terrace improvement
- Avoiding cultivation on slopes >25%
- Reforestation
- Grazing regulation
- Trail management

Land use management

Land use management consists of two major activities to reduce flash flood risk: management of settlements, and management of agricultural land and forests.

The development of settlements in a flood zone must be restricted or follow rules for special housing design. Such settlements near flood zones not only put people at risk, they also alter the natural flow of water which increases the overall risk to the whole area.

Different factors such as population growth and poverty have compelled people to convert forests and pasture lands into farmlands. Overgrazing of pasture lands adversely affects soil stability and plant cover. Moreover, it leads to a decrease in the interception and infiltration of rainwater, both of which enhance surface runoff. Thus, proper land use management activities such as terracing, reforestation, pasture regulation, trail management, and avoiding cultivation on steep slopes are important.

Land use control has much in common with floodplain management. Land use regulations are designed to reduce danger to life, property, and development when flash floods occur. Some land-use regulations include reducing the population density in flash flood prone areas (to reduce the number of potential casualties), preventing development (especially the construction of houses in the high risk areas), and maintaining natural water courses.

Cropping modifications

Floods can damage crops at any stage of their development, from the seedling stage to just prior to harvesting. Strategies for minimising the adverse effects of recurrent floods on agriculture include multiple cropping and restructuring of the cropping pattern (Swaminathan 1980). An example of multiple cropping in low-lying areas is the cropping of medium-tall Ahu rice with deep-water rice as insurance so that if the Ahu rice is damaged there will be some production from the deep-water rice. Restructuring of the cropping pattern builds on the idea that the safest way to assure crop production in flood prone areas is to grow more crops during the flood-free period.

Watercourse maintenance

Maintenance and restoration interventions in natural and artificial watercourses are necessary to assure that these waterways offer maximum discharge capacity during strong flood events. Watercourses often change their paths, but human activities such as quarrying river materials (sand, stone, water itself) can intensify this meandering process. It is wise to leave watercourses in their natural state. General maintenance measures for watercourse areas include the following.

- Delineate a buffer zone in the floodplain and restrict settlement and agricultural activities in this area.
- Develop the floodplain as an ecological corridor.

- Do not interfere with the natural course of water.
- Maintain watercourse reaches that are still in their natural state.
- Protect specific habitats.
- Undertake structural interventions to improve ecological functions. Activate old branches and create biotopes where necessary to comply with the ideal conditions established by environmental models.
- Undertake flood damage prevention measures.
- Take measures to counter harmful local influences that could be detrimental to the whole system, such as erosion and sedimentation.
- Maintain natural depressions that act as natural retention areas during floods.

Bioengineering

Bioengineering is the integration of vegetative methods with simple engineering practices. It can be very effective for watershed management using local resources (Bhatta et al. 1999). For example, bioengineering can be used to stabilise mountain slopes. Commonly practiced bioengineering techniques that can be used to stabilise slopes and to help minimise runoff include: planting trees, shrubs, and grasses (Li 1999; Wagley 1999). These can be planted on degraded slopes, either alone or in combination where together a dense network of roots in the soil and a canopy overhead helps to protect the slope from erosion, which in turn prevents landslides that can dam rivers. The type of vegetation that should be planted depends on the purpose, site condition, and availability of resources.

Bioengineering measures include the following.

- Planting woody vegetation along the contours to trap soil particles and debris moving down the slope.
- Seeding grass, trees, and shrubs directly on site, either alone or in combination. Seeds can be broadcast to cover large areas in a short time at low cost. This method can be used on steep, rocky, and unstable slopes where seedlings and cuttings cannot be planted directly.
- Planting bamboo or broom grass (rooted culm cuttings, rhisomes, or wild seedlings) to stabilise slopes.
- Wattling. Bundles of live branches with buds are put into trenches along contours and are covered with a thin layer of soil. When the branches put out roots and shoots, a strong vegetative barrier is formed that is effective in retaining the soil and stopping its movement down the slope.
- Creating brushwood check dams of bamboo and wood to stabilise gullies on slopes.
- Vegetated riprap. Side slopes of gullies and gully beds can be protected by constructing dry stone walls and sowing or planting grass in the gaps between the stones to reinforce the toe walls and gully beds.
- Constructing loose stone and gabion check dams to stabilise slopes. After the construction of the check dam, seedlings of trees, shrubs, and grasses are planted either separately or in combination on the gully heads, side slopes, and gully beds, and in and around the structure for reinforcement.
- Using jute netting to protect grass slips or seedlings planted on slopes during their early growing period. Later, once the plants are established and the netting is no longer needed, the jute decomposes into the soil.

Watersheds consist of both upstream and downstream components. For sustainable development and risk management, an integrated watershed management approach is essential. An integrated approach can introduce stall feeding to help reduce overgrazing of pasture, for example, and/or introduce biogas or solar power for household activities to reduce dependence on natural resources. Good governance, transparency, and unity in a community are fundamental requirements of proper watershed management.

Session 13 Hazard-Specific Flash Flood Management: Intense Rainfall Floods

Time: 60 minutes

Objectives

To introduce the characteristics of intense rainfall floods and to introduce forecasting as a tool for flash flood risk management, including

- The methods used to measure rainfall and to estimate catchment rainfall
- The correlation between rainfall and runoff and the factors that affect catchment runoff
- Discharge and the methods used to measure discharge
- Flood routing and the methods used to determine hydrographs
- Flood frequency and return period

Activities

Activity 13.1: Rainfall measurement and catchment rainfall

Time: 10 minutes

Step 1 Present and discuss the various types of precipitation (e.g., rain, snow, hail). Explain how rainfall is measured and recorded.

Step 2 Distinguish between 'total rainfall' and rainfall intensity. Discuss how knowing the intensity of the rainfall over a short period is more important for predicting flash floods than knowing the total rainfall over a longer period.

Step 3 Discuss how data from a rain gauge can be used to estimate rainfall at the catchment level using methods such as the arithmetic average, the Theissen polygon method, and the isohyetal method.

Step 4 Discuss the importance of rainfall measurements for flash flood forecasting and preparedness.

Activity 13.2: Runoff and factors that affect it

Time: 10 minutes

Define runoff and peak runoff rates and discuss the factors that affect runoff. Discuss how rainfall and runoff are related.

Activity 13.3: Discharge and methods of measuring it

Time: 15 minutes

Define discharge and explain how it is measured. Explain what a rating curve is.

Activity 13.4: Flood routing and calculating hydrographs at different locations

Time: 15 minutes

Step 1 Discuss the concept of flood routing and differentiate between hydrologic and hydraulic routing. Explain why flood routing is important for flash flood management.

Step 2 Discuss the various types of routing methods. Assign a simple exercise on flood routing where the participants have to calculate flow values at different times and locations. (See Box 13 in RM 13.4 for the exercise.)

Activity 13.5: Flood frequency and return period

Time: 10 minutes

Step 1 Define flood frequency and return period, and discuss the method used to determine return periods.

Step 2 Discuss why return period is an important parameter for flash flood management.

Session 13 Resource Materials

RM 13.1: Rainfall measurement and catchment rainfall

Rainfall measurement

Rainfall is a main source of water supply; other forms of precipitation include snow, hail, sleet, mist, dew, and fog. It is important to measure rainfall in order to be able to forecast and prepare for flash floods. In the case of riverine floods, the total amount of rainfall during a period of time is important. The total amount of precipitation can be measured using simple rain gauges. However, for flash floods, the total amount is less important than the intensity of the rainfall, since high-intensity rainfall for even for a short period of time can cause a flash flood. The intensity of rainfall cannot easily be determined by manual rain gauges. More appropriate are recording-type rain gauges that give a continuous record of rainfall which can be resolved into desired time intervals; examples of these are tipping bucket or siphon-type gauges.

A rain gauge gives a point measurement at a particular location, but intense rainfall can be also spatially variable, particularly in mountain areas. A dense network of rain gauges is needed to obtain a reliable spatial survey of rainfall in a catchment. If it is not possible to deploy a large number of gauges then, it is important to identify the key locations in the catchment that can provide the most crucial information for flash flood risk management.

Catchment rainfall

For flash flood risk management measures such as forecasting or modelling, point data from rain gauges alone are not sufficient. The data must be transformed into spatial data or area-averaged data for the catchment. Several methods can be used to calculate area averages. The simplest is to calculate the arithmetic average of rainfall in each rain gauge; however, this method cannot capture spatial variability and is seldom used.

A simple method is the Theissen polygon method, which uses an average based on the assumption that a gauge best represents the rainfall in the area nearest to it. The resulting polygons represent the areas closest to each gauge. 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.

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. There are various computer software models available that use sophisticated algorithms to generate isohyets. Some incorporate terrain characteristics in generating the map. Raster maps of rainfall distribution over an area can also be generated. Raster maps represent continuous rainfall fields over the area of interest. As needed, average rainfall at different spatial scales can be calculated from the raster maps.

RM 13.2: Runoff and factors that affect it

Runoff

The rainfall in a catchment is stored either on the surface or as moisture in the soil; part of it is lost by evaporation and part by transpiration. Only some of the rainfall, known as excess rainfall or effective rainfall, contributes to runoff from the catchment. In order to estimate the size of the flood that can be generated by a given amount of rainfall, the runoff must be calculated.

Table 8: **Factors affecting catchment runoff**

Climate	Physiographic: Basin characteristics	Physiographic: Channel characteristics
Forms of precipitation (e.g., rain, snow, hail)	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 and artificial drainage)	Storage capacity (backwater effects)
Transpiration (e.g., temperature, solar radiation, wind, humidity, soil moisture, type of vegetation)		

Source: Chow (1984)

Runoff from a catchment is affected by climatic factors and physiographic factors. Climatic factors vary with the seasons. Physiographic factors can be further classified as either basin or channel characteristics (Table 8).

Several complicated computer models are 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 3.1.0 model developed by the United States Army Corps of Engineers' Hydrologic Engineering Center (USACE/HEC 2011).

RM 13.3: Discharge and methods of measuring it

Discharge

The quantity of water flowing though a channel (natural or artificial) is known as discharge, sometimes it is also referred to as stream-flow. In the metric system, discharge is measured in m^3/sec system and is sometimes denoted as cumecs. In the English system, discharge is typically measured in ft^3/sec, sometimes denoted as cusecs. The discharge and the nature of the channel (e.g., cross-section area, slope, roughness of the channel) determines the extent of flooding in a given location. The graph showing discharge as a function of time is called a discharge hydrograph or stream flow hydrograph. The hydrograph can be an annual hydrograph or an event hydrograph. Annual hydrographs plot annual average discharge fluctuations over the course of a year while event or storm hydrographs show the peak discharges that occur during a particular storm event.

Measurement of discharge

Discharge can be measured in many ways. The following are a few of the more common methods.

Velocity area method. This is the most commonly used method. The cross-section of the river is divided into several vertical sections and the velocity of the water flow is measured at a fixed depth in each section. A current meter is used to measure the velocity of the water. Generally, the velocity is measured at 20% and 80% of the river's depth (*d*) (referred to as 0.2*d* and 0.8*d*, respectively). The velocity can be measured from a cable car, or if the depth is low, a wading technique can be used. 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 entire cross-section.

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

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 the discharge measurement is being conducted. The distance between the markers is measured and the cross-sectional 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 times at which the float crosses the first and the second marker are noted.

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:

$$Q = A \times V_m$$

where A is the cross-sectional area of the stream.

Dilution method. This method is particularly appropriate for mountain streams where due to the gradients, the turbulence is high and measurements by the current meter method are not possible. A tracer of known concentration is put in the water at 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 absorbed either by the bed materials of the stream or 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. The concentration at the downstream end is determined by collecting a water sample 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. The discharge Q is calculated by using following equation:

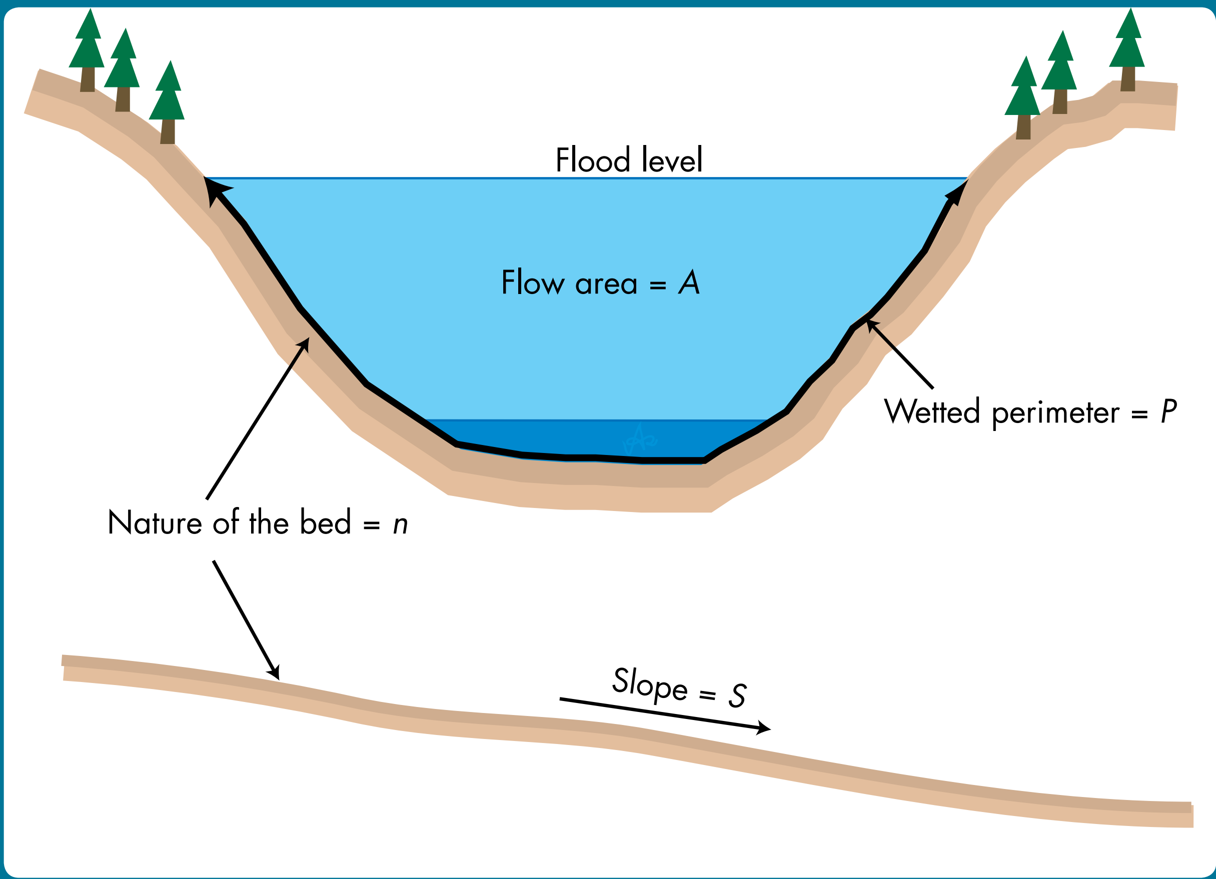
$$Q = q \times \frac{C_1 - C_2}{C_2 - C_0}$$

where q is the injection rate of the tracer and C_1, C_2, and C_0 are the concentrations of the tracer during injection, at the downstream end (sampling point), and in the background concentration of the stream water, respectively.

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

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

Figure 14: **Slope area method**



Source: Shrestha (2008)

where *n* is the Manning coefficient, *R* is the hydraulic radius, and *S* is the longitudinal slope (see Figure 14).

The steps for estimating discharge using the slope area method are as follows:
Step 1: Select as straight a section of the river with as uniform a slope, cross-section, and roughness as possible.

Step 2: Conduct a detailed survey of the river reach, and estimate its Manning roughness coefficient, *n*. The Manning coefficients are given in Table 9. The highest flood mark should also be recorded.

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

The values obtained are used to calculate the flow velocity during the flash flood using the Manning equation. Then the discharge, *Q*, is calculated using $Q = A \times V$.

RM 13.4: Flood routing and calculating hydrographs at different locations

Flood routing

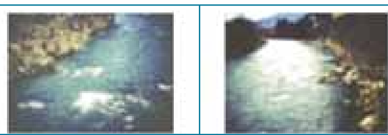
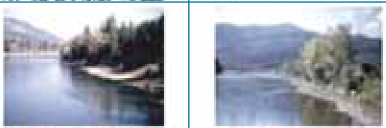
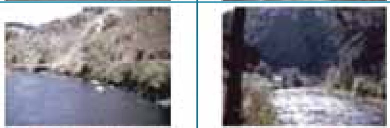
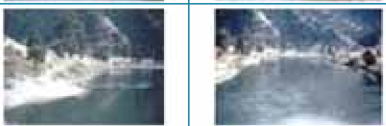
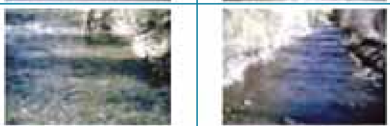
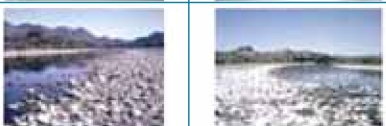
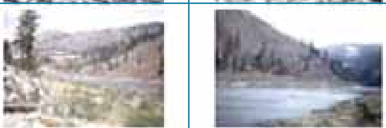
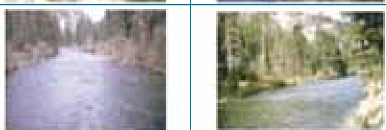
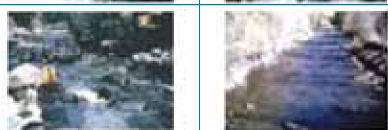
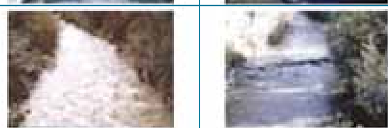
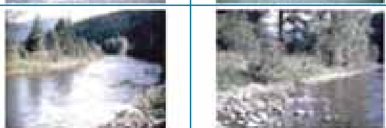
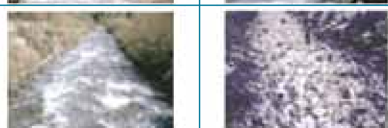
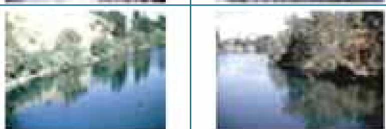
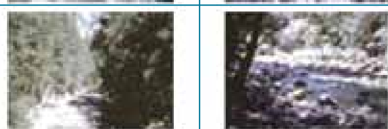
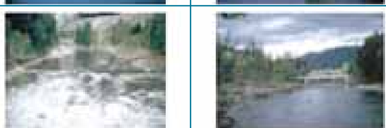
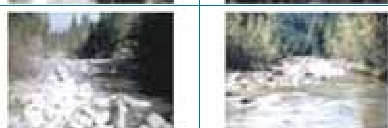
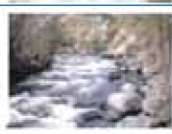
Flood routing is a procedure used to determine the time and magnitude of flow at a given point on a water course; it uses known or assumed flood parameters at one or more points upstream. The methods used to calculate the parameters are described above. Flood routing can provide information such as the impact of the flood at the locations of communities and settlements downstream of the catchment outlet. It is a highly technical procedure and various computer software programs are available to calculate this complicated flood routing.

There are two types of routing, hydrologic and hydraulic routing. Both of these methods use some form of the continuity equation.

Hydrologic routing. Hydrologic routing methods combine the continuity equation with some relationship between storage, outflow, and inflow. These relationships are usually assumed, empirical, or analytical in nature. An example of such a relationship might be a stage-discharge relationship.

Hydraulic routing. Hydraulic routing methods use the continuity equation in combination with other physical relationships that describe the physics of the movement of the water. The momentum equation is the one most commonly used. In hydraulic routing analysis, it is intended that the dynamics of the water or flood wave movement is more accurately described.

Table 9: **Values of the Manning coefficient**

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 (no date)

SESSION 13

Routing methods

The basic principle of flood routing is the continuity of flow as expressed by the continuity equation. Several methods can be used to calculate flood routing, these include: modified plus, kinematic wave, Muskingum, Muskingum-Cunge, and dynamic (Chow et al. 1988). The following discussion is limited 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.

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 exercise in Box 13 makes the method much clearer. It shows the calculation of peak discharge at 6 km distance from the origin. The calculation can be carried out in a similar way for the remaining hydrographs at 12 and 18 km distance.

RM 13.5: Flood frequency and return period

Flood frequency

Floods are recurring phenomena. The chance of a flood happening at a given location can be calculated using a probability function. One of the simplest probability functions used to determine flood intensity is the return period (*T*). It is a statistical estimate indicating the average recurrence interval based on data collected over an extended period of time. The return period is an important parameter 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/sec).

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 year. For example, a 10-year flood has 0.1 or 10% chance of being exceeded in any year while a 50-year flood has 0.02 (2%) chance of being exceeded in any year. 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.

The study of return period is useful for risk analysis (such as the natural, inherent, or hydrological risk of failure). For 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:

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

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 in years.

Box 13: Exercise on flood routing

Example:

The hydrograph at the upstream end of a river is given in the following table (Shrestha 2008). The reach of interest is 18 km long. Using a sub-reach length Δx of 6 km, determine the hydrograph at the end of the reach using the Muskingum-Cunge method. Assume C_k = 2 m/sec, B = 25.3 m, S_o = 0.001 m, and there is no lateral flow.

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12
Flow (m^3/sec)	10	12	18	28.5	50	78	107	134.5	147	150	146	129	105

Time (hour)	13	14	15	16	17	18	19	20	21	22	23	24
Flow (m^3/sec)	78	59	45	33	24	17	12	10	10	10	10	10

Solution:

Step 1: Determine K

$$K = \frac{\Delta x}{c_k} = \frac{6{,}000}{2} = 3{,}000 \text{ sec}$$

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= 3,600 sec. If we want our hydrograph to show a 2-hour interval, then we must take Δt = 7,200 sec, and so on.

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

The initial flow at 0 hours is taken as 10 m^3/sec at all three locations.

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

The flow at 1 hour at 6 km distance is given by

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

Similarly, the flow at 2 hours at 6 km distance is given by

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

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.

The flow at 1 hour at 12 km distance is given by

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

For further details, see Shrestha (2008).

Session 14 Hazard-Specific Flash Flood Management: Landslide Dam Outburst Floods

Time: 60 minutes

Objective

To introduce landslide dam outburst floods (LDOFs) and the measures that can be used to minimise the risks they pose, including:

- Types of landslides and the factors that trigger them
- Landslide dams and the factors that cause them
- How landslide dams fail
- Measures that can be used to reduce the risk of LDOF

Activities

Activity 14.1: Types of landslides and factors that trigger landslides

Time: 15 minutes

Step 1 Introduce the different types of landslides (e.g., fall, topple, slide, spread, and flow).

Step 2 Discuss what can cause landslides and their triggering factors.

Step 3 Discuss the causes and effects of the different types of landslides that can dam rivers.

Activity 14.2: Process of landslide damming and factors that can cause landslide dams

Time: 15 minutes

Step 1 Present and explain the process of landslide damming. Highlight the characteristics of possible places where landslides can dam a river.

Step 2 Discuss the factors that can cause a landslide to dam a river. Discuss the different possible compositions of landslide dams and how their composition affects their longevity. Discuss how landslide dams fail.

Activity 14.3: Case studies of landslide dam outburst floods

Time: 5 minutes

Present and discuss landslide dam outburst floods and present the case studies described in RM 14.3. Discuss the causes of landslide dam outbursts.

Activity 14.4: Measures that can reduce the risk of landslide dam outburst floods

Time: 25 minutes

Present and discuss control measures that can be used to minimise the risk of LDOFs. Focus on the following issues.

Step 1 **Landslide hazard assessment**. Discuss the methods that can be used to identify places where hazards can occur such as landslide hazard mapping using GIS. Effective assessments focus on the places where a landslide is most likely to cause the greatest damage (e.g., narrow river valleys).

Step 2 **Estimating downstream flooding**. Discuss how the magnitude of a potential flood caused by a landslide dam outburst can be estimated in order to implement the appropriate mitigation measures downstream. (See example in RM 14.4.)

Step 3 **Estimation of past floods**. Discuss how the extent of past floods can be estimated and how this estimation can be used as the basis for assessing possible future hazard and risk. Review some flood estimation methods, such as methods to estimate velocity, depth, width, and discharge. (See examples in RM 14.4.)

Step 4 **Land use regulations**. Discuss land use practices particularly in flood prone and landslide prone areas. Engage the class in a short question and answer session, asking the participants to suggest some land use regulations that can help to minimise the risk of landslide dams.

Step 5 **Early warning systems**. Explain how early warning systems can be effective in mitigating the harmful effects of outburst floods, particularly in saving lives and property.

Session 14 Resource Materials

RM 14.1: Types of landslides and factors that can trigger landslides

Landslides usually occur as secondary effects of heavy storms, earthquakes, and volcanic eruptions (Box 14). Landslides can consist of either one of two classes of material: bedrock or soil (earth and organic matter debris). Landslide are classified by the type of movement that causes them, as shown in Figure 15.

Falls. A fall is a mass of rock or other material that moves downward by falling or cascading through the air. In this category, large individual boulders can cause significant damage. Depending on the type of material involved, this type of landslide can be a rock fall, earth fall, or debris fall.

Topple. A topple occurs when overturning forces cause rocks to rotate out of their original position. A topple may not involve much movement, and does not necessarily trigger a rock fall 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 are rotational and translational slides. Rotational slides occur on slopes of homogeneous clay or shale and soil, 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; these usually occur on gentle slopes of less than 6° and typically spread only 3 to 5 m, but may move from 30 to 50 m when conditions are favourable. During an earthquake in Alaska, United States, in 1964, more than 200 bridges were damaged or destroyed by lateral spreading of flood plain deposits near river channels.

Box 14: Main triggers of landslides

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

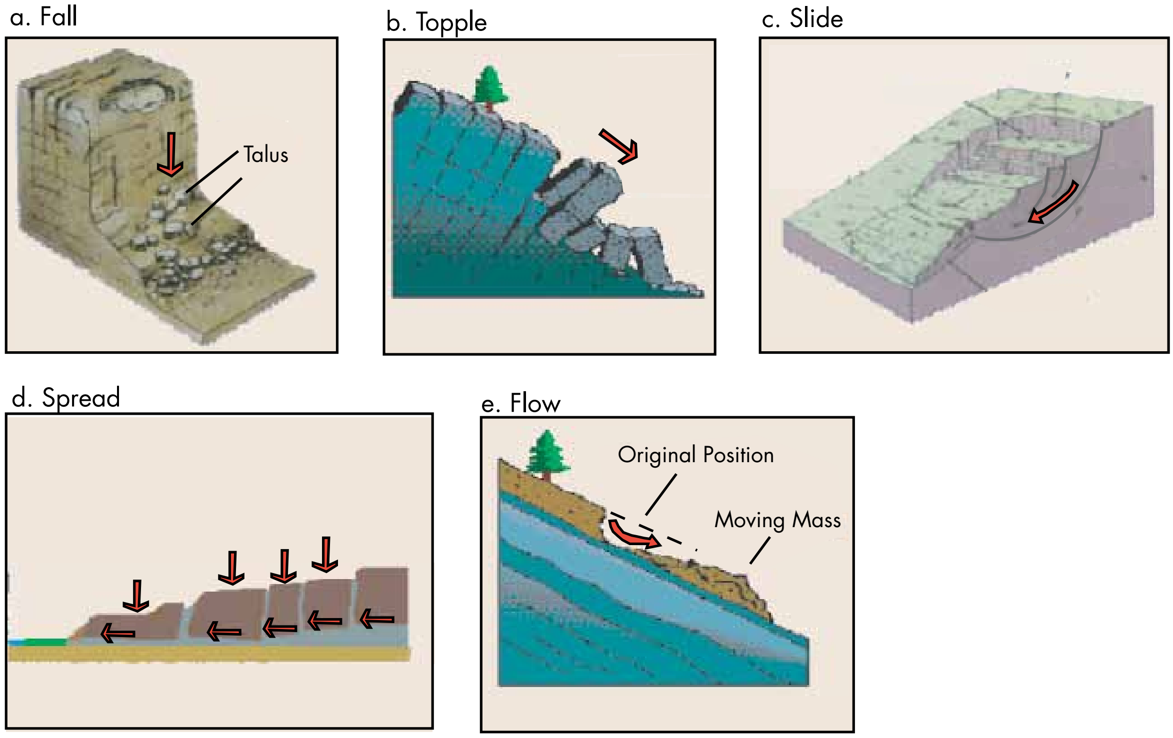
- A cumulative rainfall of 50–100 mm in one day or a daily rainfall exceeding 50 mm can cause small-scale and shallow debris landslides.
- A cumulative two-day rainfall of about 150 mm or a daily rainfall of about 100 mm in a given area greatly increases the probability and number of landslides.
- A cumulative two-day rainfall exceeding 250 mm, or an average intensity of more than 8 mm per hour in one day, rapidly increases the occurrence and number of large landslides.

Earthquakes
Earthquakes can cause many large, dam-forming landslides. Seismic accelerations, the duration of the shock, the focal depth, the angle, and the approach of the seismic waves all contribute to inducing landslides, but environmental factors such as the geology and landform are the most decisive factors. This is why small earthquakes can sometimes induce more landslides than large earthquakes.

The type of slope and the slope angle also influence the occurrence of landslides. Landslides rarely occur on slopes with a grade less than 25°. The large majority of landslides occur on slopes with grades ranging from 30° to 50°.

Source: Shrestha (2008)

Figure 15: **Types of landslides**



Source: Deoja et al. (1991)

Flows. Flows move like a viscous fluid, sometimes very rapidly, and can travel several miles. Water is not essential for flows to occur, although most flows form after periods of heavy rainfall. The different types of flow include earth flow, mud flow, debris flow, debris avalanche, and creep. Mud flows contain at least 50% sand, silt, and clay particles. A debris flow is a slurry of soil, rock, and organic matter combined with air and water. Debris flows usually occur on steep gullies. Creep is a very slow, almost imperceptible flow of soil and bedrock.

Formation and types of landslide dams

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. Excessive precipitation and earthquakes are the most important triggers that can initiate landslides that form dams (Figure 16). Other mechanisms include stream under-cutting and entrenchment.

Landslide dams can be classified geomorphologically according to their orientation relative to the valley floor (Swanson et al. 1986, in Costa and Schuster 1988) and factors causing their formation (Figure 17, Table 10).

Modes of failure of landslide dams and triggering factors

A natural landslide dam 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 and control pore pressure. It also has no channelised spillway or other protected outlet; as a result, landslide dams commonly fail by overtopping (Figure 18) (after which the overflow water erodes the dam and breaching

Figure 16: **Formation of a natural dam (left) and photograph (right) of river damming due to a landslide**

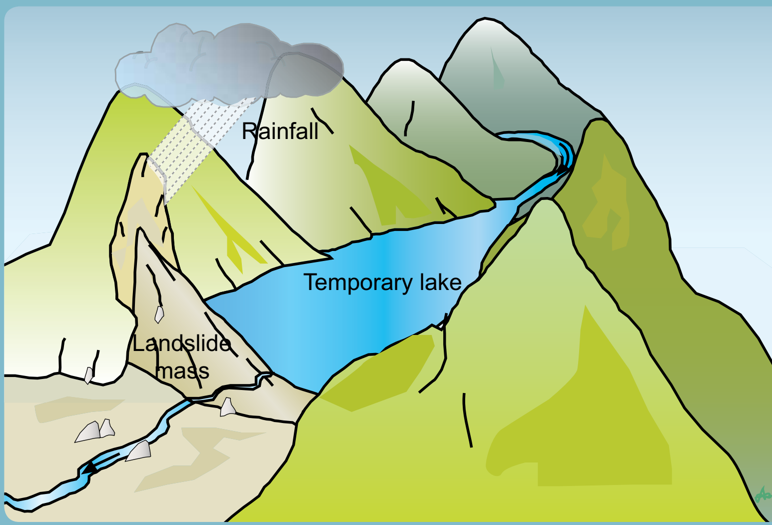
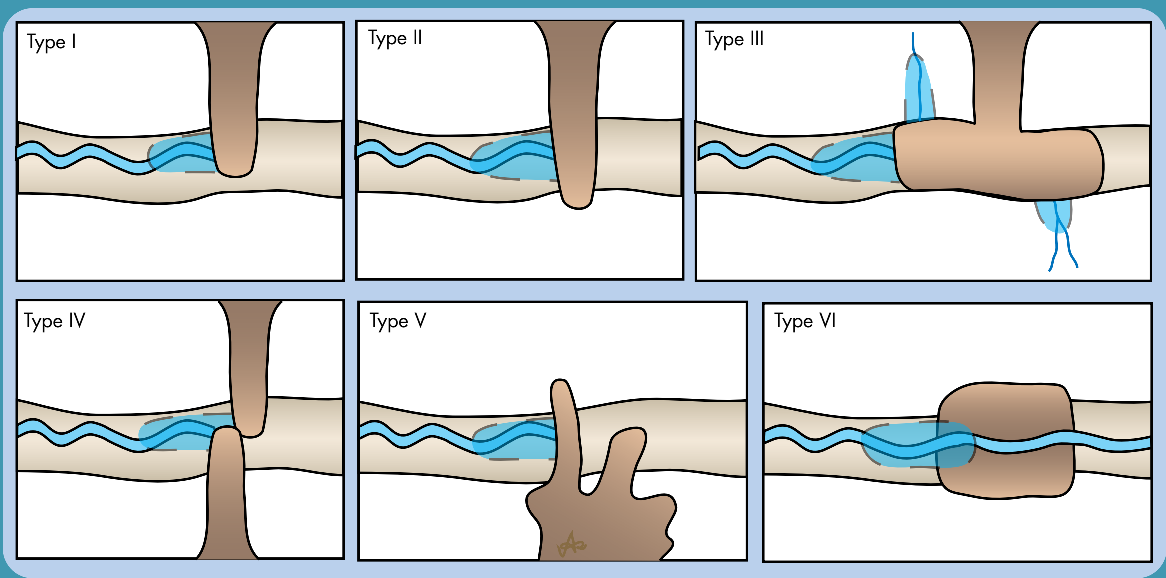


Photo source: WECS 1987

Figure 17: **Types of river-damming landslides**



Source: Based on Costa and Schuster (1988)

Table 10: **Types of landslide dams**

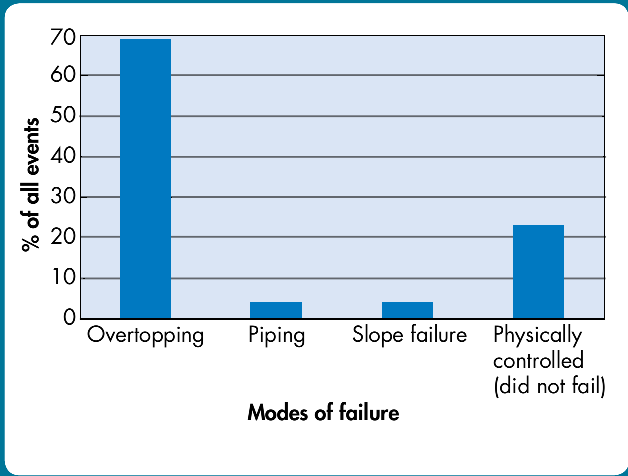
Type	Cause	Effect
I	Falls, slumps	Dams are small with respect to the width of valley floor and do not reach from one side to the other
II	Avalanches, slumps/slides	Dams are larger and span the entire valley floor
III	Flows, avalanches	Dams fill the valley from side to side and considerable distances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

Source: Shrestha (2008)

occurs). In most documented cases, the breach results from fluvial erosion of the landslide material; the head cutting typically originates at the toe of the dam and moves progressively upstream to the lake. When it reaches the lake, breaching occurs. The breach commonly does not erode down to the original level of the river bed, as many landslide dams contain some coarse material that is not swept away. Thus, smaller lakes can remain after dam failure.

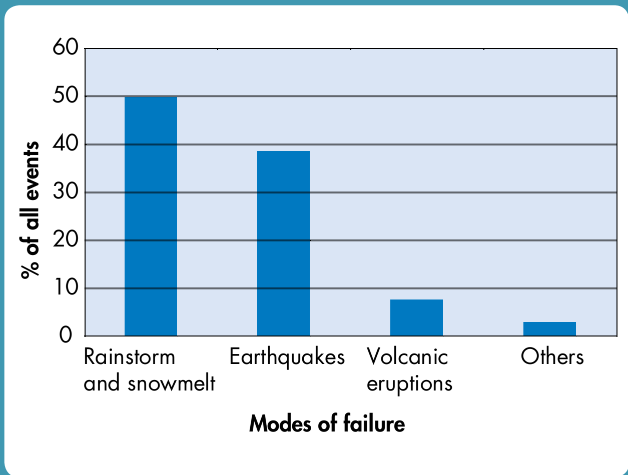
A landslide dams that have steep upstream and downstream faces and that also have high pore-water pressure are susceptible to slope failure. If a dam has a narrow cross-section or progressive slope failure, the crest may fail, leading to overtopping and breaching. Nearly all faces of landslide dams are 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 occurs when there is lateral erosion of the dam by a stream or river.

Figure 18: **Modes of failure of landslide dams**



Source: Based on Costa and Schuster (1988)

Figure 19: **Causes of landslides that form dams**



Source: Based on Costa and Schuster (1988)

RM 14.2: Process of landslide damming and factors that cause landslide dams

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

Globally, about 50% of dam-forming landslides are caused by rainstorms and snowmelt, and about 40% are caused by earthquakes (Figure 19). In the HKH region, volcanic eruptions are rare, so most landslide dams are caused by rainfall, snowmelt, and earthquakes.

Landslide dams are frequent in steep, narrow valleys bordered by high rugged mountains (Table 11). This setting is widespread in geologically active areas such as the HKH where earthquakes are common and mountain slopes are steepened by glacial activity. Steep, narrow valleys are dammed by a relatively small volume of material; thus, even small mass movements can cause landslide dams. Large landslide dams are caused by complex landslides that start as slumps of slides and become rock or debris avalanches.

Table 11: **Factors causing landslide dams**

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

Source: Shrestha (2008)

Figure 20: **a) Bhairabkunda Khola a few days after the LDOF; b) debris deposited by the LDOF; c) large boulders trapped at the highway bridge; d) Larcha village destroyed by the flash flood**

Source: NR Khanal

RM 14.3: Case studies of landslide dam outburst floods

Case 1: The Budhi Gandaki and Larcha Khola landslide dam outburst flood

In recent memory, the Budhi Gandaki River in Nepal was twice dammed near Lukubesi (Shrestha et al. 2008). In 1967, the river was dammed for three days after slope failure at Tarebhir. Another landslide in 1968 again dammed the river with a huge amount of displaced material. After the landslide dam was breached, the water level rose by 14.61 m. The peak flow was estimated to be 5,210 m^3/sec, which is significantly higher than the mean annual instantaneous flood (2,380 m^3/sec). After the breach, one bridge and 24 houses were swept away at Arughat Bazaar which is located about 22 km downstream from the damming site (Figure 20).

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

Case 2: The Tsatichhu landslide dam outburst flood

Another example of an LDOF in the HKH region is the Tsatichhu LDOF in Bhutan (Shrestha et al. 2008) (Figure 21). On 10 September 2003, material with an estimated volume of 7–12 x 10^6 m^3 failed on the wall of a valley and slid into the Tsatichhu River. The tremor cause by the landslide was felt as far away as Ladrong village some 2.5 km away. According to the inhabitants of nearby areas, the main slide occurred over a period of 30 minutes. The slide formed a river-blocking dam 110 m high. The deposited material had an estimated volume of 10–15 x 10^6 m^3. The dam crest extended approximately 580 m across the valley (Dunning et al. 2006), and the deposited material spread a distance of 200 m upstream and 700 m downstream.

Figure 21: **Tsatichhu landslide dam: a) the area at the source of the landslide; b) detailed view of the dam; c) Tsatichhu Lake**

Source: Dunning et al. (2006)

The landslide dammed the Tsatichhu river and formed a lake which was temporarily known as Tsatichhu lake. The lake extended 1 km up-valley, and had an estimated volume of 4–7 x 10^6 m^3 at its maximum level. A small surface outflow occurred in December 2003, but did not cause the dam to fail. There was also significant seepage through the dam, which together with the surface outflow maintained an equilibrium with the river inflow of 0.53 m^3/sec.

The dam survived for 10 months, then in 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, after a period of prolonged intense rainfall, the dam failed. The dam failed mainly due to a combination of downstream slope failure and overtopping. The failure caused an enormous flood downstream. Since 10 months elapsed between the formation and the failure of the dam, the Department of Energy had sufficient time to put early warning systems in place. Timely warnings saved the downstream hydropower plant. The water level in the reservoir was pre-lowered; this enabled it to cater to the flood with only minor damage to the main infrastructure. This LDOF did not result in any human casualties, but the loss of agricultural land was significant (Xu et al. 2006).

RM 14.4: Measures that can reduce the risk of landslide dam outburst floods

Control measures, such as the construction of spillways to drain the impounded water, have been attempted in various places around the world. Sometimes these measures are successful in preventing LDOFs, but at other times overtopping occurs before satisfactory control measures can be constructed. In some cases, constructions for structural mitigation can themselves trigger floods that can cause large-scale causalities. This manual focuses on non-structural measures to mitigate LDOFs.

Landslide hazard assessment

The first step in LDOF mitigation is to identify places where the hazard can occur. This identification can take place by preparing a landslide hazard map. A landslide in a narrow valley close to a stream can potentially cause a lake-forming dam. Additional analysis can be used to estimate of the volume of the dam, which together with the stream inflow rate, can give an indication of the rate at which a dammed lake could rise.

Hazard and risk mapping can be accomplished using any one or a combination of the following methods.

- Simple qualitative methods are based on experience and use an applied geomorphic approach to determine parameters, their weightings, and scores; overlays of parameter maps are used for pre-feasibility level studies.
- Statistical methods score the different parameters based on bivariate and multivariate statistical analysis.
- Deterministic methods are based on the properties of materials.
- Social mapping methods use information derived from discussions with people familiar with the area and make use of their local knowledge, experiences, and feelings.

The potential hazard may be classified as relative (by assigning ratings to the different factors that can contribute to the hazard), absolute (by deterministically deriving factors, e.g., factor of safety), or monitored (by making actual measurements such as the deformation of roads or other structures).

To assess relative hazard, these steps are generally followed:

- Determine the different factors that can contribute to slope instability.
- Develop a rating scheme to score the probability of a hazard.
- Identify and quantify elements at risk.
- Develop a rating scheme and scores for damage potential.
- Construct a hazard and risk matrix.
- Map the hazard and risk.

Estimating downstream flooding

Informed estimates of the magnitude of a potential flood are necessary in order to implement mitigation measures in downstream areas. When the time between the dam formation and the outburst is short, a detailed analysis may not be possible and estimates need to rely on simple techniques.

Costa and Schuster (1988) suggest the following regression equation to estimate the peak discharge of a LDOF:

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

where Q is peak discharge in cubic metre 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 the failure and can be calculated using the following equation:

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

where H_d 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:

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

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

Figure 22 shows a schematic diagram of the input parameters for the calculation of peak outflow. The methods of Costa and Schuster (1988) and Mizuyama et al. (2006) give entirely different results as they use different parameters; the second method uses more parameters than the first.

Sophisticated computer models can estimate the peak outflow of the LDOF and predict the route of the flood along the river reach downstream of the lake. These models can also predict the area and level of flooding, and can help in making decisions regarding relocating people or implementing structural mitigation measures.

Estimation of past floods

Estimation of past floods provides an idea of the magnitude of flood that is likely to affect the 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 and the depth and width of the channel during the flood based on the size of the boulders deposited by the flood. Details are given in Costa (1983). These estimates provide a basis for identifying the magnitude of a past floods and for assessing potential future hazard and risk.

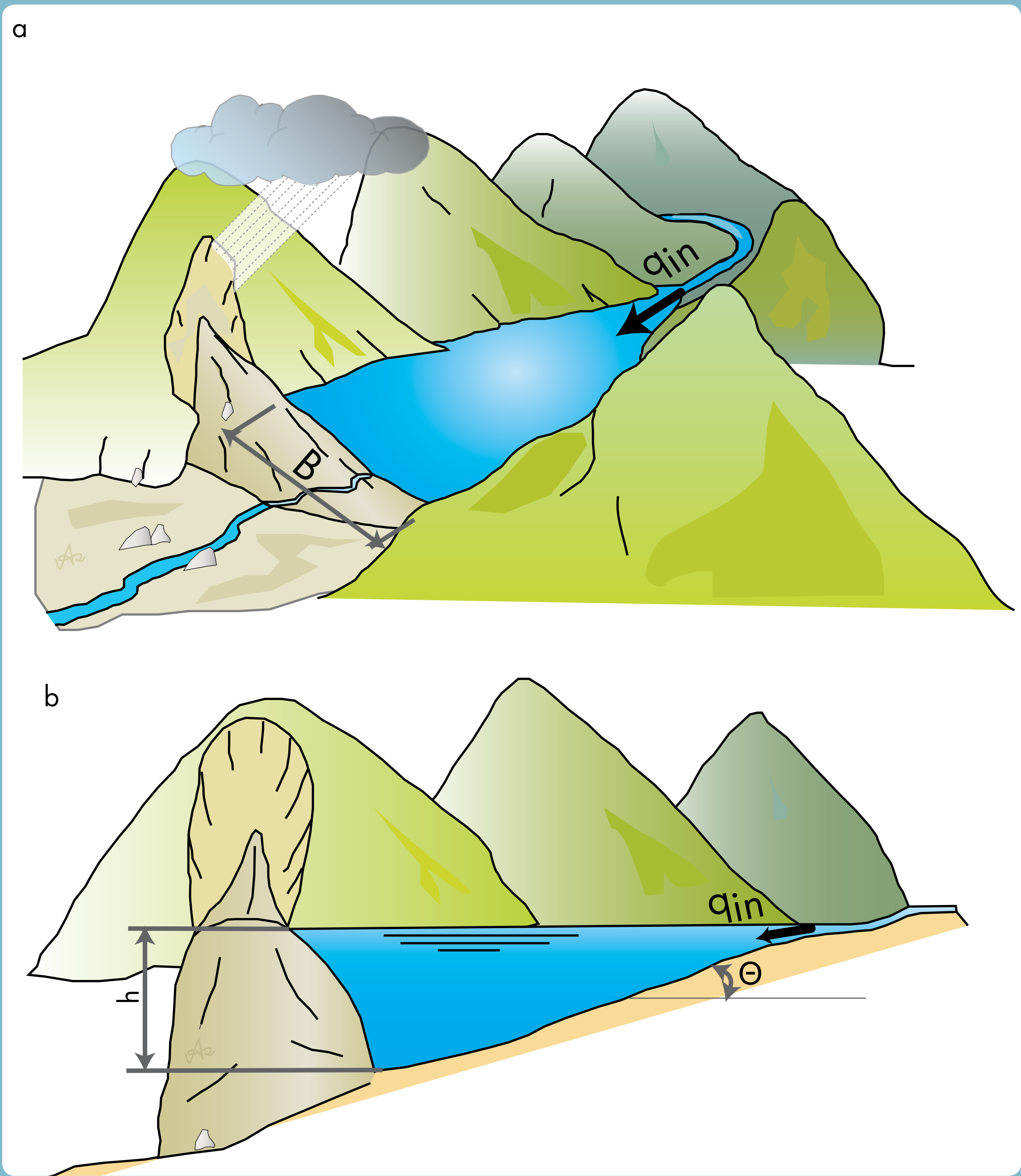
The following steps are used to estimate the magnitude of past floods:

Step 1: Velocity calculation. Several equations have been developed for calculating the mean velocity of flow ($\overline{v}$) of past floods in m/sec based on the size of boulders deposited. Here we present some of the more commonly cited ones. In all three, d is the diameter of the boulder in millimetres.

SESSION 14

SESSION 14

Figure 22: **Schematic diagram showing the parameters used in calculating peak flow discharge: a) Isometric view; b) Cross-section view**



Source: Shrestha (2008)

Mavis and Laushey (1949) calculate the velocity of bed flow, V_b, in ft/sec as

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

where S_g is the specific gravity of the boulder. The mean velocity, $\bar{v}$, is then calculated as

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

Strand (1977) uses the same equation for mean velocity, but calculates the velocity of bed flow, V_b again in ft/sec), as

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

Williams (1983) suggests that

$$\overline{V} = 0.065d^{0.5}$$

Step 2: Depth calculation. The next step is to calculate the mean depth of the flow. Several methods are available for calculating the mean depth ($\overline{D}$).

Manning's equation proposes

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

where $\overline{D}$ is mean depth, $\overline{V}$ is mean velocity, n is the roughness coefficient, and S is the slope.

Sheild (1936) suggests

$$\bar{D} = \theta d(\gamma_S - \gamma_f)/S$$

where θ is dimensionless shear stress (use 0.02), γ_f = 1,070 kg/m^3, γ_s = 2,700 kg/m^3, and S is the slope.

Williams (1983) suggests

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

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

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

Step 3: Width calculation. The width is determined using an iterative method. For the cross-section, a straight reach (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 site where the deposition took place. At least two cross-sections are selected, these should be 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, a line is drawn to represent the estimated top width of the cross section. The area of the cross-section is calculated using a planimeter; then the area is divided by the top width of the cross-section. If the value calculated in this way deviates from the estimated depth calculated in Step 2, the process is repeated by drawing a new top-width line and recalculating; the process is repeated until the two values agree. The cross-sectional area 'A' for the final top-width is then calculated.

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 equation:

$$Q = \overline{V} \times A$$

Land use regulations

The increasing hazard and risk of LDOFs are a result of the unregulated use of land and the use of flood prone areas for infrastructure development such as buildings and roads. Regulations that encourage the proper use of land can help to prevent flood prone areas from being used for settlements or as sites for important structures. Regulations may also involve relocating people or infrastructure away from hazardous areas, particularly if alternative sites exist. Restrictions can be placed on the type and number of buildings that can be erected in high-risk areas. Similarly, activities that might activate a landslide can be restricted to take place away from avalanche prone areas. Restrictions can be implemented through measures such as policy and building codes.

Early warning systems

An early warning system can be an effective measure to mitigate the impacts of LDOFs, particularly in saving lives and property. Depending on the situation, a variety of systems can be implemented. In many cases, the best option is to implement a community-based early warning system. This may consist of people placed at strategic locations from the dam site to the greatest distance downstream where an LDOF could have an impact. Each person should have visual contact with the person just upstream and downstream. An early warning system is part of a monitoring, warning, and response system (MWRS).