Guidelines for Mapping Flood Risks Associated with Dams

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DRIP
Dam Rehabilitation & Improvement Project

Central Water Commission
Ministry of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Front Cover Photograph: Floodwaters gushing out of the breached right bank protection works of Moolathara Dam near Chittur on Sunday, the 8th November 2009.

सत्यमेव जयते

Government of India
Central Water Commission
Central Dam Safety Organisation

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Government of India
Central Water Commission
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Guidelines for Mapping Flood Risks Associated with Dams is one in a series of dam safety guidelines being developed under the Dam Rehabilitation and Improvement Project (DRIP).

Disclaimer

Mapping Flood Risks Associated with a Dam is a key exercise influencing the decision in ensuring safety of those residing downstream. While these guidelines help in making appropriate assumptions and taking actions, the Central Dam Safety Organization or the Central Water Commission cannot be held responsible for the efficacy of the Flood Risk Maps prepared on the basis of the guidelines. Appropriate discretion may be exercised while preparing maps showing the flood risk associated with a dam.

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MESSAGE

Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India has taken up the Dam Rehabilitation and Improvement Project (DRIP) with the funding assistance from the World Bank, to improve the safety conditions of some of the existing dams of the country. Along with the implementation of a host of measures for improvement of the health of dams of varying ages, it also envisages to prepare a set of guidelines that will extend help to the dam professionals out in the field or remote areas. This *Guideline on Mapping Flood Risks Associated with Dams* is a first of its kind, attempting to introduce the concept of flood risk in the country, along with guidance for the procedure.

Preparation of emergency action plans for all the dams in the country is a necessity that has been neglected, partly due to non-availability of tools, techniques and data and partly due to non-availability of proper guidance on this complex topic. It is well recognized worldwide that saving human lives is the priority in case of any dam breach incidence and proper implementation of flood warning and emergency action procedures is a must for that purpose. These guidelines show the pathway to facilitate the development of emergency action plans, dealing with the complex subject of hydrodynamic modelling and geographical information system based flood map preparation.

Drawing on the excellent accomplishments by established leading agencies in the field of dam safety management and a host of other publications from across the world and taking advantage of balanced mix of the international and national expertise, these guidelines prepared under DRIP are expected to help in the preparation of development of emergency action plans in the country. I am sure, this document will be used by all dam owners for its intended purpose.

(S Masood Husain)
Chairman
Central Water Commission

New Delhi
January 2018

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FOREWORD

There are about 5,200 large dams in the country, and many more are in the planning stage. The per capita water storage in the country is still much less than that in many developed countries. Further, it is moving fast on the waning run – thanks to the trend of rapid urbanisation. The phenomena of climate change is adding to the difficulties, making the distribution of rainfall even more erratic, helping to increase the scarcity of water even further.

The dams, so important to ensure water security, may breach in spite of the best efforts in design and maintenance. The failure of Machu Dam in Gujarat was a calamity, claiming lives of more than 2,000 persons. Globally it has been recognised that ensuring absolute safety of a dam under all circumstances is not practicable. However, with proper preparations through implementation of early flood warning system and emergency action plan, it is possible to obviate or at least reduce the loss of lives to a great extent, even in case of a dam failure.

For the purpose of emergency action planning, obtaining information about areas that would be inundated is a must. With the advent of modern computers, free data and software, it is possible to carry out a two-dimensional dam breach analysis in a reasonable amount of time. Even though the field of dam breach modelling is full of complexity and uncertainty, these guidelines have been prepared to deal with the same in a simple way that is easy to follow by the engineers in the field. An attempt has been made to bring in the flavour of the best of practices from the international arena, within premise of the current status of data availability in the country. Indeed a great deal of research has to go into the field of estimation of potential loss of lives, to come up with realistic figures, more so for the large setup of rural base in India. Pending that, the *Guidelines for Mapping Flood Risks Associated with Dams* attempts to introduce the subject and the concept of risk in an unambiguous way, that is brief but comprehensive. I sincerely appreciate the efforts of the team engaged in its preparation and hope that it will be useful to the community of engineers who are entrusted with securing dam safety.

(N.K. Mathur)
Member, D&R
Central Water Commission

New Delhi,
January, 2018

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PREFACE

Central Water Commission (CWC) is Apex Organization of India in the field of Water Resources. To promote safety of the dams right through the planning, design, construction, operation and maintenance of dams, CWC implemented several initiatives including the development of guidelines and manuals to be used by dam professionals. As part of the institutional strengthening component of DRIP, an almost 8 years project being implemented with the financial support of the World Bank, development of dam safety guidelines and manuals was taken up by CWC; *Guidelines for Mapping Flood Risks Associated with Dams* is one of the series.

The severity of flooding depends on the amount of water impounded by the dam, height of the dam, the nature of failure and the downstream vulnerability. The inundation maps depict the areas that are likely to be submerged in different dam failure scenarios. The details included in the inundation maps depend upon the information available and the chosen methodology. Tiered Flood Modelling and Mapping Approach was adopted in these guidelines to promote the development of Emergency Action Plans (EAP) for all the large dams. All agencies managing dams are expected to develop the inundation maps based on the available information and resources and prepare the EAPs. Later, depending on the need, more detailed maps (upgrading to the next tier) may be prepared and included in the EAPs.

These guidelines describe through six chapters detailing the concepts of flood mapping, flood risk and hazard, and Dam Breach Analysis and modelling and ultimately the synthetic and detailed approach for flood risk management. Sample examples with alternate available equations for dam breach have been included for reference.

This document is expected to assist dam engineering professionals to develop the inundation maps for conducting DBA and arriving at inundation maps to plan Emergency Action Plan. A further revision of this document is also recommended based on future developments as well as omission of any important practice in the current document.

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CONTENTS

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LIST OF TABLES

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LIST OF FIGURES

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
AEMI	Australian Emergency Management Institute
AIDR	Australian Institute for Disaster Resilience
ASPRS	American Society of Photogrammetry and Remote Sensing
BIS	Bureau of Indian Standards
CDSO	Central Dam Safety Organisation
CWC	Central Water Commission
DEM	Digital Elevation Model
DTM	Digital Terrain Model
DSM	Digital Surface Model
DRIP	Dam Rehabilitation and Improvement Project
EAP	Emergency Action Plan
EIA	Environmental Impact Assessment
EMP	Environment Management Plan
EMV	Emergency Management Victoria
FEMA	Federal Emergency Management Agency, USA
FERC	Federal Energy Regulatory Commission, USA
FRL	Full Reservoir Level
GIS	Geographical Information System
GPS	Global Positioning System
ICDRM	Institute for Crisis, Disaster, and Risk Management
IDF	Inflow Design Flood
IMD	India Meteorological Department
INCID	Indian National Committee on Irrigation And Drainage
IS	Indian Standards
ISRO	Indian Space Research Organization
MWL	Maximum Water Level

Abbreviation	Full Form
NASA	National Aeronautics and Space Administration, USA
NFIP	National Flood Insurance Programme
NRCS	Natural Resources Conservation Service, USA
NRSC	National Remote Sensing Centre, India
NWS	National Weather Service, USA
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PPS	Planning Policy Statement
RCC	Roller Compacted Concrete
SEDAC	Socioeconomic Data and Application Centre
SOI	Survey of India
SPANCOLD	Spanish National Committee on Large Dams
SPF	Standard Project Flood
SPS	Standard Project Storm
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USDHS	United States Department of Homeland Security
WGS	World Geodetic System

Chapter 1. OVERVIEW OF FLOOD MAPPING

1.1 Potential Uses of Flood Mapping

Flood maps have a variety of uses including preparation of Emergency Action Plans (EAPs), mitigation planning, emergency response, and consequence assessment. Each type of use of the map has its unique information requirement. The map may find use in different ways, ranging from multi-year office-based planning efforts by mitigation planners and dam safety officials to field-based emergency response team members responding to a developing or imminent dam breach.

Flood maps are tools for visualisation of flood information for decision-makers and the public in general. These maps form the basis for developing different flood risk scenarios based on land use, environmental conditions and social and economic conditions. Flood maps, in their various formats and scales, form the basis of planning and implementation of development alternatives.

In addition, special uses require specific information including maps that depict exposure to floods of various recurrence periods, flood risks, vulnerability and response information such as evacuation routes, safe high grounds, and shelter areas. These maps are of great importance not only for the flood plains but also for the coastal areas having a risk of storm surges and tsunamis. Different methodologies for the production of flood maps for various purposes exist, which help to support the process of decision-making at all levels.

Maps depicting flood hazards, flood-prone areas, and related information are important components for an effective Integrated Flood Management (IFM). This assumes greater significance in the context of spatial issues like land-use planning for flood management. Detailed methodologies are available for calculating, modelling and mapping flood-prone areas and flood risks, for regions that are data-rich. For data-sparse conditions, the guidance on overall approaches to flood mapping and risk assessments are missing. There is a particular need to address such situations for the developing countries having limited expertise, limited resources, and inadequate data availability.

Flood maps portray results of flood assessments. Flood assessment and flood mapping are closely interrelated, flood mapping incorporating both preliminary and detailed flood assessments. Flood maps may exist in many formats and are highly variable. Making flood assessments and prepare flood maps is a complex, multi-disciplinary process involving technical expertise as well as human and financial resources. Presently a few publications available around the globe provide guidance on flood mapping and flood risk assessment. The Risk Map initiative by FEMA uses such detailed technical methodologies and is built for data-rich environments (FEMA, 2010).

Flood maps play an important role in decision-making, planning and implementing flood management/floodplain management. The maps provide information on the past floods and the likely or potential extent of floods and their impacts (sometimes along with other related information), in order to help in making decisions on various aspects of flood management.

Development of flood maps requires a systematic process. The data sets on which the maps are to be based and the methodology that is to be used should be specified. In addition, administrative arrangements are necessary for the development of flood mapping programs. The objective of this guideline is to provide guidance to undertake flood mapping exercises for the various planning processes on local, state or national level for addressing issues like emergency response, asset management, flood insurance, or overall public awareness.

1.1.1 Emergency Action Plans

An Emergency Action Plan (EAP) is a formal document that identifies potential emergency conditions at a dam and specifies preplanned actions which are required to be followed for minimising damage to properties and loss of life. The EAP specifies actions for the dam owner, in coordination with emergency management authorities, to be taken while responding to incidents or emergencies related to the dam. It presents procedures and information for assisting the dam owner in issuing warnings and notification messages to responsible downstream emergency management authorities.

The EAP includes inundation maps for assisting the dam owner and emergency management authorities in identifying critical infrastructure and sites with huge population-at-risk, which may require protective measures and warning as well as evacuation planning. The EAP should clearly delineate the responsibilities of all those involved in managing the flood incident, and how those responsibilities should be coordinated. In this regard, the *Guidelines for Developing Emergency Action Plans for Dams* prepared by CWC in 2016 as a part of the same series may be referred to.

1.1.2 Disaster Response

Disaster response includes the actions, which are to be taken during and in the immediate aftermath of an incident to save and sustain lives, meet basic human needs, and reduce the loss of property and the damage to critical infrastructure. To minimise the consequences of an imminent or actual dam failure, this would be the response of the dam owner, national and state level disaster management authorities, district administration, community emergency management, and first responders such as fire and police departments. Actions may include dissemination of warning and evacuating the population at risk. Dam owners should coordinate with the appropriate emergency management authorities. They should share the information obtained through dam break inundation studies and mapping projects to assist the evacuation planning process.

1.1.3 Hazard Mitigation Planning

Mitigation is the proactive effort to decrease the loss of life and property by reducing the effect of disasters. This is achieved through identification of potential hazards and the risks they pose in any given area, identification of mitigation alternatives to reduce the risk, and risk analysis of mitigation alternatives. The result is the selection of proactive measures, both structural and non-structural, which will help to reduce economic losses and potential loss of life when implemented. Inundation maps provide information about the population at risk as well as structures under potential threat to the hazard mitigation planners. The information needs to be used to identify actions for reduction of their vulnerability to inundation. Actions might include setting up a system for providing flood warning, and constructing/relocating critical infrastructure and facilities out of the flood inundation zone.

1.1.4 Dam Failure Consequence Assessment

Dam breach consequence assessment includes the identification and quantification of the probable consequences of a dam failure. Hazard mitigation planning focusses on specific projects to reduce flood risk. Consequence assessment focuses on the economic and social impacts of a probable disaster, and the organisational and government actions needed after a dam breach in order to respond and recover. Data compiled for a consequence assessment may also be used for risk assessments. Consequence assessment and risk assessment both require the information presented in dam breach inundation maps.

1.2 Tiered Flood Modelling and Mapping Approach

Given the wide range of conditions that exist at a dam and its failure action, as well as the different modelling options available, many options require selection before performing a dam breach analysis for mapping flood risk associated with dams. Since dam breach analyses do not always warrant the most sophisticated tools available, a tiered approach is recommended.

The tiered approach attempts to match the appropriate level of analysis with a given situation. The goal is to make the most efficient use of time and tools available while producing results that are conservative for the level under consideration. The level of analysis for the tiered approach should correspond to the sophistication and accuracy of the analyses, and the scale and complexity of the dam and downstream area under investigation. Thus, analysis of high-hazard potential dams located upstream of populated areas or complex floodplains should be carried out using the more sophisticated modelling approaches. In addition, sensitivity studies may be carried out to properly assess the consequences of a dam failure. Analysis of low-hazard potential dams situated upstream of sparsely populated areas may be performed using more approximate methods of analyses. Table 1-1 shows the structure of tiered dam breach analysis.

As the sophistication of the modelling increases so does the effort, time, and cost necessary to conduct the analysis. The dam failure analysis should be continued downstream to a point where the flood due to the dam breach no longer poses a significant risk to many lives and huge property damage, e.g., the confluence with a large river, or reservoir with a large capacity which is able to store the floodwaters. Analyses of the category Tier 1 and Tier 2 are appropriate for low-hazard potential/small sized and significant hazard potential/intermediate-sized dams with a limited number of structures/limited habitations downstream. More detailed surveying or modelling is required for Tier 3 analyses. This type of analysis is necessary for high-hazard potential/large sized dams, dams with a large population in the evacuation area, or dams with significant downstream hydraulic complexities, such as major diversion structures, split flows, or cases where failure of one upstream dam may lead to failure of many downstream dams in a series.

1.3 Publication and Contact Information

This document is available on the CWC website

http://www.cwc.gov.in

and the Dam Rehabilitation and Improvement Project (DRIP) website

http://www.damsafety.in

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1.4 Acknowledgments

In preparing these guidelines, work of others in India, the United States, and elsewhere has been drawn from liberally. Grateful appreciation is extended to the following organizations whose publications and websites provided valuable information on mapping flood risks associated with dams:

- Federal Emergency Management Agency (FEMA), US Department of Homeland Security

- The United States Army Corps of Engineers (USACE)
- The United States Bureau of Reclamation (USBR)

Table 1-1: Tiered approach to dam breach inundation mapping

Tier Level	Applications	Breach Parameter Prediction	Peak Breach Discharge Prediction	Downstream Routing of Breach Outflow Hydrograph	Downstream Risk Evaluation
Tier 1 – Basic level screening and simple analysis using low resolution terrain data (e.g., SRTM, ASTER, or ALOS)	• First level screening for significant or high hazard dams • Low hazard potential dams	Empirical formulae	Empirical formulae if inflow design flood hydrograph is not available, otherwise unsteady flow routing through modelled reach	Geo-Dam-BREACH, SMPDBK, HEC-HMS, or other simplified approaches	Peak discharge, water surface elevation, and flood wave travel time
Tier 2 – Intermediate level of analysis using medium resolution terrain data (e.g., 10 m INTERMAP or Lidar	• Large significant hazard dams • All high hazard dams	Empirical formulae	Unsteady flow routing through modelled breach	HEC-HMS, HEC-RAS, MIKE-11 or similar one dimensional (1D) unsteady flow numerical models	Peak discharge, water surface elevation, flood wave travel time, and approximate PAR assessment
Tier 3 – Advanced level of analysis using high resolution Lidar terrain data	• Significant hazard dams with complex downstream flooding • High hazard dams with large population at risk (PAR)	Empirical equations, WinDAM-B, or causal embankment erosion numerical models (one or two dimensional)	Unsteady flow routing through modelled breach	One or two dimensional (2D) unsteady flow numerical models	Peak discharge, water surface elevation, flood wave travel time, and detailed PAR assessment

Chapter 2. FLOOD RISK ASSOCIATED WITH DAMS

2.1 Types of Dams

Dams may be classified by the type of construction material used, being listed as either a masonry/concrete or an embankment dam. Several dams may have more than one component (e.g. earthen embankment with masonry spillway), allowing them to be categorised as composite dams. The choice of a dam type for a particular location depends on many factors including foundation and geology, topography and valley shape, availability of materials, the influence of spillway type, seismicity of the region and construction methodology. It also depends on the economy of labour availability.

2.1.1 Concrete and Masonry Dams

Concrete dams include arch, buttress, concrete gravity (Figure 2-1), multi-arch, and roller-compacted concrete (RCC) dams. These dams are typically constructed of concrete or masonry (with rubble masonry or dressed rock). Other types of concrete/masonry dams may include hollow gravity and buttress dams. Many dams constructed about half a century ago or earlier were of the masonry type, in harmony with the labour-intensive schemes of that time.

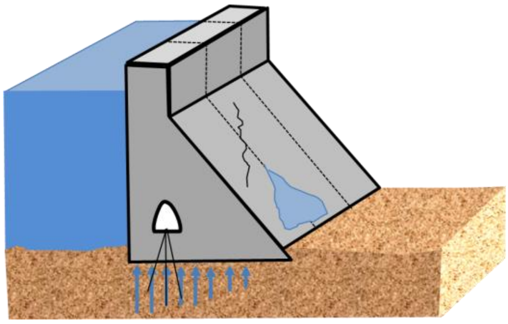

Figure 2-1: Concrete gravity dam

2.1.2 Embankment Dams

Embankment dams are made of earthen materials and may be filled with rock, clay, or other materials resistant to erosion. It may also have a cladding on the upstream face, to protect the dam from water erosion (Figure 2-2). The central core made of impervious material helps to cut down seepage losses from the dam, while the permeable filter downstream captures the seeping water and provides it a safe exit. A cut-off wall under the dam increases the length of the seepage path and reduces the chances of piping through the foundation.

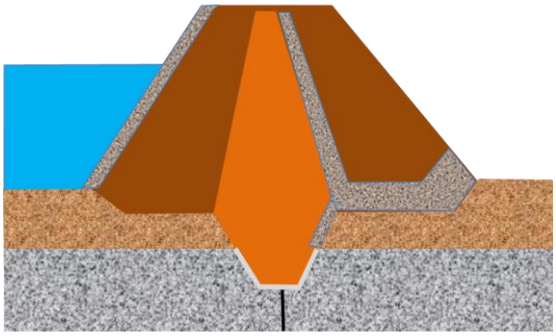

Figure 2-2: Earth dam

2.2 Dam Classification Systems

The dam classification system of India relies on the hydraulic head and gross storage of the impoundment at the full reservoir level as criteria. The classification of a dam into a category is based on the criteria that indicates the more severe category. It is taken from the Bureau of Indian Standards (BIS) in IS: 11223 (1985) "*Guidelines for Fixing Spillway Capacity*" and reproduced in Table 2-1.

The hydraulic head is the difference between the maximum water level in the reservoir and the annual average flood level on the downstream side. Since this involves pre-selection of design flood for assessment of the MWL, an alternate definition (vide Amendment No. 2, Sep 1991of IS:11223-1983) has been presented, which considers

Table 2-1. Existing dam classification for inflow design flood selection (IS:11223 - 1985)

Class	Gross storage capacity (Mm^3)	Hydraulic head (m)	Inflow Design Flood (IDF)
Small	0.5 to 10	7.5 to 12	100-year flood[a]
Intermediate	10 to 60	12 to 30	Standard Project Flood (SPF)
Large	> 60	> 30	Probable Maximum Flood (PMF)

[a]The flood having an annual exceedance probability of 0.01 (1%) or an average recurrence interval (ARI) of 100 years.

the difference between the FRL and the minimum tailwater level downstream of the dam as the hydraulic head.

2.2.1 Dam Size

The prescriptive classification mentioned in the previous section takes its roots from the hazard potential created due to breach – either due to the huge head of water or due to a huge volume. It is based on the concept that high head of water will cause devastation due to the high velocity of flowing water. With huge storage, the flooding will continue for a longer time, increasing the magnitude of loss.

2.2.2 Hazard Potential

For a detailed discussion on hazard potential of dams, *Guidelines for Classifying the Hazard Potential of Dams*, being prepared by the CWC under the same series of guidelines, may be referred to. While the hazard potential will be at its maximum when there is a dam breach failure due to overtopping, downstream hazards due to a dam failure because of piping or even passage of high discharge (design flood peak) through the open spillway gates may sometimes be serious. The sudden release of discharge of even lesser magnitudes from a dam without proper warning may also cause loss of lives; the unfortunate incident of 8th June 2014 downstream of Larji Dam in Himachal Pradesh stands witness to this. On this day, 24 engineering students from Hyderabad, engrossed in photography on the riverbed in the evening, lost their lives as the spillway gates of the dam were opened to release water into the river, which was otherwise dry.

The recent approach of categorisation of dams based on their hazard potential in countries like the US follows the assessment of potential loss of lives and property due to a dam breach (FEMA, 2013). It classifies dams into low, significant and high hazard classes. A dam qualifies for the low hazard category where there is no anticipated loss of life due to its failure or misoperation (unscheduled sudden release of water). Also, the anticipated economic, environmental and life losses are low and generally limited to the owner. A dam is categorised as having significant hazard potential if its failure may lead to no loss of life, but economic and environmental. Classification of a dam into the category of high hazard potential follows if along with economic and environmental losses, loss of one or more lives is anticipated. For failure of dams in a series, it has been recommended that the hazard potential classification of the upstream dam must be as high as or higher than that of any downstream dams, that could fail because of the failure of the upstream dam (FEMA, 2013).

While it was extremely difficult to arrive at a reasonable estimate of property and life loss in earlier days, with the advent of digital elevation models, high-performance computers, and modelling software, it has reduced to a task that can be carried out easily. Therefore, it appears logical to shift gradually towards hazard potential assessment based on anticipated loss rather than the size of the dam itself. Depending on the status of development in the downstream area, in some cases the loss of life and property due to the breaching of a smaller dam may be huge, warranting greater attention.

2.2.3 Probable Loss of Life

Loss of life is clearly the most serious consequence and the one that causes the largest impact on the public perception of any disaster. Therefore, probable loss of life is important for hazard potential classification and emergency action planning. It is often estimated based on how many habitable structures and roads are located in the area, which would be inundated due to a dam breach. Typically, improbable loss of life, such as that of a passer-by or occasional, non-overnight recreational user of the downstream area is not taken into account.

Many methodologies used for assessment of loss of life follow the process mentioned:

- Identification of a particular scenario for assessment, including the time of the day or day of the week or month and season of the year as well as the failure mode of the dam
- Estimation of downstream impact of the flood in terms of depth of inundation, velocity of water, duration of flooding, etc. from flood maps
- Conception about the public dissemination of the flood warning including its timing and methodology
- Estimation of available time for evacuation between the receipt of the flood warning and the arrival of the flood wave for each cluster of human habitation
- Estimation of the remaining number of people in each habitation under the flooded area after evacuation
- Estimation of the loss of life from the exposed population in each habitation using the mortality rates based on the floodwater flow characteristics and the refuges available (building type, number of stories, availability of flood shelters, etc.).

The scenario considered for the study will greatly influence the results of the study. The characteristics of the situation in which the dam failure takes place may include:

- The time of the day, as during the night people will be mostly concentrated in residential areas, whereas during the day they will concentrate mostly in industrial and commercial areas. In addition, the warning and evacuation processes are slower at night.
- The season of the year, especially for locations with significant seasonal fluctuations of the population, such as places with tourist attractions.
- The mode of dam failure dictates the characteristics of flood flow. It also affects the way of flood warning and the way the population perceives its severity.

Each failure situation generates consequences that are different from the other. Therefore, several combinations of consequences are to be analysed for arriving at a judicious mitigation plan.

The methodologies for estimation of probable loss of life have been developed and calibrated for the case of dam failure. However, in the absence of more specific methodologies for the cases that do not consider dam failure, the same methodologies are usually applied – even at the risk of having less accurate results. *The Guidelines for Assessing and Managing Risks Associated with Dams*, being prepared by the CWC under the same series, may please be referred to in this regard.

2.3 Dam Failure

Based on the type of dam and conditions of the dam site, a dam may fail due to multiple causes. In addition, the breach shape and timing of a dam failure varies with the type of dam under consideration. Concrete gravity dams may suffer a partial breach with the failure of one or more monolith sections. Concrete arch dams may fail suddenly and completely within a few minutes. Embankment dams do not fail completely or suddenly as their concrete counterparts. Breaching action in an earthen embankment dam continues to the point where the reservoir is depleted completely or to the point where the breached materials resist erosion, such as the dam foundation.

The most common cause of dam failure is flood or dam overtopping. The next common cause is piping or seepage. Different causes attributable to the structural failure comprise the third most common category. Sometimes a dam may even fail due to the failure of its spillway gate, earthquake or even poor design/construction. The many types of dam failures may be summarised using five failures scenarios/events: hydrologic, geologic, structural, seismic, and human-influenced.

2.3.1 Hydrologic Failure Mode

Hydrologic dam failures are induced by extreme rainfall or snowmelt events that may cause natural floods of variable magnitude. The main causes of hydrologic dam failure include overtopping, structural overstressing, and surface erosion due to high-velocity flow and wave action.

Overtopping because of flooding is the most common failure mode for embankment dams. It occurs when the water surface elevation in the reservoir exceeds the height of the dam. The flow of water over the crest of the dam, an abutment, or a low point in the reservoir rim follows as a consequence. The foundation and abutments of a concrete dam may also be eroded due to overtopping, leading to loss of support and failure due to sliding or overturning. Overtopping usually results from a design inadequacy of the dam/spillway system and reservoir storage capacity to handle the flood event. A failure may also occur when a reservoir outlet system is not functioning properly, thereby raising the water surface elevation of the dam.

Failure of a dam will begin when water starts overflowing the dam, eroding its surface along the path. For embankment dams, the failure begins at a downstream location, with head cutting progressing upwards gradually. As it reaches the dam top, the width of the dam crest is eroded fast, before the reduction in height starts taking place. This proceeds at a fast rate and may include the phase of maximum outflow for a reservoir with capacity small compared to its height. In this phase, the earthen dam without a core behaves mostly like a sharp-crested weir (discharge coefficient C = 1.77, to be used with variables in metric units).

The opening created by erosion expands gradually, almost in the shape of a trapezoid (Figure 2-3). As the height is reduced to the foundation level, outflow may continue for a long time if the reservoir is of sufficiently large capacity. For such cases, the peak rate of outflow is also expected to occur during this phase. The flow mostly resembles the overflow pattern observed over a broad crested weir with long crest (discharge coefficient C = 1.44, to be used with variables in metric units).

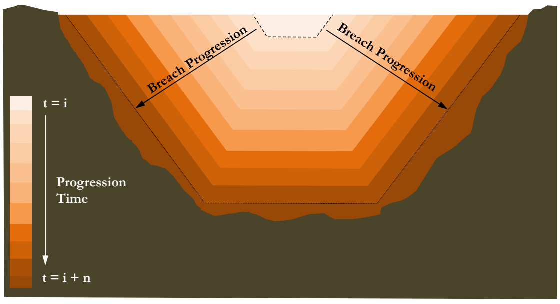

Figure 2-3: Breach progression in case of an overtopping failure

However, based on conditions like headwater and tailwater during a breach development, flow characteristics may vary between weir flow, converging flow, and channel flow. In general, for the earth dams, large breach dimensions are associated with poorly constructed dams, dams constructed using easily erodible material, and dams having large volumes of storage. Apparently, dam breach outflow from a monolithic earthen dam with a reservoir of not so large capacity may be adequately modelled by considering it as a sharp-crested weir.

If a clay core is present or the dam is made predominantly of clayey material it may be more appropriate to consider the flow as one occurring over a sharp-crested weir (C = 1.77, to be used with variables in metric units). If there is the presence of a lot of sandy/ gravelly material, it may tend to behave more like a broad crested weir (C = 1.44, to be used with variables in metric units). The continuously varying flow conditions that occur during a dam breach may hardly be taken into consideration for a modelling exercise. However, it is important to select the flow type as that similar to one over a sharp/broad crested weir, because it may lead to serious overestimation/ underestimation of the peak discharge otherwise.

2.3.2 Geologic Failure Modes

Geologic failure modes may include piping and internal erosion as well as slope instability and hydraulic fracturing. For embankment dams, geologic failures may be caused by continuous seepage of water stored in the reservoir. The water seeps through the dam or the foundation and its abutments, weakening the embankment along the pathway over time. If seepage remains unattended for a long time, it may lead to internal erosion or piping of the embankment materials.

A geologic failure may also be the result of the inadequate geotechnical design of the embankment and foundation, inadequate seepage controls, or increased load situations such as the rapid increase of water level or drawdown of water level – which may occur due to a flood, landslide, earthquake, or wave action.

2.3.3 Piping Failure/Internal Erosion

Piping occurs when concentrated seepage paths develop within an embankment dam. The seepage slowly continues to erode the dam embankment or foundation, leaving behind large voids in the soil.

Piping begins near the downstream toe of the dam and works its way toward the reservoir upstream. Erosion proceeds at a more rapid rate as the voids become larger and larger. As the erosion reaches the reservoir upstream, it may enlarge and cause total failure of the dam. Piping failures occur in earthen dams only. The failure begins when water seeping through the dam core increases in velocity and quantity, starting to erode fine sediments out of the soil matrix. As enough material erodes, a direct pipe connection from the reservoir water to the downstream face of the dam is established. This process of removal of soil particles along the path of water flow continues until the roof of the pipe is unable to support itself, and therefore, collapses. Once such a pipe connection is formed, it is almost impossible to save the dam from failure.

Piping failure begins at a point in the downstream face of the dam and expands gradually as a circular opening. As this circular opening reaches the dam top, it continues to expand as a trapezoid. The process of internal erosion and piping may be broken up into four phases: initiation of erosion, continuation of erosion, progression to form a pipe and ultimately, the formation of a breach. The breach progression in case of a piping failure has been shown in Figure 2-4. Piping may also occur along conduits, outlet works, and abutments.

Towards the beginning of the piping process, the movement of water through the dam may be modelled as a pressurized ori-

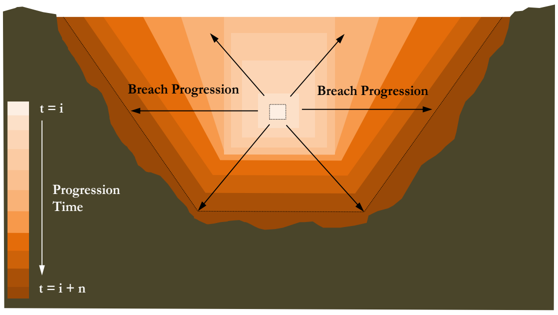

Figure 2-4: Breach progression in case of a piping failure

fice flow. Values of piping/pressure flow coefficients in the range of 0.5 to 0.6 have been recommended (USACE, 2014). As the piping hole develops, material above the hole begins to fall off and be carried with the moving water. When the hole is large enough, mass caving of material occurs, resulting in a large rise in the outflow through the breach that accelerates the breaching process further. The flow hydraulics changes from a pressurised orifice type flow to an open-air weir type flow. The breach may continue to cut down and widen to the channel bed if the volume of water behind the dam is large. Thereafter, the breach continues to widen. The flow of water through the circular opening may be modelled as orifice flow, but the flow of water through the trapezoidal section should be modelled as weir flow.

Internal erosion occurs where two adjacent zones meet within the embankment, or at the zone of contact between the embankment and foundation. In other words, it is the transportation of the finer grained soil portion of a well-graded soil by water due to either mechanical or chemical action. Internal erosion near the dam foundation may be a result of poor foundation treatment. The potential for soil grain movement is governed by its size. Internal erosion is different from piping as it originates internally, while piping originates externally. When voids of the material through which seepage is occurring are larger than a critical size that is required to retain the particles, the material with the smaller particle size are transported into or through the adjacent material with larger particle size, resulting in internal erosion.

2.3.4 Structural Failure Modes

Structural failures occur when there is a failure of a critical dam component. It may be related to an inadequate design, poor construction, poor construction materials, inadequate maintenance and repair or gradual degradation over time. In addition, structural failure of a dam may be related to other modes of failure. For example, structural failure of the main embankment of a dam may be related to internal piping; or due to overloading during a flood event, a critical component of the dam may fail.

Structural failures of concrete dams may occur with the loss of the entire concrete dam structure or loss of particular monolith sections only. Structural failures of earthen or embankment dams may occur in the main embankment or appurtenant structures like guide banks/saddle dams. Failure of an appurtenant structure such as the spillway may lead to failure of an embankment dam, because of increase in the reservoir water level leading to eventual overtopping.

Conditions leading to overloading because of high reservoir water levels and consequent structural failure are common in dams where the reservoir elevation is increased due to flood in the upstream catchment. Even when the dam is not overtopped, the surcharge may increase, overstressing the different structural components of the dam. This overstressing may consequently result in an overturning failure, sliding failure, or failure of specific components/sections of the dam. Embankment dams may be at risk where increased water surfaces result in increased pore pressures and seepage rates, which exceed the design rates of the seepage control measures for the dam.

2.3.5 Seismic Failure Modes

Earthquakes are also an important cause of dam failures, especially in zones that have high seismic activity. For this purpose, the country has been classified into four seismic zones (IS: 1893, 1984), with the severity of potential earthquake hazard increasing with increase in zone number. Seismic failures are related either to ground movement or to liquefaction. Ground movements may result in a shift, settlement, or cracking of a dam into an undesirable configuration, which prevents the dam from performing as designed.

For embankment dams, two failure scenarios are envisaged: liquefaction and seismic-induced piping. Earthquakes may cause extreme stress on a dam, and liquefaction may occur when soils are loaded causing the soil to be transformed from a solid into a liquefied state. Soil liquefaction may result in almost instantaneous failure of a dam. It may also cause slumping, which exposes the dam crest to overtopping and subsequent erosion failure. Seismic-induced piping may occur through the internal cracks developed due to ground motions of an earthquake. Failure mechanisms due to seismic activities may include slope instability, permanent deformations, fissures or cracking, differential settlement, breaking of principal spillway and liquefaction.

2.3.6 Human-Influenced Failure Modes

Human-influenced dam failure may be related to improper design or maintenance, misoperation (sudden/uncontrolled/ unscheduled/accidental opening of gates), or acts of terrorism. Misoperation may also include the release of floodwater because of an emergency, without any warning. The inability to operate a gate in an emergency, a condition that may lead to overtopping of the dam and consequent breach may also be considered as misoperation. Acts of terrorism may range from purposeful misoperation of the dam to physical attacks carried out on the dam structure (e.g., rapid failure of spillway gates, and a lowering of the dam crest). For an embankment dam, lowering of the dam crest may lead to overtopping and subsequent erosion failure of the dam.

2.4 Floods due to Large Controlled Release

Flood risks at locations downstream of the dam may also arise without any failure of the dam/its components. After construction of a dam, the safe carrying capacity of the river channel normally keeps on decreasing, due to the diversion of water as well as flood moderation by the reservoir. Consequently, after many years of dam construction, the river channel downstream of a dam loses its capacity to carry the peak flood magnitudes. So, extensive bank overflows become associated with flood discharges. The situation gets further aggravated due to developmental activities taking place in the floodplain because of reduced frequency of inundation.

In the event of a severe flood in the dam catchment having a magnitude of peak discharge near to the design flood of the dam, the priority of dam operation will shift to saving the dam. Otherwise, a dam breach may endanger the lives of many more persons residing in the downstream area. With the passage of flood flows near to the spillway capacity, severe floods causing huge inundation may occur. It may even lead to loss of lives. Incident leading to huge damage downstream of Hirakud Dam due to the release of water through spillway gates in 2011 has been reported. Future losses of this type should be minimised through implementation of strict floodplain regulatory management plans and flood warning.

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Chapter 3. DAM BREACH ANALYSIS – THE CONCEPT

3.1 Introduction

Dam breach inundation studies may be required for a host of purposes, including evaluation and establishment of the hazard potential class of a dam, estimation of the potential loss of life downstream of a dam and evaluation of dam safety risk and prioritisation of dams within a group of dams being managed by an organisation. In addition, it may be necessary for selection of the appropriate IDF for the dam and its spillway design, preparation of EAPs, preparation of inundation maps for implementing flood-warning systems as also for planning flood mitigation including emergency evacuation. Dam breach inundation maps may also find its use in risk communication, for informing the public about the risk of living downstream of dams. There are two primary approaches for dam breach analysis. These are the event-based approach and the risk-based approach.

3.2 Event-Based Approaches

The event-based approach has traditionally been the most widely used approach for the analysis of dam breach. It is a deterministic method based on specific rainfall events for the dam breach analysis and downstream inundation mapping. These events may include extreme rainfall and runoff events, which may lead to natural floods of significant magnitude.

The maximum flood for which a dam is to be designed or evaluated is often dependent on its existing hazard potential classification (discussed in detail in the *Guideline for Classifying the Hazard Potential of Dams*) or size classification (as currently practiced in India). For the event-based approach, both a “fair weather failure” (piping failure), and a specific hydrologic failure event, such as dam break due overtopping under the Probable Maximum Flood (PMF), are usually considered, based on the hazard potential classification of a dam.

The main advantage of using an event-based approach is that it is a direct approach, is less complicated to perform and regulate, and produces more conservative breach inundation zone mapping as compared to a risk-based approach. Large and important dams having high-hazard potential in terms of loss of lives and property are evaluated for safety against the PMF. Dams with smaller storage volume or lower hydraulic head or dams with limited probable damage to property and lives in the event of a failure are evaluated for floods of lower magnitude, as dictated by the category of the dam.

Several hydrologic and non-hydrologic events of different magnitudes should be evaluated as part of an event-based dam safety analysis. For magnitudes of flood ranging from 50-year flood or 100-year flood to the PMF, the results of the analysis may indicate varying zones of inundation with varying economic loss and a varying potential threat to life. The flood management plans should be chosen in a prudent way to ensure the best utilisation of resources.

3.2.1 Non-flood Failure (Piping/ Internal Erosion)

A fair weather dam breach event is a dam failure that occurs during fair weather (i.e., no rainfall) condition. Other than piping or internal erosion in the dam body, failure may also be caused due to erosion along hydraulic structures like spillways or conduits, erosion due to animal burrows, and cracks in the dam structure. Since piping/ internal erosion may occur under normal operating conditions, it may pose higher risks to a dam than loading conditions like floods and earthquakes that have a very small probability of occurrence.

A fair weather breach is analysed by considering an initial reservoir water level and initiating a breach analysis without additional high inflow from a storm event. The minimum flow may be considered as the inflow into the reservoir. A fair weather breach is typically used to model piping failures. However, it may be appreciated that floods may increase the possibility of occurrence of piping, due to higher gradients of seepage flow.

The possibility of occurrence of piping in a dam primarily depends on the dam itself, including the configuration of the dam, the construction quality of the dam, and the geologic conditions. Potential locations at risk for piping failure may be anywhere in the body of the dam, its foundation or appurtenant structures. A faulty foundation may lead to piping failure, if the bedrock in the foundation contains faults not adequately treated, allowing development of seepage through the foundation. Soft soils in the foundation may lead to differential settlement cracks in the dam body, which ultimately results in piping through the dam body. Weak seams left at the interface between the dam body and the foundation may result in contact seepage along the interface.

Sometimes piping may occur if filter materials are gap graded (most of the material being of a single particle size), instead of being well graded (an assortment of different particle sizes). Dams having an impervious core generally have good control of seepage through the dam body. However, hydraulic fracturing is a phenomenon that creates preferential flow paths through clay core of dams. Subsequently, the core clay erodes as water flows along the hydraulic fractures. Therefore, foundation, abutment, or their interfaces with the dam body are potential locations at risk for earth dams with a core. In addition, contact along any embedded structure makes vulnerable points.

Breaching of the dam at the normal pool elevation level/full reservoir level is used to estimate the volume of water and associated peak of breach discharge that would result from a failure event during fair weather conditions.

3.2.2 Extreme Flood Failure (Overtopping)

Hydrologic failures that cause dam breach events are generally analysed based on the Inflow Design Flood (IDF) established by the hazard potential class of the dam/size of the dam, typically a PMF for high-hazard potential dams. While reviewing design floods for dams under DRIP, it was found that many of the older dams in the country have been designed for floods of smaller magnitudes, based on the methodology prevalent and data available at that time.

Following the recent estimation procedure, the design flood has been observed to increase significantly. In cases of other dams in the country, the threat of having a flood that is greater than its spillway capacity, with consequent chances of eventual overtopping may not be ruled out either. It may even be worthy to mention that the estimation of PMP, the rainfall driving the PMF, follows a certain procedure based on observed events with extreme rainfall. However less it might be, there still exists a chance of having extreme rainfall, which is greater than that observed or estimated currently. Therefore, a statistically small chance to have a flood that exceeds the PMF may still be present.

Even with the inflow flood less than the inflow design flood for the dam, there is a probability of reservoir fill up and overtopping, if the flood impinges at a level higher than that assumed in the flood routing studies. In case the required release from gated spillways during a flood event exceeds the safe carrying capacity of the channel downstream, gate operators may be reluctant to pass on the discharge at that high rate, allowing accumulation of water in the reservoir and increase of water level. In addition, one or more gates of a gated spillway may fail during a flood, due to mechanical failures, loss of power or gate jam.

Spillway discharge curve used in flood routing is sometimes based on ideal discharge conditions without consideration of downstream interference. Actual discharge during flood may be less. Spillway openings may be significantly blocked by debris, lowering the discharge. For gated spillways, flow at a given water surface elevation will vary depending on whether the condition allows free flow or orifice flow. Orifice flow will result in significant reduction of discharge.

Breaching of the dam at the Maximum Water Level (MWL, attained during the passage of the IDF) is used to estimate the volume and associated breach discharge that would result from a failure event during extreme flood failure conditions. It may even be the storage volume at the crest level or Top of the Bank Level (TBL) of the dam.

3.3 Risk-based (Consequences - based) Approach

Over the recent past, risk-based approaches to dam breach analysis have become more acceptable for dam safety and dam design purposes. There is a gradual shift towards the use of the risk-based approach to establish the IDF for a dam for the purpose of dam design. For the risk-based approach, the consequences for a range of hydrologic dam failure events downstream of a dam are evaluated. The consequences evaluation are not based on estimation of flood with a definite probability of occurrence (in other words, floods with a particular return period) and the resultant impacts, but relies instead on the potential loss of life or increase in economic losses caused by the potential failure of a dam under a diverging set of situations.

A benefit of the risk-based approach is that it may demonstrate, through an incremental damage assessment, that areas located downstream of a dam may be affected only marginally due to a dam breach, following a a reduction in the IDF for a dam. In general, this appears to increase the threat to the population residing downstream of a dam due to an increased risk of overtopping dam failure. However, by lowering the IDF requirements, the limited available funds, required for execution of the needed rehabilitation measures, may now be used for more dams, resulting in an overall increase in dam safety (FEMA, 2013).

A disadvantage of the risk-based approach is that by reducing the IDF to lesser magnitudes (from the flood magnitudes dictated by the hazard/size class of the dam) based on downstream consequences, the impact of future developments in the downstream of a dam is set aside from the present considerations. New development in the downstream zone that comes under inundation due to a dam breach may alter the consequences. This may result in the need for dam rehabilitation measures in the future to meet the demand of increasing the spillway capacity. Effective risk communication as a component of the local development approval process may assist in reducing the occurrence of “hazard creep,” an occurrence where new downstream development in a dam breach inundation zone increases the hazard potential classification of the dam and consequently its design IDF requirement.

Considering the huge expenditure going into the rapid development of infrastructures like highway networks and smart cities, it may be worth to plan the developments with due considerations of the dams existing upstream. This assumes importance as development of the area because of completion of the infrastructure projects will make implementation of dam rehabilitation schemes (e.g., increase of spillway capacity) further difficult in the future.

3.3.1 Inflow Design Flood and the Incremental Hazard

Incremental hazard evaluation and the establishment of the IDF is part of a risk-based approach. The selection of the IDF is based on the evaluation of the magnitude of several flood events of different magnitudes. The incremental hazard evaluation begins with a simulation of a dam failure during a hydrologic flooding condition, typically beginning with the PMF, SPF or 100-year flood, as governed by the dam class. The same hydrologic event is then carried out considering non-failure conditions.

The water surface elevations attained by both the breach and non-breach events are compared to determine the increase in the water surface elevation resulting from the dam breach. If the incremental increase in downstream water surface elevation between the failure and non-failure scenarios due to the passage of the IDF results in an unacceptable increase in consequences, a flood of larger magnitude is used to repeat the process. The process is repeated until the PMF or the situation where the incremental increase in consequences due to failure is within acceptable limits, and it is apparent that a larger IDF would not result in a larger incremental increase in consequences due to failure. Tentative acceptable consequence limits of failure may be set at an incremental depth of 0.3 m or 0.6 m at the downstream of a dam, depending upon the importance (FEMA, 2013). Engineering judgment and sensitivity analyses are needed to make final decisions on the acceptability of consequences and selection of the IDF.

Once the appropriate IDF for the dam is selected, it is then routed through the dam to assess whether the flood can be safely passed through the spillways without failure. If the IDF can pass safely, then no further evaluation or action is required; however, if the IDF cannot pass safely, then measures must be taken to enable the project to safely accommodate all floods up to the IDF to reduce the incremental increase in unacceptable additional consequences a failure may have on areas downstream.

3.4 Evaluation Approach

The probable consequences of a dam failure include loss of life, destruction of residential, commercial, industrial, and agricultural structures, equipment, and infrastructure, damage to structures and infrastructure, loss of services, and road closures resulting from flood damage, fallen trees, and accumulated debris. A major factor influencing the dam breach flood hazard is the loss of human life. By the hazard potential based system adopted worldwide in the recent times, the population at risk dictates the dam classification itself. In a large thickly populated country like India, it may not be practically feasible now to categorize all the dams to the highest class if it poses a potential threat to a single life, as followed in the countries like the US. However, evaluation of the number of persons whose lives may come under potential threat due to a dam breach may form the logical basis for an assessment of the relative importance of one dam over the other.

3.4.1 Loss of Life/Population at Risk

Estimation of probable loss of life is an important factor used in hazard potential classification systems and emergency action planning. The population at risk may be defined as the number of persons present in areas downstream of a dam and may be in danger in the event of a dam failure. Persons residing in the area downstream of a dam may be estimated by multiplying the number of residences with the average prevailing rate of occupancy for the area.

Site-specific information about the probable occupancy should be used for water or wastewater treatment works, factories/ manufacturing or production facilities, farmhouses, fish hatcheries, and similar facilities. Estimated number of persons at temporary use facilities such as resorts, camping grounds, and recreational areas should be evaluated separately. In all cases, estimation of the population at risk in areas that might be inundated should be based on conservative judgment (Dam Safety Guidelines, 2007). This has been discussed later in greater details. In addition, the *Guidelines on Assessing and Managing Risks Associated with Dams*, being prepared in the same series may be referred to.

The following steps need to be followed to complete an analysis for estimation of loss of life:

Step 1: Decide upon dam failure scenarios for evaluation of the consequences

Step 2: Estimate time categories for which loss of life estimates are needed

Step 3: Fix when dam failure warnings would be initiated

Step 4: Estimate the area flooded for each dam failure scenario

Step 5: Estimate the number of people at risk for each failure scenario and time category

Step 6: Apply empirically based equations or other methods for estimating fatalities. Alternatively, assess fatality from the depth of inundation, flow velocity, and population density maps.

Step 7: Evaluate uncertainty

The number of fatalities resulting from dam failure is mostly influenced by three factors:

1. The number of people occupying the area inundated due to the dam failure,
2. The amount of warning provided to the people exposed to dangerous flooding, and
3. The severity of the flooding, which can be assessed in terms of the depth of inundation and the velocity of inundation.

Without exception, dam failures that have caused high fatality rates were those in which residences were destroyed and timely dam failure warnings were not issued. Estimating when dam failure warnings would be initiated is probably the most important part of estimating the loss of life that would result from dam failure.

For each failure scenario and time category, the population at risk must be calculated. The population at risk is defined as the number of people occupying the dam failure floodplain prior to the issuance of any warning. The methods developed for estimating the loss of life provides recommended fatality rates based on the flood severity, amount of warning time, and a measure of whether people understand the severity of the flooding. Possible fatality rates for estimating the loss of life may be determined based on a set of criteria that includes different combinations of flood severity, warning times, and flood severity understandings. For tiered estimation of the population at risk, an attempt to provide guidance about the requirements has been made in Table 3.1.

Table 3-1. Tier-wise estimation of population at risk

Tier level	Appropriate Approach for Estimating PAR
Tier 1	Basic approaches: crude assumptions about inundated area, population at risk based on district wise population density maps
Tier 2	Intermediate level approaches: analysis of dam breach inundation area using coarse resolution DEM, more detailed estimation of population at risk, estimation of potential loss of life using empirical approaches (e.g., USDI, 1999)
Tier 3	Detailed estimation: detailed analysis of dam breach flood inundation area, estimation of population at household level, application of advanced models like LSM to estimate potential loss of life

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Chapter 4. DAM BREACH MODELLING

4.1 Introduction

Carrying out a dam breach modelling exercise involves prediction of the dam breach hydrograph and the routing of that hydrograph downstream. A number of modelling tools are available to perform dam breach modelling, ranging from simple methods to complex models. With advancements in Geographical Information System (GIS) - based modelling, many models can interface with digital terrain data to produce automated dam breach inundation zone delineations.

Fortunately, failures of large embankment dams (measured either by their height or by the volume of water they store) are comparatively rare. However, if they occur, it may cause immense destruction and numerous fatalities. Small dams fail considerably more often. The level of detail of hydrologic and hydraulic analyses needed to evaluate the consequences of dam-breach floods depends on the downstream hazards they present.

The impacts of a dam failure depend on its type of construction (e.g., earth, rock, concrete, masonry, and other materials), the volume of the reservoir at the time of failure and the height and length of the dam. It also depends on the purpose of the dam and reservoir (e.g., flood control, water supply, generation of hydropower) as it dictates the water storage level at any point of time (FEMA, 2012).

4.2 Embankment Dams

Although breaching in embankment dams may occur due to a variety of reasons, breaches in embankment dams are most often modelled as overtopping or piping failures. Overtopping failures may occur very differently depending on the composition of the dam. Perhaps the simplest of the overtopping failure is the failure of a cohesive soil embankment.

Generally, a small head cut typically forms on the downstream face of a cohesive soil embankment and progresses upstream. The breach is considered to begin when erosion occurs across the width of the dam crest. After the breach initiates at the top of the dam crest, it enlarges to its ultimate extent. If there is no other physical reason to believe that the embankment would fail at a certain location, the breach should be modelled as initiating at the maximum section typically located at the centreline of the downstream main channel. The stages of dam breach due to overtopping of an earthen embankment are shown in Figure 4-1 (adopted from USACE, 2014). The stages of a breach in case of a piping failure are shown in Figure 4-2 (adopted from USACE, 2014).

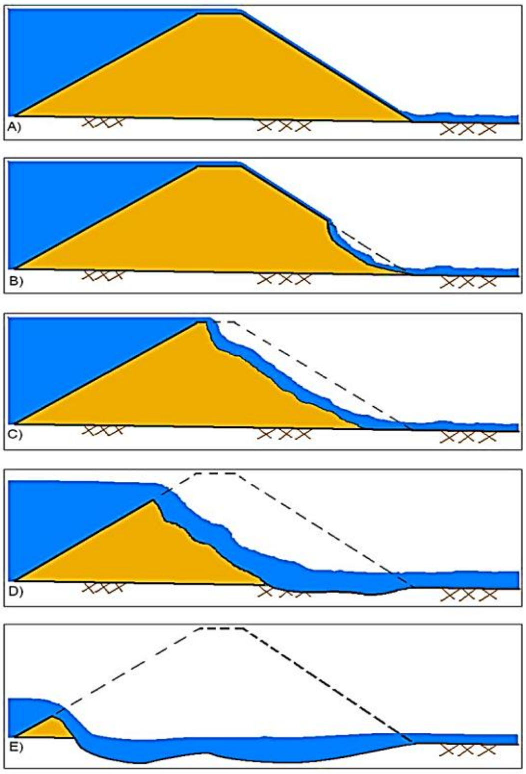


Figure 4-1: Stages of earth dam breach during overtopping failure (adopted from USACE, 2014)

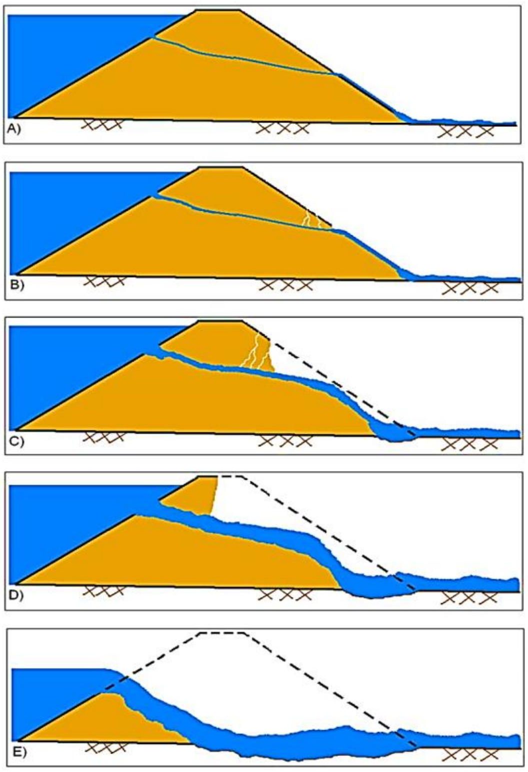


Figure 4-2: Stages of earth dam breach during piping failure (adopted from USACE, 2014)

The breach may stop growing when the reservoir has emptied and there is no more water to erode the dam or the dam has completely eroded to the bottom of the reservoir or has reached bedrock. The breach progression may be modelled as either a linear progression or a sine wave progression:

- Linear progression: the rate of erosion remains the same for the duration of erosion development.
- Sine wave progression: breach grows very slowly at the beginning and end of development and rapidly in between.

Many statistical regression equations were developed for use with empirical methods of evaluating dam failure and breach parameters. The breach modelling process was further advanced with the prediction of the reservoir outflow hydrograph and the routing of the hydrograph downstream.

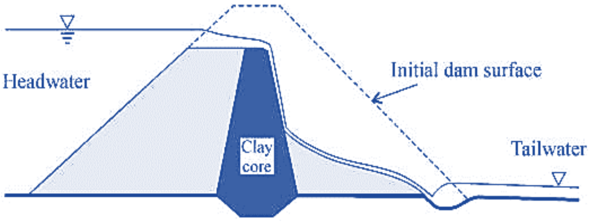


Figure 4-3: Overtopping dam breach of a composite earth dam with clay core (adopted from ASCE, 2011)

Out of these equations, those developed by Froehlich (1995, 2008), McDonald and Langridge-Monopolis (1984), Von Thun and Gillette (1990) and Xu and Zhang (2009) are the ones most commonly used. Based on the data from 111 dam failures, Froehlich (2017a) developed formulae to compute the dam breach model parameters for embankment dams, along with their variances and prediction intervals. These equations for estimating the breach parameters have been presented later in the document.

For dams having a clay core, the breaching process will be similar to that of an embankment dam without a core. The major difference will be in the progression of the breaching process and the time taken for a breach. The final breached section is not expected to be largely different. Schematic representation of the breach of an embankment dam with a clay core as obtained from ASCE (2011) has been presented in Figure 4-3.

4.3 Concrete and Masonry Dams

For concrete and masonry dams, only limited data are available. Analyses by agencies like USACE, FERC, and NWS (USACE, 2014) show that unlike the earthen dams, the failure is almost instantaneous in this case, and the breach formation time is limited to 6 minutes to a maximum of 30 minutes. In case of concrete arch dams, it would be even less than 6 minutes. The side slopes of the breached section are vertical. In addition, the width of the breach is governed by the length of the monolith blocks, usually, less than 50% of the length of the dam failing. The limiting peak discharge can be estimated using the formula for estimation of peak discharge discussed subsequently.

4.4 Dam Breach Parameters

For arriving at a dam breach hydrograph through dam breach modelling, estimating the breach parameters related to the geometry and timing of the breach formation (e.g., width, depth, shape, and time of failure) is a key step. It has been noted that the selection of breach parameters for modelling dam breaches contain the greatest uncertainty of all aspects of dam failure analysis and therefore a careful evaluation and understanding of the associated breach parameters is necessary.

A number of methods are available for estimating breach parameters for use in dam breach studies. Since the selection of the breach parameters is specific to each dam, guidance is provided by describing methods currently applied by dam safety professionals without recommending a single standardized method:

1. Physically Based Erosion Methods – These methods predict the development of an embankment breach and the resulting breach outflows using an erosion model based on principles of hydraulics, sediment transport, and soil mechanics.
2. Parametric Regression Equations – These equations, developed from case study information, are used to estimate the time-to-failure and ultimate breach geometry. The breach may then be simulated to proceed as a time-dependent linear process with the computation breach outflows using principles of hydraulics.

The regression-based methods enjoy the advantage of having low complexity and simple data needs. They yield rapid results that are satisfactory for appraisal level. However, there is a host of equations available, and the associated uncertainty is high.

On the other hand, the physically based models are expected to yield better results, since they factor in parameters like erosion rates, level of compaction, angle of repose, shear stress, and slope protection works. However, the accuracy of the results will depend on the availability and accuracy of the inputs, which are often difficult to obtain. Detailed information on physically based models is available in literature (USDI, 1998; Hanson et al., 2011; USDI, 2012).

4.4.1 Breach Parameters for Embankment Dams

The dimensions of a trapezoidal dam breach are shown in Figure 4-4. Breaching begins when the reservoir water surface elevation reaches the failure elevation Y_f (above the datum).The formulae are (Froehlich, 2017a):

$$\widehat{B}_{avg}=0.23\times k_M\times V_W^{1/3}$$

Where, $\widehat{B}_{avg}$ = expected value of B_{avg}in metres (shown as in the figure as $\overline{B}$)

$$k_M=\begin{cases}1.0, \text{ for internal erosion failures}\\1.5, \text{ for overtopping failures}\end{cases}$$

$$\widehat{m}=\begin{cases}0.6, \text{ for internal erosion failures}\\1.0, \text{ for overtopping failures}\end{cases}$$

Where, $\widehat{m}$ = (shown as ‘z” in the figure) expected average breach side-slope ratio (horizontal: vertical) and,

$$\hat{t}_f=60\times\sqrt{\frac{V_W}{gH_b^2}}$$

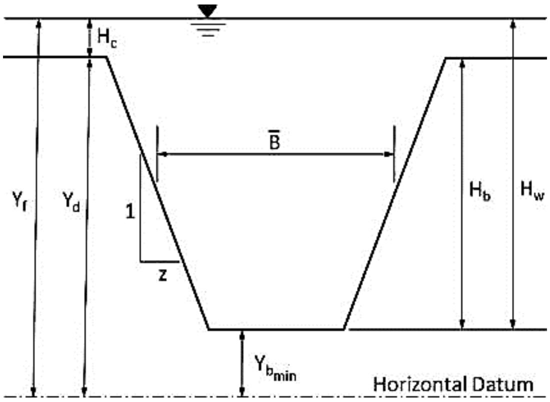


Figure 4-4: Final dimensions of a trapezoidal embankment dam breach approximation in metres (adopted from Froehlich, 2008)

Where, $\hat{t}_f$ = breach formation time in seconds

V_W =Volume of water above breach bottom in m^3

H_b = Height of breach in metres

An example showing the calculations has been presented in Appendix B. A few other commonly used equations used for estimation of dam breach parameters for embankment dams have been provided in Appendix C.

4.4.2 Breach Parameters for Concrete and Masonry Dams

The following equation (Froehlich, 2017b, personal communication) can be used for estimation of the average width of the breach in case of concrete and masonry dams:

$$B_{avg}=0.12\times1.5^{Type}\times\left(\frac{V_W}{H_b^3}\right)^{1/4}\times\left(\frac{L_a}{H_b}\right)^{2/3}\times H_b$$

Where,

$$Type=\begin{cases}1\text{, for concrete dams}\\0\text{, for masonry dams}\end{cases}$$

L_a= approach flow width

4.5 Dam Breach Hydrograph and Peak Outflow

Because embankment dams are so extensive in number, it is important to estimate potential flood hazards that would be generated by uncontrolled releases of impounded water through a breach, for preparation of emergency action plans. Many of the methods for estimating peak discharge rely on reported flow rates from past embankment dam failures, or from small-scale laboratory experiments, to evaluate model coefficients.

Froehlich (2016) presents two nonlinear mathematical models (one empirical and the other semi-theoretical) to predict the peak discharge from a breached embankment dam based on examination of measured outflows from 41 dam failures of the past. Being based on the largest data set so far, these equations are expected to yield better results and are presented in the next sections.

The average embankment width for the 41 dams is estimated to have a range of 9.63 m to 250 m (Froehlich, 2016). The volume of water above breach bottom has a range of 0.0133 Mm³ to 701 Mm³. The height of water above breach bottom is shown to vary between 1.68 m and 77.4 m. The height of breach may have values between 3.66 m and 86.9 m. The approach flow width varies between 40 m and 4,100 m. Consequently, the measured peak discharge varies between 30 m³/s and 65,120 m³/s. It is seen that the variations extend up to two orders of magnitude.

4.5.1 Empirical Equation for Estimating Peak Discharge

The empirical expression given by Froehlich (2016) for the expected value of peak discharge is:

$$\hat{Q}_p=0.0175\times k_M\times k_H\times\sqrt{\frac{gV_WH_WH_b^2}{W_{avg}}}$$

Where, $\hat{Q}_p$ = Peak discharge in m³/s

$$k_M=\begin{cases}1\text{, for non-overtopping failure modes}\\1.85\text{, for overtopping failure modes}\end{cases}$$

$$k_H=\begin{cases}1\text{, for }H_b\le H_S\\\left(\frac{H_b}{H_S}\right)^{1/8}\text{ for }H_b>H_S\end{cases}$$

H_b= height of breach in metres

H_S=6.1 m

H_W= height of water above the breach bottom

g = acceleration due to gravity

W_{avg}= average width of the embankment above breach bottom

The effect of embankment height on peak breach discharge as described by the factor k_H changes significantly for $H_b > 6.1$ m. Peak discharge from breaches of smaller dams will be greater than would otherwise be expected. Soil properties including the degree of compaction, cohesion, and particle size have a more pronounced influence on the rate of erosion of the embankments, thus causing breach growth to speed up and peak discharge to increase.

4.5.2 Semi-theoretical Equations for Estimating Peak Discharge

The semi-theoretical formula is presented below:

$$\widehat{Q}_P = Q_{P_{max}} \times \left(\frac{1}{1+\alpha \times t_f \sqrt{\frac{g}{H_b}}} \right)^{\beta}$$

Where, $Q_{P_{max}}$ = maximum possible peak discharge from a breach of specified dimensions that forms instantly (equations given at the bottom of this page),

$$\alpha = 0.000045$$

$$\beta = 500 \times \left[\left(W_{avg} \times H_b^2 \right) / V_W \right]^{2/3}$$

While $\widehat{Q}_P$ is applicable for embankment dams only, $Q_{P_{max}}$ quantifies the upper limit of peak discharge due to instantaneous removal of a water barrier. Therefore, $Q_{P_{max}}$ being developed on theoretical considerations, may be considered as the upper limit for checking the validity of the estimated peak discharge for concrete dams.

4.6 Dam Breach Parameter Uncertainty

Owing to the large variations in dam construction material and process, dam dimensions, a multitude of ways in which breaches develop in embankment dams, and a large number of factors that influence the speed and extent of embankment erosion, it is difficult to describe the dam breach parameters with rigorously precise mathematical formulae. In addition, most of the available data on dam breach represents the dams that are of smaller size. Consequently, huge uncertainty exists between the breach parameters estimated using different available models. Froehlich (2008) used data from 74 embankment dam failures to compare the observed and predicted breach widths, as shown in Figure 4-5.

The regression-based methods were developed with a view to providing rapid results for appraisal-level estimation in an economical way. Nevertheless, due to their low complexity (compared to physically based models) and simple data needs (and difficulties in satisfying data requirements for physically models), they are actually used for purposes that are more important as well. Again, there are a host of such regression equations available, which yield breach parameter values largely different from one another.

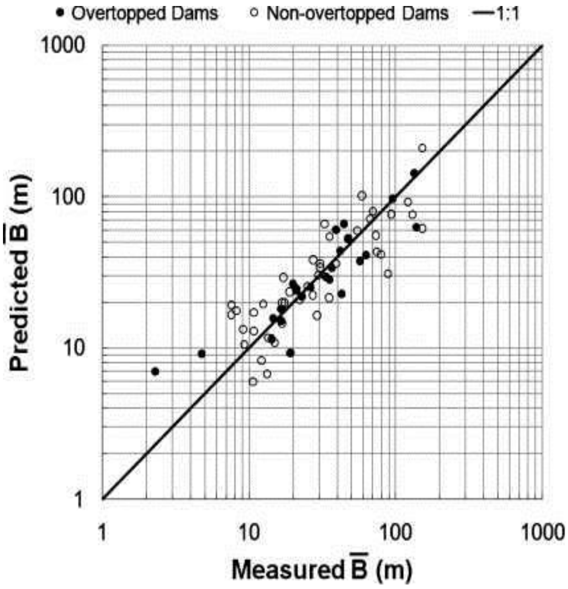


Figure 4-5: Average breach widths: measured and predicted (adopted from Froehlich, 2008)

$$Q_{P_{max}} = \begin{cases} \frac{8}{27}\left(\frac{L_a}{B_{avg}}\right)^{0.28} \left[B_{avg} - m\left(H_b - \frac{4}{5}H_W \right) \right] \sqrt{gH_W^3}, & \text{for } H_W \leq H_b \\ \frac{8}{27}\left(\frac{L_a}{B_{avg}}\right)^{0.28} \left\{ \left(B_{avg} - mH_b \right) - \frac{4}{5} mH_W \left[\left(1 - \frac{H_b}{H_W} \right)^{5/2} - 1 \right] \right\} \sqrt{gH_W^3}, & \text{for } H_W > H_b \end{cases}$$

The same is also true for physically based methods, as data on input parameters like erosion rates, level of compaction, the angle of repose, shear stress and slope protection are seldom available from observations. Therefore, these values often have to be entered based on judgement. As a result, it is a challenge to choose the right equation, and after the estimation is carried out, to be sure that the obtained values are reasonable.

In order to have confidence on the reasonableness of the results, guidelines prepared by reputed agencies (e.g., USACE) may be used. The values suggested by USACE (2014) are shown in Table 4-1. The obtained values may be modified if they do not match with the suggested range of values presented in Table 4.1. It is to be remembered that these values are only for the purpose of providing guidance and obtaining confidence about the rationality of the computed values. Under certain circumstances, the estimated values may not compare with those in the table and still be correct

The outputs may also be compared to the output parameters predicted by the envelop curves. The envelope curves from USACE (2014) are presented in Figure 4-6. However, it is also cautioned that this envelope curve was developed based on fourteen datasets only, and thus may not represent a true upper bound of peak flow versus hydraulic depth. Sensitivity analysis of the results may be able to demonstrate the implications of choice of equations on the predictions. Figure 4-7 (USACE, 2014) shows that the difference in predictions of peak outflow is conspicuous near the dam, but at greater distances downstream, they are minor. This helps to demonstrate that the relative importance of making the correct choice during model selection is more for locations immediately downstream of the dam than for locations which are further downstream.

Considering the uncertain nature of the input breach parameters predicted outcomes (peak stages and peak flow rates) may be obtained for a host of input parameter combinations with a stochastic model of dam breach flooding using Monte Carlo

Table 4-1: Range of possible breach parameters (adopted from USACE, 2014)

Dam Type	Average Breach Width (B_{ave})	Horizontal Component of Breach Side Slope (H) (H:V)	Failure Time, t_f (hours)
Earthen/Rock fill	(0.5 to 3.0) × H_D (1.0 to 5.0) × H_D (2.0 to 5.0) × H_D (0.5 to 5.0) × H_D*	0 to 1.0 0 to 1.0 0 to 1.0 (slightly larger) 0 to 1.0	0.5 to 4.0 0.1 to 1.0 0.1 to 1.0 0.1 to 4.0*
Concrete Gravity	Multiple Monoliths Usually < 0.5 L Usually < 0.5 L Multiple Monoliths	Vertical Vertical Vertical Vertical	0.1 to 0.5 0.1 to 0.3 0.1 to 0.2 0.1 to 0.5
Concrete Arch	Entire Dam Entire Dam (0.8 x L) to L (0.8 x L) to L	Valley wall slope 0 to valley walls 0 to valley walls 0 to valley walls	<0.1 <0.1 <0.1 <0.1
Slag/Refuse	(0.8 x L) to L (0.8 x L) to L	1.0 to 2.0	0.1 to 0.3 <0.1

*Note: Dams that have very large volumes of water and long dam crest lengths, will continue to erode for longer durations (i.e., as long as significant amount of water continues flowing through the breach), and may therefore have longer breach widths and times than what is shown here.
H_D = height of the dam; L = length of the dam crest

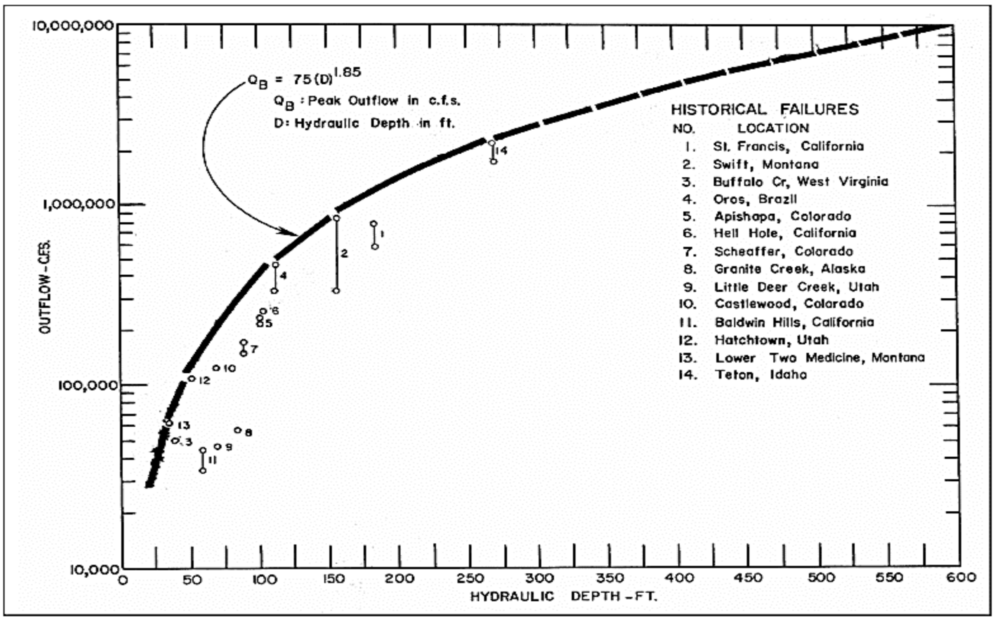


Figure 4-6: Envelope of experienced outflow rates from breached dams (adopted from USACE, 2014)

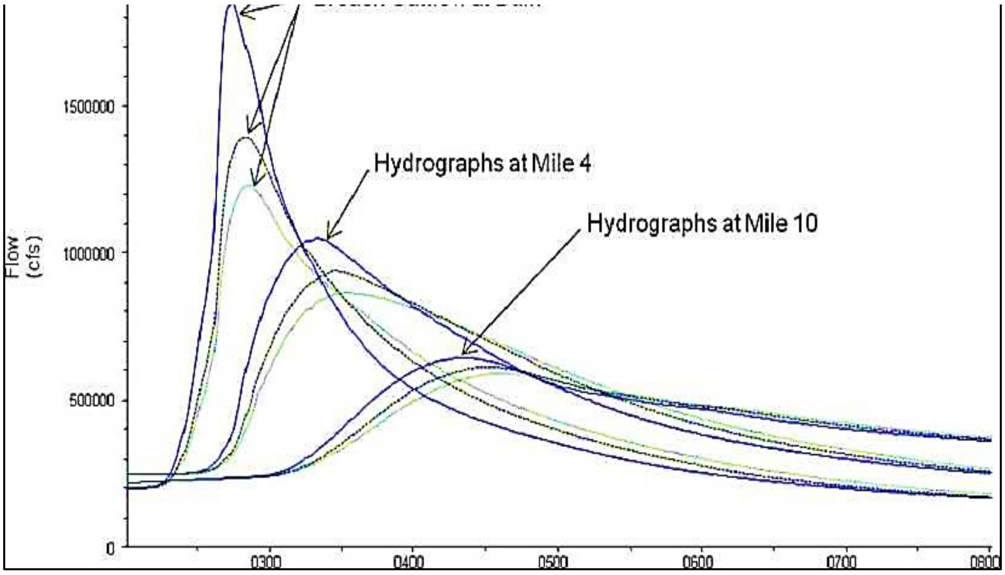


Figure 4-7: Dam break wave progression downstream (adopted from USACE, 2014)

simulation approach. The stochastic dam breach model will randomly sample the probability distributions for each of the input variables, carry out a dam breach simulation using the generated parameters, and then repeat the process many times.

The outcomes (range of breach width, time of breach formation and breach side slope) of simulation will cover all potential consequences of the flood model. This will allow estimation of confidence intervals for outputs like peak discharge at a downstream location. The results of Froehlich and Goodell (2012) showing the peak discharges for Big Bay Dam breach in the US with different levels of confidence has been presented in Figure 4-8. It also shows the peak discharge realised during the breach.

These profiles of predicted peak discharges for various exceedance probabilities were

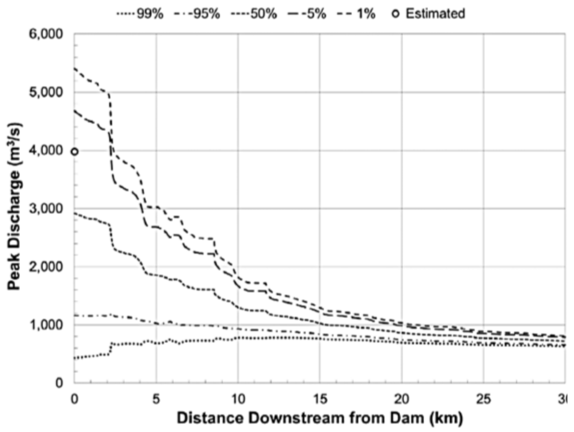


Figure 4-8: Peak discharges predicted at different confidence intervals and observed peak discharge (adopted from Froehlich and Goodell, 2012)

obtained through multiple simulations with varying average width, side slope and time of failure (considered as uncorrelated variables). The values of these parameters corresponding to different probabilities were estimated using the estimated variance of the parameters. It was revealed that the observed values in most cases were between the 50% and 99% exceedance probability limits.

The reasons for these differences were attributed to several factors including: uncertainty of estimated high-water marks, one-dimensional flow approximations that consider water-surface elevation to be constant along cross sections, imprecise estimates of coefficients of flow resistance, expansion and contraction coefficients, and cross-section representations, and the effect of debris blockages at bridges and other channel constrictions that remains unaccounted for.

One may prepare such plots for dam breach outputs like flood peak arrival time at a particular location, as also others. Depending on the demand for the situation, the choice of the appropriate confidence interval may be made.

Generally, for each failure mode, a range of breach sizes and failure times is predicted using several methods. Several regression equations may be used to estimate breach parameter values. In case the dimensions of the dam under investigation are outside the range of data that were used for developing the dam breach regression equation, resulting breach parameter estimates should be examined closely for its reasonableness. Type of dam should be considered with care for choosing the breach equation. All the breach parameters should be estimated using the same set of equations chosen.

For advanced levels of study, physically based computer models should also be used in addition to the regression equations. Another parameter that introduces uncertainty in the outputs is the pool water level elevation. It has to be chosen based on engineering judgement.

Check for reasonableness should also be carried out for velocities through the breach during the breach formation process. The existence of very high flow rates and velocities through the breach at the full breach development size and time are indicative of breach size too small or breach time too short if there are no physical constraints limiting the size of the breach. Otherwise, very small flow rates and velocities through the breach before the breach reaching its full size and development time are indicative of breach size too large or the breach time too long.

The breach progression curve and the hydraulic coefficients (weir and piping) are other important factors that need consideration. The level of effort to estimate breach parameters should commensurate with the type of risk assessment. The effort and detail will increase with the increase in the hazard potential of the dam.

Depending on the need, the uncertainty may be reduced to acceptable limits by using guidelines prepared by several agencies (e.g., USACE, FERC, NWS etc.), envelope curves, sensitivity analysis or probabilistic analysis. While following the guidelines or envelope curves may be sufficient for Tier 1 level analysis, sensitivity analysis and probabilistic analysis may be warranted for the Tier 2 and Tier 3 level analysis. Taking the analysis to higher levels may be required if there are important cities/structures of national importance (e.g., power plant) in the immediate downstream area of a dam.

4.7 Upstream Flood Routing

As per current practice in the country, the routing through the reservoir upstream is carried out considering a level pool, using approaches like the Modified Puls method. This may be expected to yield satisfactory results for reservoirs that are wide and short. An example of such reservoir (Marudhanadhi Dam of Tamil Nadu) is shown in Figure 4-9. For a long and narrow reservoir like the one behind Sathanur Dam, Tamil Nadu (Figure 4-10), this may introduce significant error. In such cases, use of hydrodynamic routing is warranted. It has been shown (USACE, 2014) that under certain circumstances the errors may reach even 45% or more.

4.8 Downstream Flood Routing

Once the peak of flood discharge coming out of a breached dam is estimated, the most important inputs required for carrying out an emergency evacuation plan are the areas that will be inundated, depth of flooding and velocity of flow of the floodwaters. In addition, information about the time available before inundation takes place is crucial. All these are estimated through flood routing exercise, with roughness and other parameters chosen based on judgement.

In Appendix D, Figure D-1 a methodology to estimate the limits of the model in case of a cascade effect of dams is presented.

4.8.1 Downstream Extent of Study

The downstream area to be considered for a dam breach analysis is to be chosen judiciously. As discussed earlier, the two-dimensional modelling is quite demanding

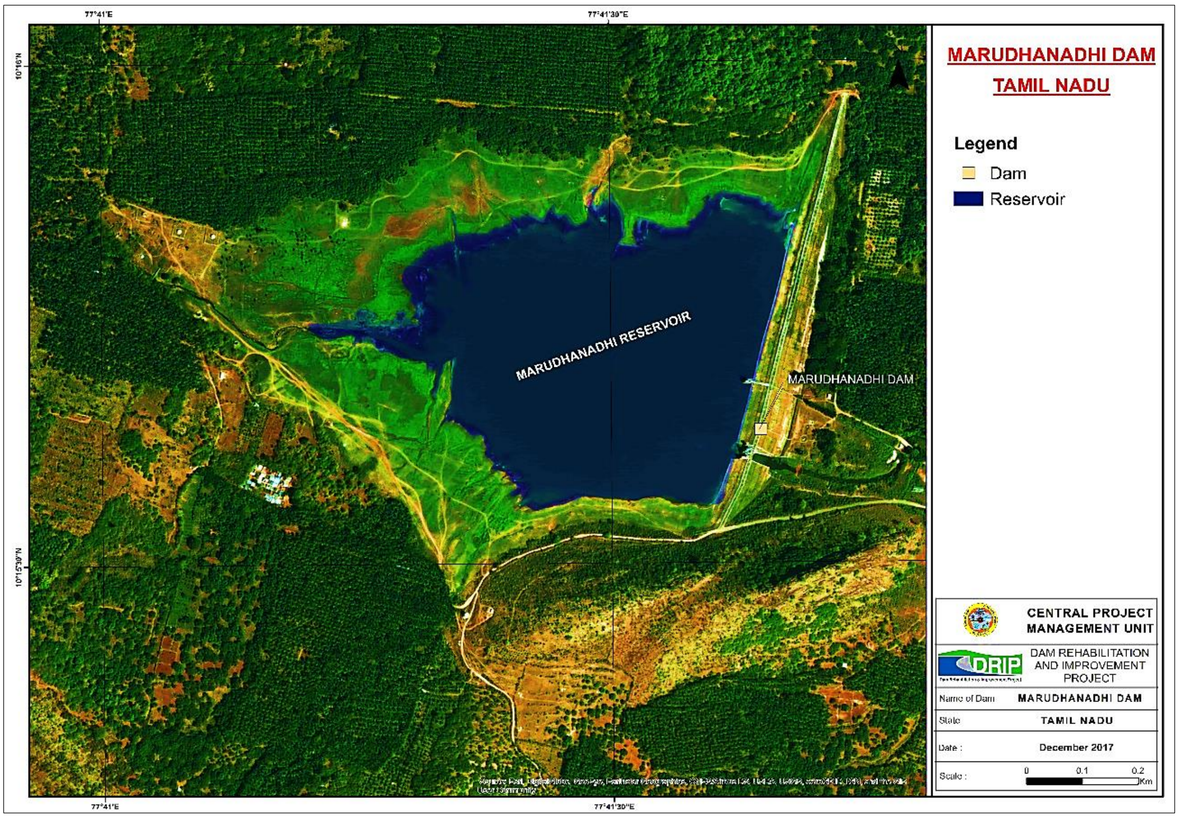


Figure 4-9: Wide and short reservoir behind Marudhanadhi Dam, Tamil Nadu

computationally, and with the hardware configurations available at present, each run may take hours together. Depending on the chosen cell size of the grid, the time required increases rapidly with increasing area. In general, the study area should extend downstream up to the point where the river under study debouches into the sea/larger river/large reservoir. In case this does not happen within a few tens of kilometres, it is checked whether the flow velocities have reduced to nominal values of 0.3 m/s or less/the flow area is restricted to the normal boundary of river flow.

4.8.2 Overview of Modelling Approach

Dam breach modelling can be classified into two categories, each of which has a number of models, tools, or equations, ranging from simple to advanced:

1. Tools that generate the dam breach peak discharge and/or hydrograph only; and
2. Tools that develop a breach hydrograph and perform downstream flood routing using a one- or two-dimensional hydraulic model.

Simplified numerical models typically relate the breach hydrograph (or breach peak flow) to simple reservoir characteristics such as reservoir volume and dam height. These models may or may not include hydrologic modelling to determine the envelope of maximum water depths to calculate the breach flow.

Most simplified models do not consider complicated downstream conditions such as backwater effects. Additionally, reservoir routing (if present) uses level pool routing methods; in other words, the reservoir water surface is considered to be horizontal during the drawdown. This simplification is not applicable to all situations. The main benefit of simplified numerical models is that substantially less time is required to set up and run these models.

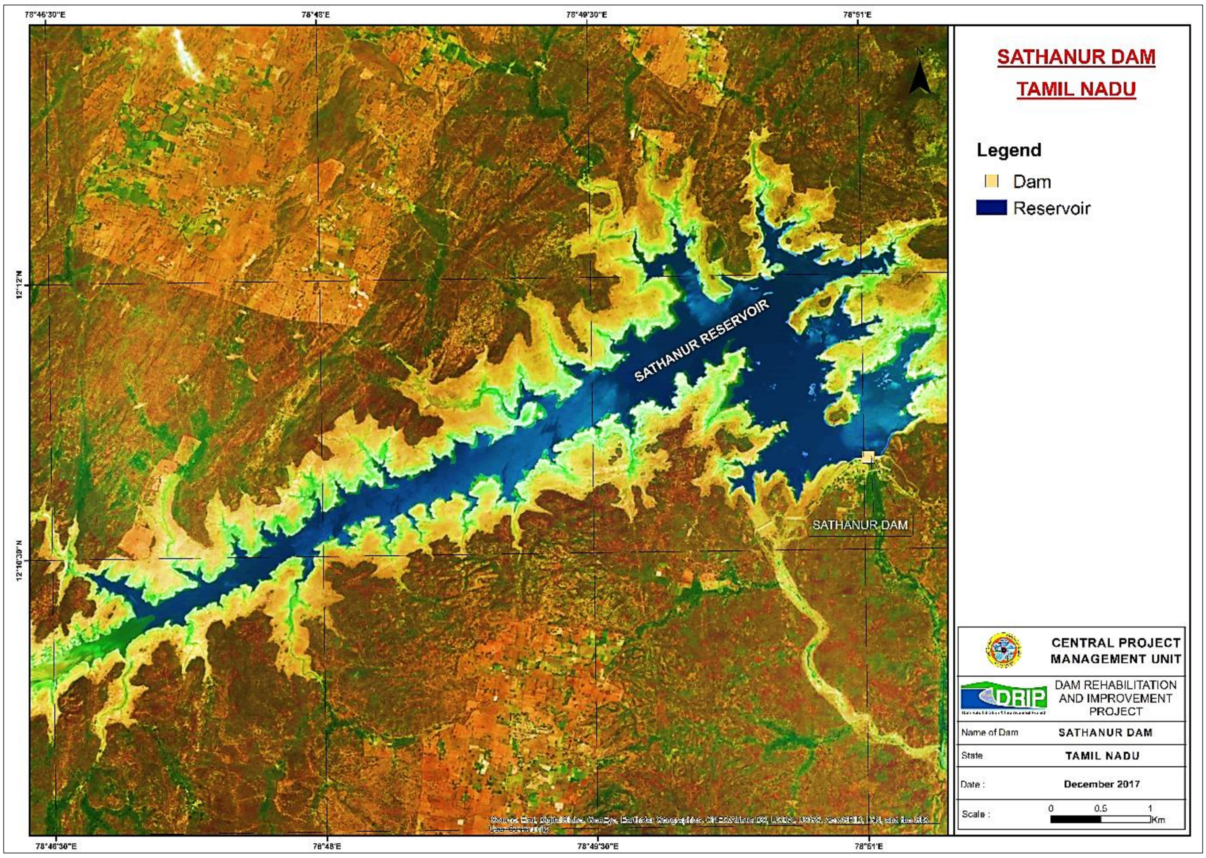


Figure 4-10: Long and narrow reservoir behind Sathanur Dam, Tamil Nadu

It is a common practice to first estimate breach parameters through empirical equations and then to use another model to define the breach hydrograph. The breach hydrograph is then routed downstream using either a one-dimensional cross-section averaged or a two-dimensional depth-averaged hydraulic model. Kinematic wave equation (the simplest of all) is valid only for uniform flow during a large, steady flood. In this case, backwater effects are not reproduced either. Diffusion wave equations are most applicable in subcritical flows where effects of viscosity prevail and effects of inertia are not pronounced. Full dynamic wave equations (Saint Venant's or shallow water equations) are applicable in almost all hydraulic problems. However, it is the most complex to deal with, and computation time demand increases in the same way. For dam breach analysis, this last approach should always be used. However, for some rough preliminary assessment, diffusion-wave equations may be applied.

The modelling software handles the full hydraulic complexity through numerical solutions. For each time step, diffusion wave or full hydrodynamic equations (Saint Venant's equations) are solved for each grid cell, ensuring continuity of the flow at all stages. In this way, the best mathematical representation of the flood flow through the channel and over the floodplains is ensured.

4.8.3 Modelling Software

For analysing the dam breach process and routing the peak breach outflows to determine inundation depths downstream of the dam, a model DAMBRK was developed in 1977. It was followed by NWS Flood Wave Dynamic Model (FLDWAV), HEC-1, HEC- HMS, and HEC-RAS, amongst others. Some more developments include the NWS SMPDBK, GeoDamBREACH developed by FEMA, Decision Support System for Water Infrastructural Security (DSS-WISE) developed by the National Centre for Computational Hydroscience and Engineering of the University of Mississippi, MIKE software by DHI, FLO-2D by FLO-2D Software Inc., SIMBA by ARS, and Win-DAM developed through a collaborative effort between ARS, NRCS, and Kansas State University.

Amongst all these, the recent version of HEC-RAS has a few advantages:

- It is capable of modelling at a courser grid cell size while taking sub-grid scale variation of bathymetry (from terrain model with finer resolution) into account
- It can handle structured and unstructured mesh together
- It has a very wide user community and strong support
- It comes free of cost

Though this guideline does not recommend any particular software/programme over the other, owing to the advantages mentioned above, HEC-RAS has been chosen for dam break analysis in the DRIP project. Therefore, a brief discussion on HEC-RAS has been presented in the flowing section.

4.8.4 The HEC-RAS Software

HEC-RAS has been developed by the Hydrologic Engineering Centre of the US Army Corps of Engineers. The program has the ability to solve either the 2D full Saint Venant shallow water equations (with optional momentum additions for turbulence and Coriolis effects) or the 2D Diffusion Wave equations, as chosen by the user. The 2D unsteady flow equations solver uses an Implicit Finite Volume algorithm, allowing for larger computational time steps with improved stability and robustness in handling subcritical, supercritical and mixed flow regimes. The 1D and 2D solution algorithms are coupled through time steps. Each cell and cell face are defined as tables to have properties like elevation-volume, elevation-area, elevation wetted perimeter and roughness based on the resolution of the terrain model which is much smaller than the grid size of the mesh used for 2D computation. This allows much faster computation without losing details. It also has detailed flood mapping and flood animation capabilities.

4.8.5 One-Dimensional Models

One-dimensional models solve either full dynamic or simplified forms of one-dimensional, cross-section-averaged shallow water equations. These models are more sophisticated than simplified numerical models and do typically consider backwater effects.

Many one-dimensional models are capable of carrying out dynamic reservoir routing rather than level pool routing. Many of these one-dimensional models also have downstream routing capabilities. One-dimensional routing is fairly sophisticated, being best suited for modelling flow through a well-defined, confined channel.

One-dimensional models provide reliable results for many situations. These models are best suited to geographic regions with moderate to steep slopes where floodwaters are constrained within a relatively narrow floodplain and generally flow in the direction of a single streamline without major or frequent divergence of flow. An example of one-dimensional model in HEC-RAS is shown in Figure 4-11. However, one-dimensional models in unconfined floodplains do not accurately represent the breach flood wave moving downstream. For routing over wide, flat surfaces, such as floodplains, one-dimensional models make certain assumptions (such as uniform flow velocity over a cross-section) which do not hold good and may have significant consequences on the accuracy of the model. Routing under these situations using one-dimensional models is possible using appropriate, conservative modifications. Another option is to use two-dimensional models that can more accurately model flow over floodplains.

4.8.6 Two-Dimensional Models

Two-dimensional models use full dynamic or simplified forms of one- and two-dimensional shallow water equations to

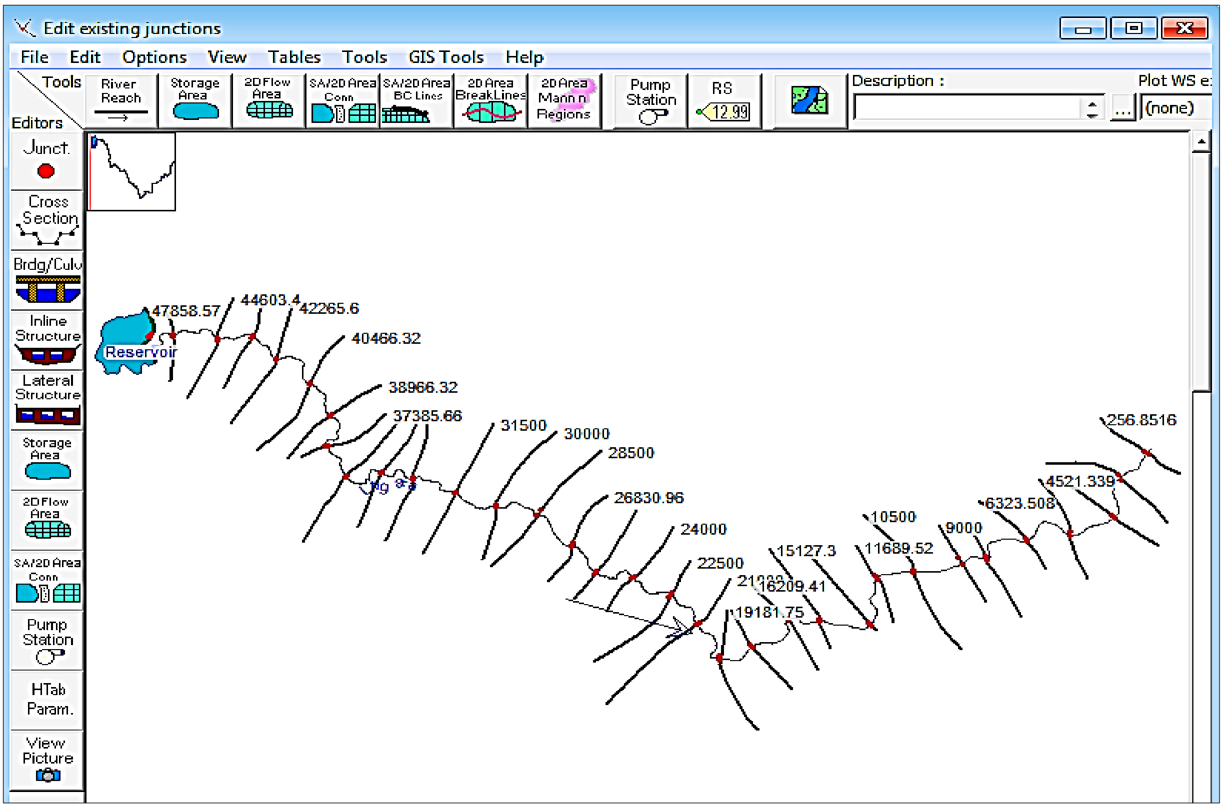


Figure 4-11: One-dimensional model in HEC-RAS

solve both one-dimensional channel flow and two-dimensional overland flow. Two-dimensional models are capable of routing flow over unconfined floodplains where floodwaters are not constrained within a defined channel. Two-dimensional models and coupled one- and two-dimensional models have the capability to route both channel flow (one-dimensional) and overland flow on flat terrain (two-dimensional). Predefinition of the flow routes, a prerequisite for the one-dimensional models is not a requirement for 2D. It may be more accurate as velocity variation on floodplains is taken into account.

Geographic regions with flat to mild slopes, areas of depressed terrain, poorly defined flow paths, alluvial fans, and fluvial areas typically exhibit unconfined floodplains where floodwaters are not constrained within a well-defined channel and generally flow in multiple directions, often with frequently diverging and converging flows. Unconfined floodplains are highly unpredictable and may exhibit both deep and shallow flooding with significant lateral differences in water surface elevations. In flat areas, the results of a dam break are likely to be highly influenced by the location of the breach because the flat terrain has the potential to allow dam break floodwaters to flow in many directions without being confined to a river channel. These are modelled best using two-dimensional models. An example of a two-dimensional model in HEC-RAS is shown in Figure 4-12.

4.9 Geographical Data Requirements for Modelling

The starting point of dam breach analysis is the exact geographical location of the dam in terms of its latitude and longitude. For two-dimensional dam breach analysis, the spatial dataset on terrain elevation is necessary. It is the elevations of each cell that guides the flow and depth of inundation. Spatial data about land use and land cover is required to have representative values of roughness related to the movement of water in the floodplain. In order to assess population at risk due to a dam break flood, the spatial dataset on population is required.

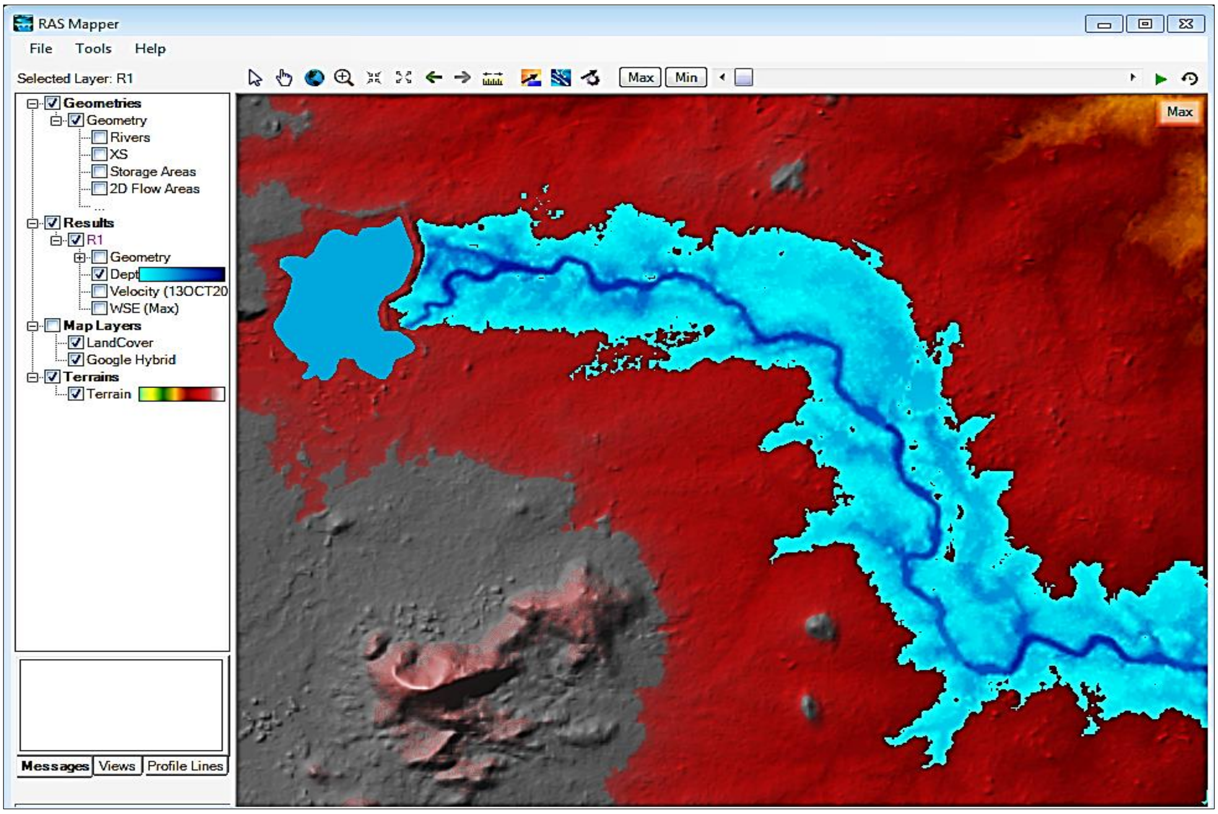


Figure 4-12: Two-dimensional dam break modelling results in HEC-RAS

4.9.1 Terrain Data

Terrain data forms the backbone of two-dimensional dam breach analysis. It is also known as Digital Elevation Model (DEM), which is a digital representation of three-dimensional information (x,y,z) of topography. It is available in raster data format, where every pixel denotes the elevation value. The common sources from which DEM are generated include:

- spot heights obtained through field survey
- spot heights obtained from maps
- contours obtained from topographical maps
- stereo photographs from air survey or stereo imagery obtained from remote sensing satellites
- Radio Detection and Ranging (Radar) data from air survey or satellite, and
- Light Detection and Ranging (Lidar) data obtained through ground-based or aeroplane/drone based survey.

The resolution of the DEM plays a crucial role in modelling the flow of flood waters. While a large river in a sparsely populated wide floodplain without much complexity in terms of topography and cross drainage structures may be adequately modelled with a coarser resolution DEM, the water levels and time of arrivals for a river with many protection embankments along the river banks and bridges across the river modelled with the same coarse DEM, may be misleading. For the Tier 2 and Tier 3 analysis, use of high-resolution topographic data is required. DEM of an area as depicted with a 30 m resolution is shown in Figure 4-13. The same area in DEM of 5 m resolution appears in Figure 4-14. The Lidar DEM of the area with a resolution of 1 m is presented in Figure 4-15. The difference in the representation of topography due to variation in DEM resolution is clearly displayed in these images.

Figure 4-13: An area as portrayed in DEM with 30 m resolution (adopted from Miller and Hess, 2016)

At the same time, use of very high-resolution data (e.g., Lidar data) for flood modelling of a large area is not warranted because it will not only prove costly but also pose difficulties for analysis due to the limitations of computer hardware to handle data of such enormous size. Of particular importance is the use of bathymetric information of the river (obtained through a hydrographic survey, or ground-based survey during the dry season) and the information about the embankments/bridges and culverts. Fortunately, HEC-RAS allows the use of high-resolution DEM at some locations (e.g., riverbeds and areas near important towns/cities) with coarser resolutions being used elsewhere. Some guidance about the tentative requirement of resolution for different tiers of preparation of emergency action plan has been provided in the first chapter.

Figure 4-14: The same area as portrayed in DEM with 5 m resolution (adopted from Miller and Hess, 2016)

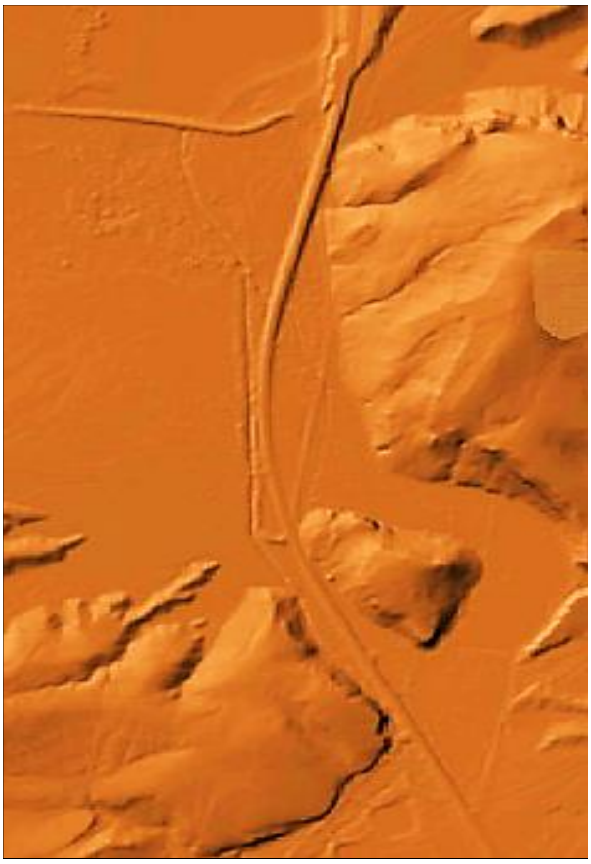


Figure 4-15: The same area as portrayed in Lidar DEM with 1 m resolution (adopted from Miller and Hess, 2016)

As on date, DEM for the Indian region is available for free download at resolutions of 30 m from the websites of the following satellite missions:

- Shuttle Radar Topography Mission (SRTM) DEM from National Aeronautics and Space Administration of the USA (NASA)
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM from NASA
- Carto-DEM from Indian Space Research Organisation (ISRO) /National Remote Sensing Centre (NRSC)
- Advanced Land Observing Satellite (ALOS) DEM from Japan Aerospace Exploration Agency (JAXA).

The vertical accuracies associated with these data are less than ±16 m for SRTM; ±20 m for ASTER; ±3.4 m near the sea and ±4.72 m near the hills for Carto-DEM version 2; and ±5 meters for ALOS. However, the absolute errors in topography do not lead to inaccuracies of the same order in the dam breach flooding analysis, because the relative elevation differences between the different topographic features are much smaller. So, the slopes that rule the flow are more accurately represented.

4.9.2 Land Use / Land Cover Data

There are multiple uses of land use/land cover data in the mapping of flood risks. The first use is in the formulation of appropriate roughness factors for the different categories of land use/land cover in the floodplain, as they pose different resistances to the flow, affecting travel time as well as the elevation of water surface. Land use/land cover information is also required to estimate the economic losses due to inundation under different conditions of breach/emergency (overtopping failure of the dam/piping failure of the dam/large controlled release/flood with 100-year return period/others) for each land-use category (e.g., agriculture, industry etc.). The Globcover raster land use/land cover data having a resolution of 300 m set may be downloaded from the website of the European Space Agency free of cost. This has been used in DRIP for the creation of inundation maps suitable for preparation of EAPs of Tier 1 level.

Land use/land cover of finer spatial resolution will be required for preparation of evacuation plans, noting down the patches that would become isolated due to inundation / the high-rise buildings, which may be used as a shelter to save persons residing in single-storied buildings.

Recent road/railway maps are also required to figure out whether the approach roads connecting habitations are inundated due to a flood. In such a case, alternative roads passing through higher reaches should be planned and constructed. The vector maps showing road/railway lines may be downloaded from the website of the Open Street Maps. The distance to the nearest approach road may be one of the critical factors in deciding upon the adequacy of the time of warning to be issued in case of any flood emergency.

4.9.3 Manning's n value for different Land Cover Classes

Choice of Manning's n for different land cover classes assumes importance as it influences flow velocities and consequently, flow depths. The more irregular the surface, the greater will be the roughness. Choice of roughness will also depend on the data scale/ spatial resolution of raster data. For use with two-dimensional dam breach analysis in HEC-RAS modelling software, an indicative range of values is presented in Table 4-2 (adopted from NRCS, 2016).

It is recommended to have site visits to view and assess the reach below a dam, especially in the context of analysis of low flows. Rather than using these values blindly, it is recommended that the model results be checked for reasonableness of the assumptions regarding the n values. In case the model predicts excessive high velocities or high Froude numbers (greater than 1.5 – 2), all the model parameters including the Manning's n should be checked again. A sensitivity analysis of the n values may also be carried out. The Manning's n values used with Globcover dataset for dam breach analysis in DRIP have been presented in Table 4-3 for guidance.

4.9.4 Population Data

Data on the spatial distribution of population plays a crucial role in assessing the hazard due to the breaching of a dam/high release from a dam. This may be the starting point of the hazard categorisation of dams, as it is not always necessary that breaching of a small dam will lead to potential loss of a smaller number of lives and vice versa, arising out of the difference in population density. It is also required for preparation of evacuation plan under EAP. In India, websites of the Census Department provide information about population and its breakup (male, female, persons and children in different age groups, the status of literacy etc.) at District, Taluka (sub-district) and village level.

Once the habitations that get inundated under a dam breach condition are identified, population information may be collected through field survey also.

Under DRIP, raster dataset showing Gridded Population of the World (GPW) with a spatial resolution of 1 km has been used for the preparation of Tier 1 level estimation of population at risk under the different categories of emergency considered. The data can be freely downloaded from the website of Socioeconomic Data and Application Centre (SEDAC) of NASA.

Table 4-2: Manning's n values for various land covers to be used for dam break analysis (adopted from NRCS, 2016)

Normal Manning's n Value	Allowable Range of n values	Land Cover Definition
0.040	0.025-0.05	Open Water - All areas of open water, generally with less than 25% cover or vegetation or soil
0.040	0.03-0.05	Developed, Open Space - Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
0.100	0.08-0.12	Developed, Low Intensity -Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.
0.080	0.06-0.14	Developed, Medium Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single- family housing units.
0.150	0.12-0.20	Developed, High Intensity - Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover.
0.025	0.023-0.030	Barren Land (Rock/Sand/Clay) - Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
0.160	0.10-0.16	Deciduous Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
0.160	0.10-0.16	Evergreen Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
0.160	0.10-0.16	Mixed Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover.
0.100	0.07-0.16	Shrub/Scrub - Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
0.035	0.025-0.050	Grassland/Herbaceous - Areas dominated by herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
0.030	0.025-0.050	Pasture/Hay - Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.
0.035	0.025-0.050	Cultivated Crops - Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled.
0.120	0.045-0.15	Woody Wetlands - Areas Where forest or shrub land vegetation accounts for greater than 20 percent of area. Substrate is periodically saturated with or covered with water.
0.070	0.05-0.085	Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Table 4-3: Manning’s n values used with Globcover land use/ land cover data in DRIP

Value	Glob cover global legend	Colour Code	Manning's n
11	Post-flooding or irrigated croplands	🟦	0.034
14	Rainfed croplands	🟨	0.06
20	Mosaic Cropland (50-70%) / Vegetation (grassland, shrubland, forest) (20-50%)	🟩	0.034
30	Mosaic Vegetation (grassland, shrubland, forest) (50-70%) / Croplands (20-50%)	🟨	0.034
40	Closed to Open (>15%) Broadleaved evergreen and/or semi-deciduous forest (>5m)	🟩	0.1
50	Closed (>40%) broadleaved deciduous forest (>5m)	🟩	0.1
60	Open (15-40%) broadleaved deciduous forest (>5m)	🟩	0.05
70	Closed(>40%) needle leaved evergreen forest (>5m)	🟩	0.11
90	Closed (>40%) needle leaved deciduous or evergreen forest (>5m)	🟩	0.05
100	Closed to open (>15%) mixed broadleaved & needle leaved forest (5m)	🟧	0.11
110	Mosaic Forest/Shrubland (50-70%) / Grassland (20-50%).	🟩	0.035
120	Mosaic Grassland (50-70%) / Forest / Shrubland (20-50%).	🟩	0.035
130	Closed to open (>15%) shrubland (<5m)	🟧	0.07
140	Closed to open (15%) grassland	🟫	0.034
150	Sparse (>15%)Vegetation (woody vegetation, shrubs, grassland)	🟧	0.09
160	Closed (>40%) broadleaved forest regularly flooded-fresh water	🟨	0.04
170	Closed (>40%) Broadleaved semi-deciduous and/or evergreen forest regularly flooded-Saline water	🟦	0.1
180	Closed to open (>15%) vegetation (grassland, shrubland, woody vegetation) on regular flooded or waterlogged soil-Fresh brackish or saline water	🟩	0.02
190	Artificial surface and associated areas (urban areas >50%)	🟥	0.4
200	Bare areas	⬜	0.035
210	Water Bodies	🟦	0.04
220	Permanent snow and ice	⬜	0.04

Chapter 5. MAPPING FLOOD HAZARD

5.1 Mapping

A map is a graphic depiction of all or part of the earth surface showing the location and distribution of various natural or cultural phenomena, in which the real-world features are replaced by symbols in their correct spatial location on a flat surface at a reduced scale. Unlike photographs that show all the objects which are physically present, a map shows only the details that are chosen to be represented on the particular map. The objects shown on a map may have physical existence (like habitations/ roads/ houses/ hospitals), or they may be the results of some analysis only (like flood hazard zones), without any demarcation present on the ground.

A map uses different colours, symbols, and labels to represent features. Map-making/ cartography has been an integral part of the human history for a long time, probably dating back to a few thousand years. Map making or cartography combines the use of science, aesthetics and technical ability to create a balanced and readable representation that is capable of communicating information effectively and efficiently.

The process of mapping comprises the steps of planning (including fixation of project specification), data acquisition (and data analysis to generate the results to be mapped, as in the case of flood hazard maps), cartographic production (including cartographic design, drafting and proofreading, printing) and product delivery (including storage and dissemination). Only a judicious blending and proper coordination of the scientific and artistic skills that go into its production can produce a good map. One of the basic problems in cartography is to transfer the shape of the earth on a plane surface.

5.2 Map Projection

The earth is an oblate spheroid, flattened slightly at the poles and bulged somewhat at the equator. The complex graphical, geometrical and mathematical methods of transforming the shape of the earth on a plane surface are collectively known as a map projection. An ideal map projection is one, which represents the meridians and the parallels in the same way as a globe (Mishra and Ramesh, 2002).

The key properties portrayed by a globe are conformality or orthomorphism (maintaining true shape), equivalence (maintaining proportional sizes), equidistance (maintaining correct distances between points), azimuthality (maintaining true representation of directions), and simplicity (maintaining an arrangement of longitudes and latitudes that it is easy to locate a point). As such, it is not possible to maintain all the five properties required to make a perfect map. It is only possible to maintain one or more of the properties, which leads to the choice of a projection system for a particular map. Numerous projection schemes have been developed, out of which the two systems with wide use in India are being discussed.

5.2.1 Polyconic Projection

Survey of India, the authority for producing and distributing maps in the country since 1767, was using Polyconic projection for its topographic maps. The maps were available in scales 1: 1 000 000 (million sheets), 1: 250 000 (degree sheets) and 1: 50 000 and 1: 25 000 (toposheets). The projection is neither conformal nor equivalent. For preparing topographical sheets, separate central meridian was used for each strip.

In polyconic projection, the central meridian is a straight line and it intersects the equator and all parallels at right angles. Parallels are parts of a circle drawn with different centres. The parallels are equally spaced along the central meridian, away from the central meridian distances between parallels increasing rapidly. Each parallel is projected as a standard parallel, developed from its own cone (Figure 5-1). The scale is correct along the central meridian and along every parallel. The datum used is Everest (India and Nepal).

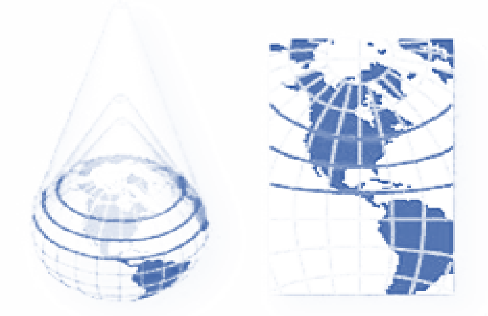


Figure 5-1: Polyconic map projection

5.2.2 Universal Transverse Mercator (UTM) Projection

Since the implementation of the National Map Policy in 2005, Survey of India has switched to Universal Transverse Mercator projection (Figure 5-2) system with WGS84 as a datum. The UTM projection is conformal; shapes and angles within any small area are essentially true. All distances, directions, shapes, and areas are reasonably accurate close to the central meridian. Multiple cylinders touch the globe at 6° interval, resulting in 60 projection zones each 6° longitude wide. In order to avoid extreme distortions in polar areas, projection zones are limited between 84° N and 80° S.

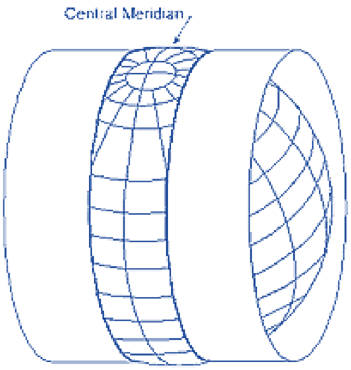


Figure 5-2: UTM map projection

The UTM coordinates are expressed as distance in meters to the east (easting) and distance in meters to the north (northing). Easting is referred to central meridian, which is assigned a value of 500 000 – eliminating the use of negative coordinates. For the northern hemisphere, equator has a northing value of 0 m N. For southern hemisphere, equator has a northing value of 10000000 m S. This offers the advantage of measurement of distances and areas in common metric units.

5.2.3 The WGS84 Datum

Choosing correct datum is important, as the accuracy of the estimated elevations are directly dependant on it. A datum is an information that is required to fix a coordinate system to the earth. Without a datum, coordinates have no meaning. A geodetic datum describes the relationship of coordinate systems for an ellipsoidal model of the earth with the real earth. WGS84 is an earth-centred terrestrial reference system and geodetic datum. It is based on a consistent set of constants and model parameters, which describe the size, shape, and gravity and geomagnetic fields of the earth (Figure 5-3).

It comprises a reference ellipsoid (a smooth three-dimensional surface generated by rotating an ellipse), a standard coordinate system, altitude data and a geoid (an equipotential surface, i.e., a surface on which the grav-

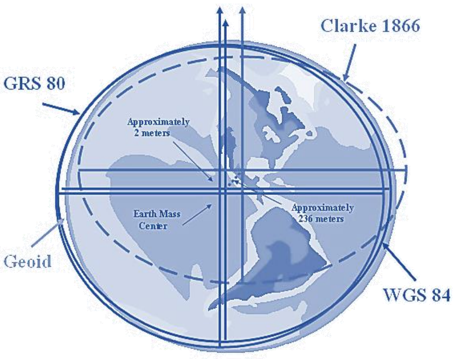


Figure 5-3: Datum WGS 84

ity potential is constant everywhere, a surface to which the direction of gravity is perpendicular everywhere). It is defined precisely using the GPS satellites. The error of WGS84 is considered to be much less, compared to any other datum. In addition, these values are universal, leaving no room for confusion.

5.2.4 Coordinate System Transformation

Coordinate system transformation is required when existing data are in different coordinate systems or projections. It allows users to manipulate the coordinate system using mathematical models, adjustments, transformations, and conversions (inbuilt with GIS). It is important to include the map projection and coordinate system in metadata documents. Coordinate system transformation is reversible and does not destroy or damage data.

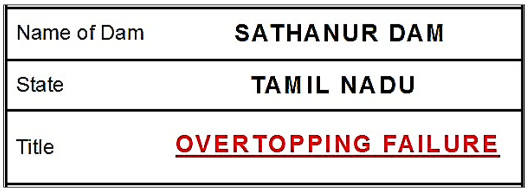
For carrying out the analysis with multiple layers of maps, it is necessary to have all of them on the same projection system. For DRIP, UTM coordinate system with datum WGS84 has been used. This allows measurement of distances and areas in kilometres and square kilometres, respectively.

5.3 Map Elements

In all maps, certain common features called map elements are present. The elements used in any particular map and their location and style vary with the purpose, targeted viewer, and scale. Not all map elements are necessarily present in each map. The most commonly used map elements are:

5.3.1 Title / subtitle

The title is the largest and most noticeable text on a map (Figure 5-4). It should reflect the purpose of the map. It should include the name of the area and the main subject of the map in most precise manner.

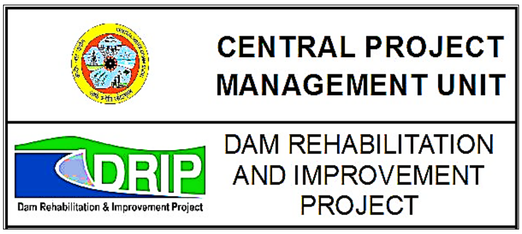


Name of Dam	**SATHANUR DAM**
State	**TAMIL NADU**
Title	**OVERTOPPING FAILURE**

Figure 5-4: Map title

5.3.2 Author / source(s)

The author information includes the names of organization/ person involved in the process of preparation of the map (Figure 5-5). It may also include information on source of the data if it is different from the author himself/organisation.



CENTRAL PROJECT MANAGEMENT UNIT

DAM REHABILITATION AND IMPROVEMENT PROJECT

Figure 5-5: Author/ source(s)

5.3.3 Index

A map index helps to show the position of the current map within a map series/ administrative zone covered under the current context (Figure 5-6). Since the potentially inundated area for many of the DRIP dams is too large to be covered in a single map with suitable scale, index showing the coverage of any particular map within the inundation zone has been included in every map.

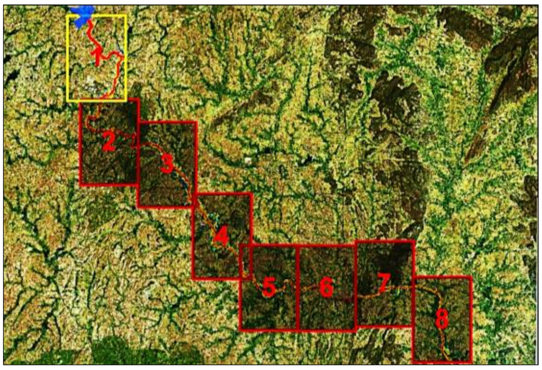


Figure 5-6: Map index

5.3.4 Legend/symbology

Legend or list of symbols helps to explain the symbols used on the map. They are one of the most important map elements to consider during map making. It should be clear, legible, and easily comprehensible. The symbol may be a dot, a line, an area with color code, shape, or an icon that looks similar to what it represents (Figure 5-7).

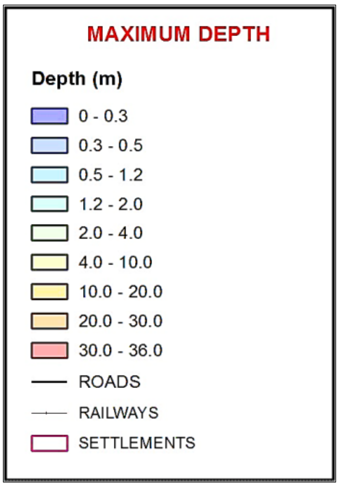


Figure 5-7: Map legend

The symbols should preferably follow that of the standard maps. In addition, the symbology should be chosen in a way that features with greater importance draw greater attention naturally, even before it is decoded with the help of the legend. The legend is usually a small box in a corner of the map or on the side. It includes the symbols and their meaning. It is also referred to as the map key. It should be checked to ensure that all the features shown on the map by symbols are contained in the legend.

5.3.5 Date of preparation/survey

The date of map preparation or the date of survey/data collection should clearly be mentioned on the map (Figure 5-8). In connection with flood hazard mapping, it will help to indicate the relevance/validity/ correctness of the map with respect to the developments that have taken place in the intervening period.

Date : December 2017

Figure 5-8: Date of preparation

5.3.6 Orientation /north arrow

Even though maps are generally drawn with north towards top and south towards the bottom, it is required to provide the north arrow on the map (Figure 5-9) to avoid any confusion. North arrows should point towards the geographic north cardinal direction (and not towards the magnetic north direction, which is always changing).

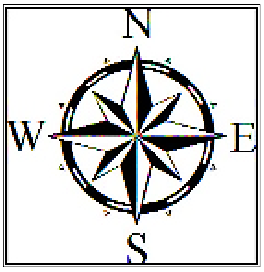


Figure 5-9: North arrow

5.3.7 Grid/coordinates

The grid is a series of horizontal and vertical lines running across the map. The grid often indicates the latitude and longitude of different points on the map (Figure 5-10). They provide handy guides for horizontal and vertical measurements. It may be used to scale the coordinates of important locations.

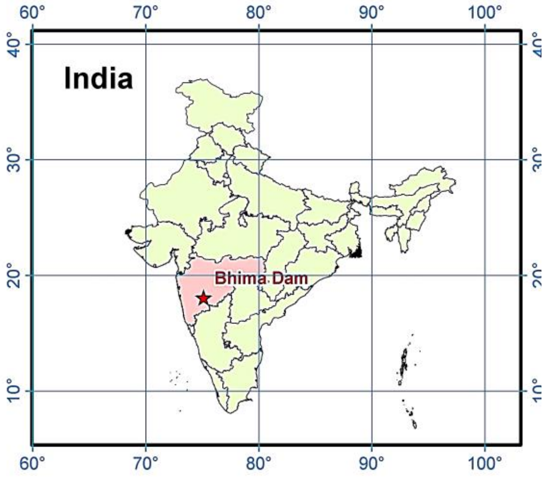


Figure 5-10: Map grid

5.3.8 Scale

Map scale is one of the essential map elements (Figure 5-11). It may be expressed either as graphic scale or verbal scale or as a representative fraction. A graphic scale or scale bar pictorially shows the distance units on a map. Verbal scale mentions the map distance to ground distance as text. A representative fraction mentions the map distance to ground distance as a ratio or fraction. It is better to have graphic scale on maps as sometimes distortions are introduced either inadvertently or otherwise (during reduction/enlargement) when a map is reproduced/copied at a scale other than that at which it was originally prepared. The verbal scale or representative fraction will add to confusion in such cases. In DRIP, the maps produced bear graphical scales.

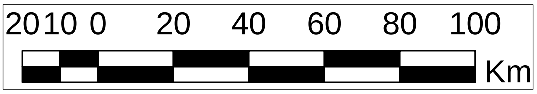


Figure 5-11: Map scale

Choice of a map scale is important to convey the right amount of information in an optimal way. For the preparation of Tier 1 inundation maps under DRIP, map scales of 1:50 000 have been used for most of the maps. This has been chosen so that the maps may be compared easily to the SOI toposheets of the area – which is the most commonly available source of mapped information. For some dams having much lesser inundation area, a scale of 1:25 000 were chosen. This also matches with the other scale at which toposheets are available. For a few dams, a scale of 1:40 000 were chosen, as the mapped village boundaries were too small to be legible at the smaller scale. At the larger scale, the region was spreading unnecessarily over many maps.

In general, it may be considered that a scale of 1:50 000 or larger is suitable for Tier 1 level of analysis. For Tier 2, the scale may be 1:10 000 or larger, depending on the area to be covered. For Tier 3, a scale of 1:4000 or larger may be more appropriate for estimation of losses at individual property level.

5.3.9 Others

Other map elements include information on map projection, graphic primitives (e.g., a neat line inside the border, and the map border) and inset maps to provide perspective to the viewer in case the map represents a small area out of a larger area that is better known. Sometimes it is also required to put the logo of the company/client on the map. The names of the places/objects may be shown with the help of labels. Sometimes, if only a single feature of a type is to be shown on a map, it may be preferred to use labels for it in place of including it as another entry in the map legends. The font types for the labels should be chosen to match the map theme. The font size should be large enough to ensure readability, yet small enough to blend with the aesthetics of the map design.

5.4 Planimetric Accuracy

For different scales of mapping, the American Society of Photogrammetry and Remote Sensing (ASPRS, 1989, 1990) standards require the level of planimetric accuracy as mentioned in Table 5-1 below.

Table 5-1: Planimetric accuracy requirement by ASPRS (adopted from ASPRS 1989, 1990)

Map Scale	Required Planimetric Accuracy (m)
1:500	0.125
1:1000	0.25
1:2000	0.5
1:4000	1
1:5000	1.25
1:10000	2.5
1:20000	5

5.5 Map Design

Map design is the most crucial and complex part of map preparation, demanding depiction of all information with clarity, simplicity, accuracy and aesthetic touch. Understanding the human perception plays an important role in map design. Map symbols may be point symbols, line symbols or area symbols, depending on the scale and the object depicted.

5.5.1 Colours

Often, colours are used to enhance map appearance. Human eyes are most sensitive to red, followed by green, yellow, blue and purple - in that order (Misra and Ramesh, 2002). Colours like yellow, blue, green, red, white and black appear as individual colour, while the others appear as mixed colour. The human eye has difficulty deciphering more than 12 colours in one view. The human eye can decipher at most 7 or 8 shades form the 256 shades of one colour. In addition, a fraction (≈ 5 to 7%) of the population is colour blind. The map may sometimes also be reproduced in black and white. So, the colour balance should be observed to see that dominant colours occupying large areas do not overpower the remainder of the map. On large areas, pastels appear better than saturated colours.

5.5.2 Legibility

The minimum line thickness that can be produced with good quality equipment is 0.1 millimetres. The minimum size of hollow symbols should not be less than 0.5 millimetres, in order to be legible. For solid symbols, it should not be less than 0.4 millimetres. The minimum separation between two symbols should not be less than 0.2 millimetres.

5.5.3 Balance

The human eye expects balance in map layout around visual centre and alignment. Visual centre lies about 5% higher than the geometric centre. The human eye interprets hill shades with the light source coming from the northwest. Good map design may require practice, patience and many revisions.

5.5.4 Principles of Cartographic Design

Cartographic design deals with the use of symbols and typography to convey information that is both easily understood and visually appealing to map user. The factors that influence cartographic design include:

- Objective: The purpose of map preparation.
- Audience: Their education, age, and background.
- Reality: Data representation limitations and aspects of data accuracy.
- The Scale of Mapping: Depends on the quality of the available data.
- Technical Limitations: The feasibility of reproduction of true colour and complex shape or line type correctly in print/ display device should be considered beforehand.
- Use: Wall mounting/report writing/presentation warrants different map scales, font sizes, symbology.

A few **basic** principles of cartographic design has been mentioned underneath:

1. Concept before compilation: Implies including only those features in the map that fit the context (out of the many available), and designing the map from the whole to the part. It also involves redesigning the map to suit different user categories or use categories.
2. Hierarchy with harmony: Involves making important things appear important and vice versa. Associated items should be treated in an associated manner, in keeping with the harmony of the whole map.
3. Simplicity from sacrifice: Comprises following simplicity by taking out all except the most im-

portant through generalization (sacrifice). The extent of generalization depends upon the scale of the map and its content.

4. Maximum information at minimum cost: Implies providing maximum functional utility that is visible at a glance.
5. Engage the emotion to engage the understanding: Involves focusing the attention of the user to pass on the message with aesthetics and emotional contents, i.e., the message of the map should be understood by the viewer even before the map keys are used for interpretation.

Together, these principles help to prepare a map that has aesthetic appeal.

5.5.5 Cartographic Generalisation

Cartographic generalisation is a part of the mapping process by which map data are abstracted and transformed into a representation at a reduced scale. The need for cartographic generalisation arises, as the data is normally available at a larger scale than the one in which it is to be presented. In addition, reduction of complexity is needed to make the map aesthetically more pleasing at the scale appropriate for the application. The benefits include reduced data storage requirement and faster data processing.

The conditions that lead to the use of cartographic generalisation include:

- Congestion: Where there are too many features in limited geographic space.
- Coalescence: Where features touch each other as separating distance is less than the resolution of the output device or the symbol size.
- Conflict: Where any spatial representation is in conflict with its background (e.g., a road bisects two portions of a park, generalisation necessitates combining the two park segments across the road).
- Complication: Where data from different sources/ at different scales/ generalized with different tolerance levels are combined to arrive at the results.
- Inconsistency: Where a set of generalisation decisions applied non-uniformly across a map lead to bias in the generalization between the mapped elements. However, it may not always be an undesirable condition as important features are sometimes shown in a way that overrides the general rule of generalisation.
- Imperceptibility: Where a feature smaller than minimum representation size of the map is to be shown on the map.

Some methods used to deal with the above problems include (Shea and McMaster, 1989):

1. Simplification (Figure 5-12): Representing original line using the most representative subset of initial coordinates (e.g., kinks on a road are removed, except the most important ones).

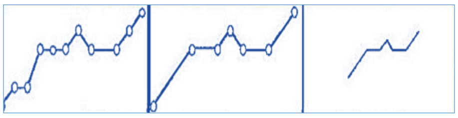


Figure 5-12: Simplification (adopted from Shea and McMaster, 1989)

2. Smoothing (Figure 5-13): Relocating or shifting coordinate pairs to even out small perturbations (e.g. removing all kinks on a road up to the chosen level of smoothing).

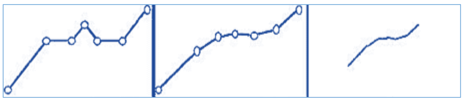


Figure 5-13: Smoothing (adopted from Shea and McMaster, 1989)

3. Aggregation (Figure 5-14): Grouping point features into higher order class (e.g., different elements of the same class clubbed together).

Figure 5-14: Aggregation (adopted from Shea and McMaster, 1989)

4. Amalgamation (Figure 5-15): Joining smaller features of the same type into a larger map element retaining the general characteristics of a region (e.g. merging small ponds or intricate boundaries of a pond into a single large one).

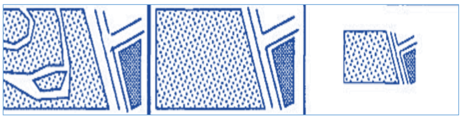


Figure 5-15: Amalgamation (adopted from Shea and McMaster, 1989)

5. Merging (Figure 5-16): Representing parallel line features using single line (e.g. representing divided highways with a line).

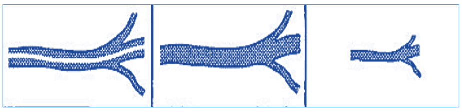


Figure 5-16: Merging (adopted from Shea and McMaster, 1989)

6. Collapsing (Figure 5-17): Decomposing features with multiple dimensions into features with lesser dimensions and less complex boundaries (e.g. airport with a dot).

Figure 5-17: Collapsing (adopted from Shea and McMaster, 1989)

7. Refinement (Figure 5-18): Discarding smaller features from among a cluster of features and depicting only selective number and pattern of the symbols, which is accomplished by leaving out the smallest or least important features.

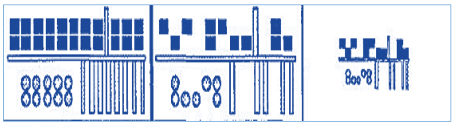


Figure 5-18: Refinement (adopted from Shea and McMaster, 1989)

8. Typification (Figure 5-19): it is a kind of refinement that using representative pattern of features or symbols.

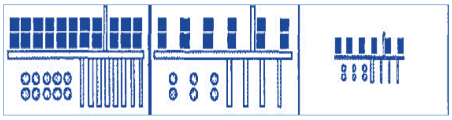


Figure 5-19: Typification (adopted from Shea and McMaster, 1989)

9. Exaggeration (Figure 5-20): Amplifying the shape or size of features for better readability (e.g. widening of openings to show navigability).

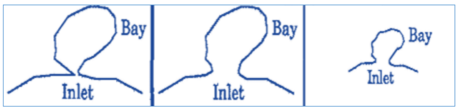


Figure 5-20: Exaggeration (adopted from Shea and McMaster, 1989)

10. Enhancement (Figure 5-21): Dealing with exaggeration of shapes and sizes of symbols to meet specific map requirements (e.g. a bridge shown at a larger scale than that dictated by the scale of mapping).

Figure 5-21: Enhancement (adopted from Shea and McMaster, 1989)

11. Displacement (Figure 5-22): Shifting position of features to improve clarity when two or more features are in

conflict (e.g., road by a canal very close to each other shown separately).

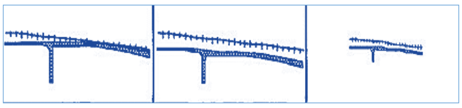


Figure 5-22: Displacement (adopted from Shea and McMaster, 1989)

12. Classification (Figure 5-23): Grouping objects into categories of features sharing identical or similar characteristics into fewer categories.

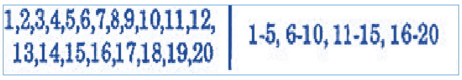


Figure 5-23: Classification (adopted from Shea and McMaster, 1989)

To the advantage of the users, the GIS software used for preparation of maps applies some of the cartographic generalisation techniques by default, particularly for vector maps, while the exercise of discretion is required to apply the other ones as per the need. The consideration of the cartographic generalisation is important for planning the mapping process to ensure compatibility of the data collection and analysis with the final map scale, so that resources are used optimally, avoiding chances of misrepresentation.

5.6 Planning the Mapping Process

Planning of the mapping process includes steps from data acquisition to cartographic production. The final scale of the map production has to be decided upon. The choice of data to be acquired depends on the final scale of output. Data acquired with much detail (suitable for large-scale mapping) will require extra time and cost for processing and finally may not be properly displayed in the output, requiring generalisation. Data acquired with limited detail (suitable for small-scale mapping) may bring difficulties at a later stage in case of some new developments cropping up to dictate mapping at a larger scale than that initially conceived. This may cause not only financial consequences but also project delay. It may be prudent to select the level of data acquisition (data selection in case of existing data) just enough to meet the needs of mapping at a scale one-step larger than that in the initial plan.

5.7 Geographical Information System (GIS)

In the earlier days, the maps were prepared on papers, so it was difficult to update them. In addition, the map prepared for showing a particular extent of the area was seldom found suitable for extracting information on smaller or larger areas. With the advent of Geographical Information System (GIS) since the latter part of the last century, preparation of soft copy of maps with possibilities of dynamic change of display scale with easy update and overlay came up.

Geographical information system (GIS) is an information system that is used to input, store, update, retrieve, manipulate, analyse and output geographically referenced data or geospatial data, in order to support decision-making for planning and management of land use, natural resources, environment, transportation, urban facilities and other administrative needs. It comprises an organized collection of computer hardware, software, geographic data, and personnel, enabling the performance of the tasks mentioned.

GIS, in one sense, may be thought of as a modern extension of traditional cartography with one fundamental similarity and two essential differences. The similarity lies in the fact that both a cartographic document and a GIS contain examples of a base map to which additional data are added. The differences are that there is no limit to the amount of additional data that may be added to a GIS map and secondly the GIS uses analysis and statistics to present data in support of particular arguments that a cartographic map cannot do.

Nowadays GIS is being used for supporting a multitude of planning needs that have a geospatial connection. It includes making spatial queries about the attribute value at any particular location, finding locations with a particular range of attribute values, analysing change detection, analysing spatial patterns and checking regularity of arrangement. It also includes finding an association between two entities/ phenomena, modelling with multiple parameters, finding the optimum path, locating suitable sites etc. In short, it has become an integral and indispensable part of planning and decision-making.

5.8 A Few GIS Software

In recent times, many GIS software are available including quite a few of open source type that are available free. A few open source Desktop GIS include GRASS GIS, gvSIG, ILWIS, JUMP GIS, MapWindow GIS, QGIS, SAGA GIS, uDig, GeoDa, OpenJump, Diva GIS, Capaware, FalconView, OrbisGIS, Kalypso, TerraView, Whitebox GAT. Other than desktop GIS, the following web-based map servers are also free: GeoServer, MapGuide Open Source, Mapnik MapServer. PostGIS, SpatiaLite, and TerraLib are some of the free spatial database management systems.

A few popular commercial or proprietary GIS software include ArcGIS, GeoMedia, MapInfo, and Smallworld. Besides, AutoCAD (with Map 3D, Topobase and MapGuide), MicroStation (including Bentley Map and Bentley Map View), eSpatial, Maptitude, CARTO, Simple GIS Client, MapItFast, MapViewer, Map Business Online, Ubiquiti, SuperGIS Desktop, 3-GIS Network Solutions, Agile GIS, AziMap and CartoVista are some other software in use. The list continues. Out of all these, ArcGIS by ESRI has been used for mapping flood hazard at the CPMU under the DRIP project. However, it should be clear that CPMU does not advocate or endorse the use of any particular commercial/ free software, as the capability of performing the task of mapping efficiently is common to many, if not all of them.

5.9 Data Types in GIS

The real world is represented in the GIS database as a stack of different layers – each containing information about a particular property of the object. The files are of two types: raster and vector. All the files have some spatial information (related to the place on earth where the data belongs to) and some attribute information (related to properties of the object like its name, elevation, land use etc.). A brief description of the data types is provided underneath.

5.9.1 Raster Data

Raster data represents phenomena with the help of a continuous set of variables, each one defined at each possible position. The geographic space is represented by a matrix of equal-sized square cells. Each cell has a numeric value that represents a geographic attribute (like elevation) for that unit of space. The number of rows and columns, the cell size and the coordinate system defines the grid. The grid values may be either of the integer or the floating point (decimal) type. Raster data representing a point, line, and area feature have been shown in Figure 5-24, Figure 5-25 and Figure 5-26, respectively. In case of flood hazard mapping, the DEM and land use are input raster data, while water surface elevation, depth of water, the velocity of water and flood arrival

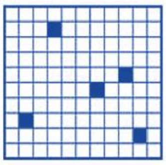


Figure 5-24: Raster data representing point features (location of flood shelters)

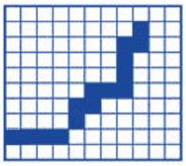


Figure 5-25: Raster data representing line features (river)

time are output raster data.

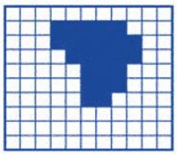


Figure 5-26: Raster data representing area features (reservoir)

5.9.2 Vector Data

Vector data represents the real world as a finite number of variables, each defined at a position as a discrete entity in space. They have distinct location/ boundary. The geographic features in the real world are represented as any of the three following entities:

i. Points or dots (nodes): representing trees, towers, airports, cities.

ii. Lines (arcs): representing streams, streets, sewers, railway lines.

iii. Areas (polygons): representing land parcels, cities, counties, forest, soil type.

Vector data representing point, line and area feature (polygon) are shown in Figure 5-27, Figure 5-28 and Figure 5-29, respectively. The boundaries of human habitation used in flood hazard mapping are vector layers.

Figure 5-27: Vector data representing point features (location of flood shelters)

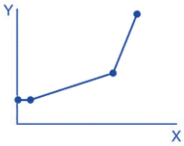


Figure 5-28: Vector data representing line features (river)

Figure 5-29: Vector data representing area features (reservoir)

5.10 Imperfections in GIS

Maps generated using GIS generally have appealing appearances, which may lead to erroneous assumptions about their inherent accuracy. It has to be appreciated that the accuracy of these maps is limited by the accuracy of the input data, along with the magnification of errors imbibed during analysis and output. Imperfections arise because of the world being too complex and detailed and decisions on data categorization, zone definition being not always fully justified (like categorisations of vegetated land through boundaries demarcating open forest and dense forest). Using either raster or vector data format, it is impossible to represent world perfectly, and therefore, uncertainty is inevitable. This uncertainty degrades the quality of spatial representation.

From the real world, the propagation of error takes place through the stages of conception, measurement and representation, data conversion and analysis and finally the presentation of the result, being amplified at each stage. The process of conception may involve the spatial uncertainty (objects do not have a discrete, well-defined extent), vagueness (criteria that define an object are not explicit or rigorous), ambiguity (a substitute or indicator is used in lieu of the original parameter because the original is not available). It may also suffer from regionalization problems (spatial distributions tend to change gradually, while zones imply that there are sharp boundaries between them).

The errors associated with measurement may include physical measurement error (instruments and procedures used are not perfectly accurate), digitising error (overshoot, undershoot, duplicate arc, sliver, label error or miss) or error caused by combining data sets from different sources (with different resolution, projection, and data accuracy standards). The uncertainty in the representation may comprise uncertainty in earth model (ellipsoid models, datum, and projection types), uncertainty in the raster data model (presence of impure cells or mixels), and uncertainty in the vector data model (fitting data in zones with boundaries not respecting its natural distribution patterns).

The uncertainty in the data conversion and analysis may include data conversion error, georeferencing, and resampling error (nearest, bilinear, cubic), error due to projection and datum conversions and classification errors. Coupled with a thickness of a dot, its placement may have a positional error of 0.5 millimetres. At a scale of 1: 5 000, it implies an accuracy of 2.5 metre, which increases to 500 metres at a scale of 1: 1 million. In addition, the reliability of data decreases with its age. Further, use of data available at different scale because of non-availability of data on the proper scale introduces error.

Uncertainty being inevitable, metadata should be used to document the uncertainty. Sensitivity analysis may be carried out to find the impact of input uncertainty on output. Finally, the results of GIS analysis should be reported in honest and informative manner.

5.11 Flood Hazard

A flood hazard is an indication of the possible source of danger due to flooding. It, however, does not imply any risk unless persons or objects that are vulnerable to damage are exposed to it. Flood hazard varies with flood severity (i.e. for the same location, the greater the return period of the flood the more severe the hazard) and location within the floodplain for the same flood event. This varies with both flood behaviour (velocity and depth, the rate of rising of floodwater and the time from rainfall to flooding) and the interaction of the flood with the topography. The hazards to be mapped include themes like the flood inundation areas, water depths and velocities, and arrival times of flood waves.

As the depth of water increases, the damage increases. However, even shallow water moving at high velocity may significantly damage a structure or dislodge/damage its foundation. Flowing water may also carry debris, which, by way of colliding with existing structures or infrastructure, cause significant damage. Faster the velocity of flowing water, greater is the chance of loss of life. Persons unable to evacuate may become trapped in a home or business centre that is being destroyed by high-velocity water or rising floodwaters. Emergency responders may not be able to reach the area. Vehicles can get washed off roads and bridges. During a flood, the death of people trapped in their vehicles may be significant in number. Increased velocity leads to increased erosion, or scour (FEMA, 2012). The velocity of water flow will vary throughout the area of inundation, and damage to assets close to the dam may be very high, while damage several kilometres downstream might be negligible.

5.11.1 Hazard to People

The most important factors affecting human stability in flood waters are firstly depth and secondly velocity. Depth dictates what type of failure is to occur, either sliding (friction) or tumbling (moment) failure. High depths increase buoyancy and reduce friction under foot. Low depth-high velocity flows may cause instability but the chances of drowning are less than in the more dangerous deep-water situations. While distinct relationships exist between a subjects height and mass (H×M; m.kg) and the tolerable flow value (D×V; m^2s^{-1}), the definition of general flood flow safety guidelines according to this relation is not considered practical given the wide range of such characteristics within the population. Hazard regimes may be defined for adults (H×M > 50 m.kg) and children (H×M = 25 to 50 m.kg). Infants and very young children (H×M < 25 m.kg) or frail older persons are unlikely to be safe in any flow regimes without adult support.

For children with a height and mass product (H×M) of between 25 and 50, a low hazard exists for flow values of D×V < 0.4 m^2/s, with a maximum flow depth of 0.5 m regardless of velocity and a maximum velocity of 3.0 m/s at shallow depths. For adults (H×M > 50), a low hazard exists for flow values of D×V < 0.6 m^2/s with a maximum depth limit of 1.2 m and a maximum velocity of 3.0 m/s at shallow depths. Moderate hazard for adults exists between D×V = 0.6 to 0.8 m^2/s, with an upper working flow value of D×V < 0.8 m m^2/s recommended for trained safety workers or experienced and well-equipped persons. Significant hazard for adults exists between D×V = 0.8 to 1.2 m^2/s. The flood hazard regimes for infants, children, and adults, adopted from Cox et al. (2010) have been presented in Table 5-2 and Figure 5-30.

Loss of stability may occur with lower flows when adverse conditions are encountered including uneven, slippery conditions or obstacles in the bottom, the presence of floating debris, low temperature, poor visibility, unsteady flow and flow aeration, strong wind or poor lighting.

5.11.2 Hazard to Vehicles

The total number of registered vehicles in the country exceeds three crores, which is increasing by the day. The total length of roads in the country is more than 55 lakh kilometres, many more being under planning and construction stage. During a flood emergency arising out of fair weather failure of a dam or gate misoperation (unscheduled opening of gates to pass discharge downstream), a significant number of persons may be on a road travel. In addition, vehicles play a crucial role in an emergency evacuation. Therefore, securing the safety of vehicles during flood assumes importance.

During a flood emergency, vehicles may suffer from instability due to sliding, toppling or floating. Shand et al. (2011) propose the stability criteria for stationary vehicle categorised into three classes: small passenger cars, large passenger cars and four-wheel drive vehicles (Table 5-3 and Figure 5-31). These classes were considered to have floating limits of 0.3 m (small passenger vehicles), 0.4 m (large passenger vehicles) and 0.5 m (four-wheel drive vehicles). All stability criteria were considered to have a limiting velocity of 3.0 m/s. This is in agreement with human stability criteria to ensure that, in the event of vehicle failure, safety is not compromised once people abandon their cars.

5.11.3 Hazard to Buildings

The range of forces that might affect building stability includes hydrostatic actions, hydrodynamic actions, debris actions, wave action from wind and wakes, and erosion and scour due to flood actions. At velocities

Table 5-2: Flood hazard regimes for infants, children and adults (adopted from Cox et al., 2010)

D×V (m^2s^{-1})	Infants, small children (H.M ≤ 25) and frail/ older persons	Children (H.M = 25 to 50)	Adults (H.M > 50)
0	Safe	Safe	Safe
0 – 0.4	Extreme Hazard; Dangerous to all	Low Hazard	Low Hazard[1]
0.4 – 0.6		Significant Hazard; Dangerous to most	
0.6 – 0.8		Extreme Hazard; Dangerous to all	Moderate Hazard; Dangerous to some
0.8 – 1.2			Significant Hazard; Dangerous to most
> 1.2			Extreme Hazard; Dangerous to all

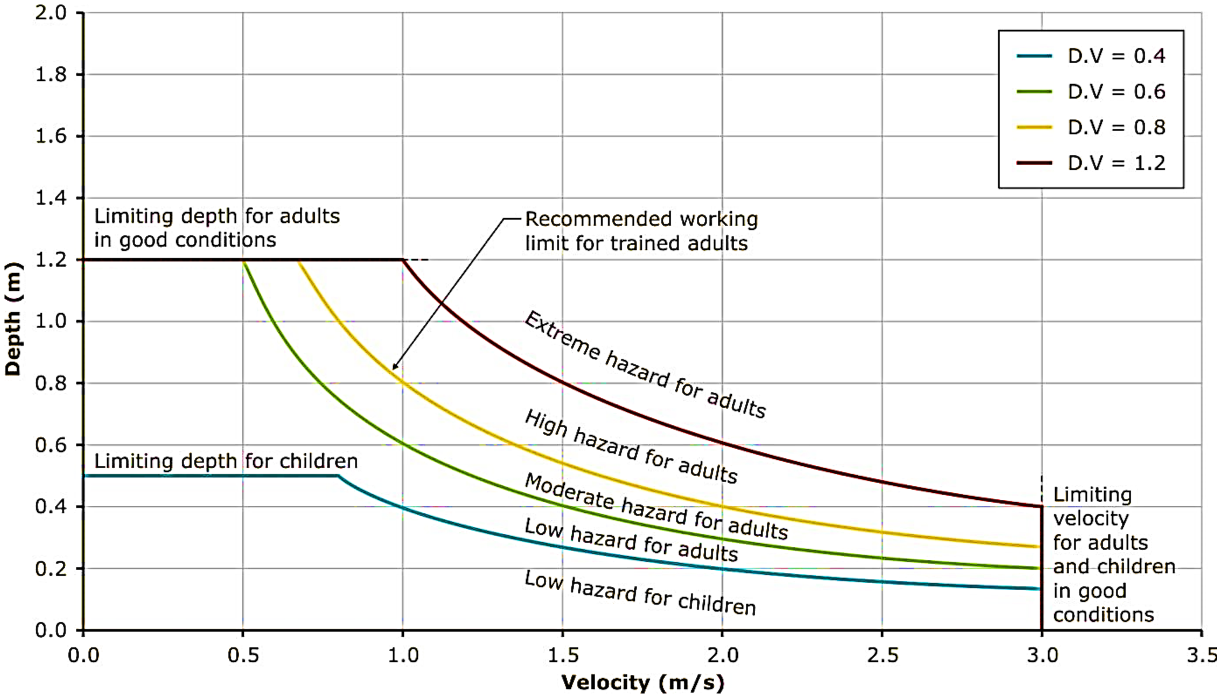


Figure 5-30: Threshold for stability of persons in flood (adopted from Cox et al., 2010)

in excess of 2 m/s, the stability of foundations and poles can get affected by scouring. As grass and earth surfaces begin to erode, scour holes may develop. At depths in excess of 2 m, lightly framed buildings may be damaged by water pressure, floatation and debris impact, even at low velocities.

The major failure mechanisms that may make a building unsafe are:

- Filling with water to a depth that is unsafe for people inside
- Structural damage leading to building collapse and injury to occupants, or even death
- The buoyant and lateral force of the water overcoming the strength of the anchors and weight of the building holding it to its foundation – making it float.

The thresholds for building stability in floods has been adopted from Smith et al. (2014) and presented in Figure 5-32.

Table 5-3: Flood hazard criteria for stationary vehicle stability (adopted from Shand et al., 2011)

Class of vehicle	Length (m)	Kerb Weight (kg)	Ground clearance (m)	Limiting still water depth at velocity = 0 m s^{-1}	Limiting high velocity flow depth at velocity = 3 m s^{-1}	Limiting velocity at low depth (m s^{-1})	Equation of stability
Small passenger	< 4.3	< 1250	< 0.12	0.3	0.1	3.0	$DV \leq 0.3$
Large passenger	> 4.3	> 1250	> 0.12	0.4	0.15	3.0	$DV \leq 0.45$
Large four-wheel drive	> 4.5	> 2000	> 0.22	0.5	0.2	3.0	$DV \leq 0.6$

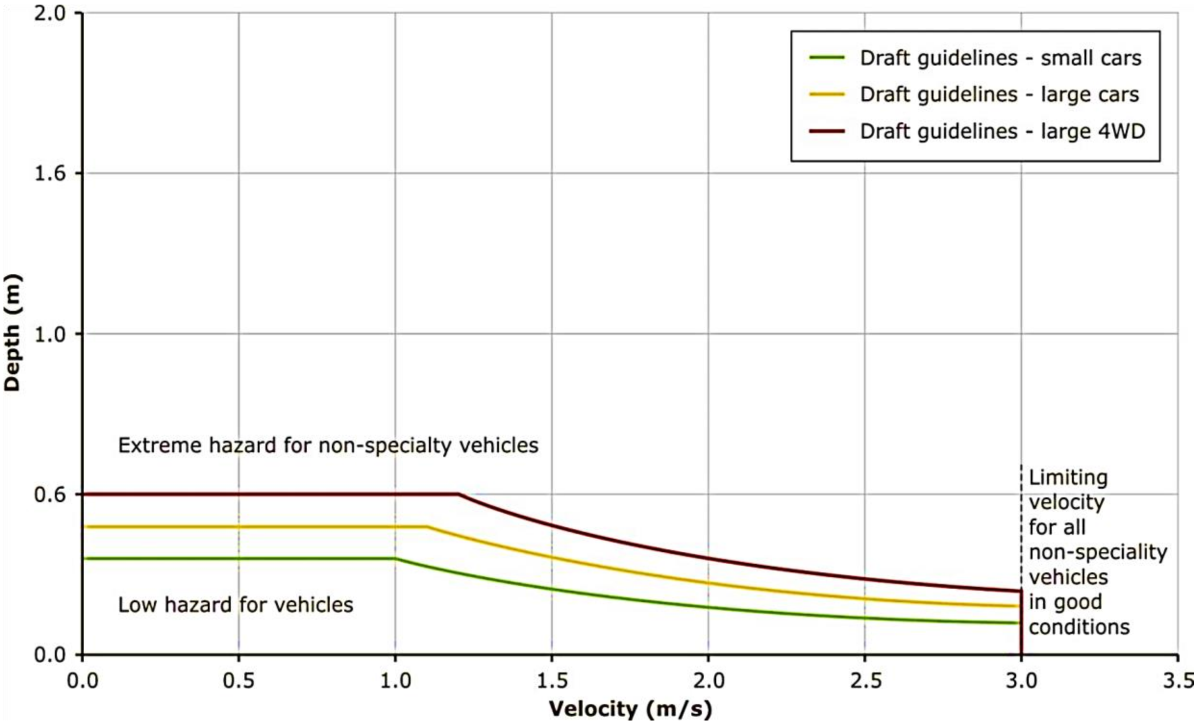


Figure 5-31: Threshold for stability of vehicles in flood (adopted from Shand et al., 2011)

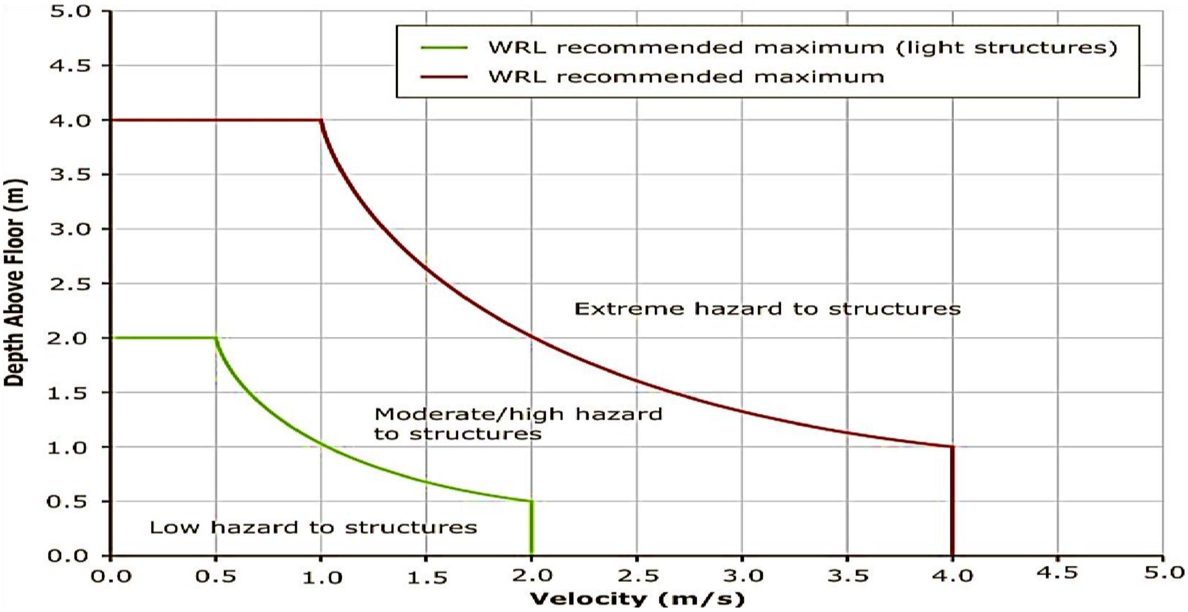


Figure 5-32: Thresholds for building stability in flood (adopted from Smith et al., 2014)

5.11.4 Combined General Flood Hazard Classification

In preliminary analyses, there is a need for a combined set of hazard vulnerability curves, which can be used as a general classification of flood hazard on a floodplain to feed into a constraints analysis. A set of curves (AEMI, 2014) based on the thresholds mentioned above has been presented in Figure 5-33. These thresholds relate to the vulnerability of the community when interacting with floodwaters. These combined curves are used to make hazard classifications that relate to specific vulnerability thresholds as

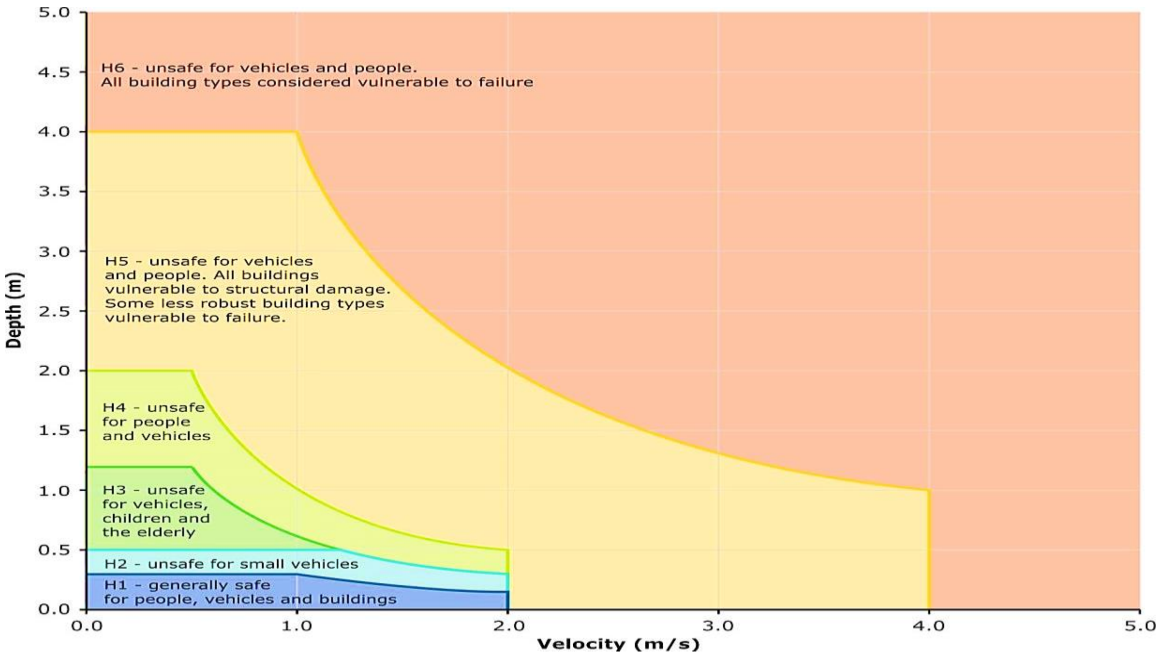


Figure 5-33: Combined flood hazard curves (adopted from AEMI, 2014)

Table 5-4: Vulnerability thresholds for combined hazard curves

Hazard Vulnerability Classification	Description
H1	Generally safe for vehicles, people and buildings.
H2	Unsafe for small vehicles.
H3	Unsafe for vehicles, children and the elderly.
H4	Unsafe for vehicles and people.
H5	Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust buildings subject to failure.
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.

described by Smith et al. (2014), and shown in Table 5-4. Table 5-5 provides the limits for the vulnerability thresholds corresponding to the classifications indicated in Table 5-4. In addition, factors like isolation during a flood, effective warning time and rate of rising of floodwater and time of the day play important roles in describing the flood hazard.

The flood depth used as the basis of hazard for people and vehicle stability is referenced to the ground level, but for building stability it is referenced to the floor level. The vulnerability of the community and its assets can be described by using thresholds related to the stability of people as they walk or drive through floodwaters, or take shelter in a building during a flood. The vulnerability to hazard will also be influenced by whether the primary consideration is strategic land-use planning aimed at ensuring that the land use is compatible with the flood risk or assessing development proposals or emergency management planning aimed at addressing residual flood risks.

It may be wondered why the estimation of crop loss due to a dam breach flood has never merited a discussion in literature under the classification of flood hazard. It is because of the fact that with the range of magnitude of water depths and velocities generated due to such an event, all the standing crops are expected to be completely washed off, irrespective of the crop type or stage of crop development. So a complete loss of all crops in all the inundated area may be assumed with fair confidence.

Table 5-5: Classification limits for vulnerability thresholds of combined hazard curves

Hazard Vulnerability Classification	Classification Limit (D and V in combination, m^2s^{-1})	Limiting Still Water Depth (D, m)	Limiting Velocity (V, $m\ s^{-1}$)
H1	$D \times V \leq 0.3$	0.3	2.0
H2	$D \times V \leq 0.6$	0.5	2.0
H3	$D \times V \leq 0.6$	1.2	2.0
H4	$D \times V \leq 1.0$	2.0	2.0
H5	$D \times V \leq 4.0$	4.0	4.0
H6	$D \times V > 4.0$	-	-

5.11.5 Use of Flood Inundation Maps

Inundation maps may have a variety of uses including preparation of EAPs, emergency response planning, hazard mitigation planning and consequence assessment. An EAP includes inundation maps to assist the dam owners and emergency management authorities in identifying critical infrastructure and sites with population-at-risk that may require protective measures and warning and evacuation planning. An emergency response plan may include warning and evacuating the population at risk. These evacuation plans should be developed before the occurrence of an incident, based on worst-case scenarios.

Hazard mitigation is the selection of proactive measures, both structural and non-structural, that will reduce economic losses and potential loss of life when implemented. This may include the provision of systems for advanced flood warning and relocating critical infrastructure and facilities out of the inundation zone. Consequence assessment includes identifying and quantifying the potential consequences of a dam failure or incident, based on the economic and social impacts of a potential disaster and the organizational and government actions needed in the aftermath of a dam breach to respond and recover. Data compiled for a consequence assessment may also be used for risk assessments.

5.11.6 Inundation Mapping

After completion of a dam breach simulation, the inundation boundary is the most important output dataset of inundation mapping. It may be generated in HEC-RAS directly, without the help of any other software. The output may also be exported for further analysis/map generation to any other GIS software. The selection of the terrain dataset with a particular resolution and accuracy limits the potential accuracy of an inundation model and consequently may limit the accuracy of the inundation delineation. Therefore, evaluating and understanding the accuracy of a selected terrain dataset should be done carefully.

5.12 Flood Hazard Mapping

Flood hazard mapping provides land-use planners, flood risk managers and emergency managers with an overview of changes in the severity of flood hazard for a range of events. Under DRIP, output grids of HEC-RAS were converted to Keyhole Markup Language, an XML based file format used to display geographic data in an Earth browser such as Google Earth, Google Maps (kml) and displayed through Google Earth as an overlay. Transparency levels were adjusted to make the settlements on Google Earth visible. Layers with boundaries of human settlements (polygons) were created as kml files using Google Earth. These kml layers were converted to vector files in GIS platform. Contours for water surface elevations, depths of water, water velocities and flood arrival times were created. These layers were also classified with suitable intervals. For mapping vulnerability, both the water depth layer and the layer portraying depth × velocity were used together.

5.13 Flood Hazard Maps

The outputs of dam breach modelling from HEC-RAS includes a host of important parameters, which contribute to the assessment of the flood hazard. These are:

- Depth of inundation
- Water surface elevation
- Velocity of water flow
- Inundation boundary
- Shear stress
- Depth × velocity
- Depth × velocity^2
- Flood arrival time
- Time of flood recession
- Duration of flooding
- Percent time inundated
- Stream power

Out of these, the inundation boundary, depth of inundation, the velocity of water flow, flood arrival time and duration of flooding are the parameters used most commonly. The map showing the depth of inundation due to overtopping failure of Sathanur Dam of Tamil Nadu for Tier 1 level of analysis has been shown in Figure 5-34.

The map indicating the velocity of water flow for the same case has been shown in Figure 5-35. The map showing time of flood arrival for the same case has been presented in Figure 5-36. The map showing vulnerability (due to the combined effect of water depth and water velocity) has been reproduced in Figure 5-37. Other than the overtopping failure due to the inflow design flood impinging the reservoir, inundation maps due to fair weather failure (piping failure) under minimum inflow conditions are also being prepared under DRIP.

The maps showing the depth of inundation, the velocity of water flow, time of flood arrival and vulnerability for the piping failure of the same dam has been presented in Figure 5-38 to Figure 5-41. In addition, inundation maps due to large controlled release (corresponding to the discharge equalling the spillway capacity) continuing for a long time are also being prepared. The maps portraying the depth of inundation, the velocity of water flow and vulnerability due to a large controlled release (passage of the design flood through the spillway gates) are shown in Figure 5-42 to Figure 5-44. These maps will form the backbone for preparation of emergency action plan in the short term and floodplain regulatory management in the long term. These maps will also help to point out important places for which Tier 2 and Tier 3 level analysis are warranted.

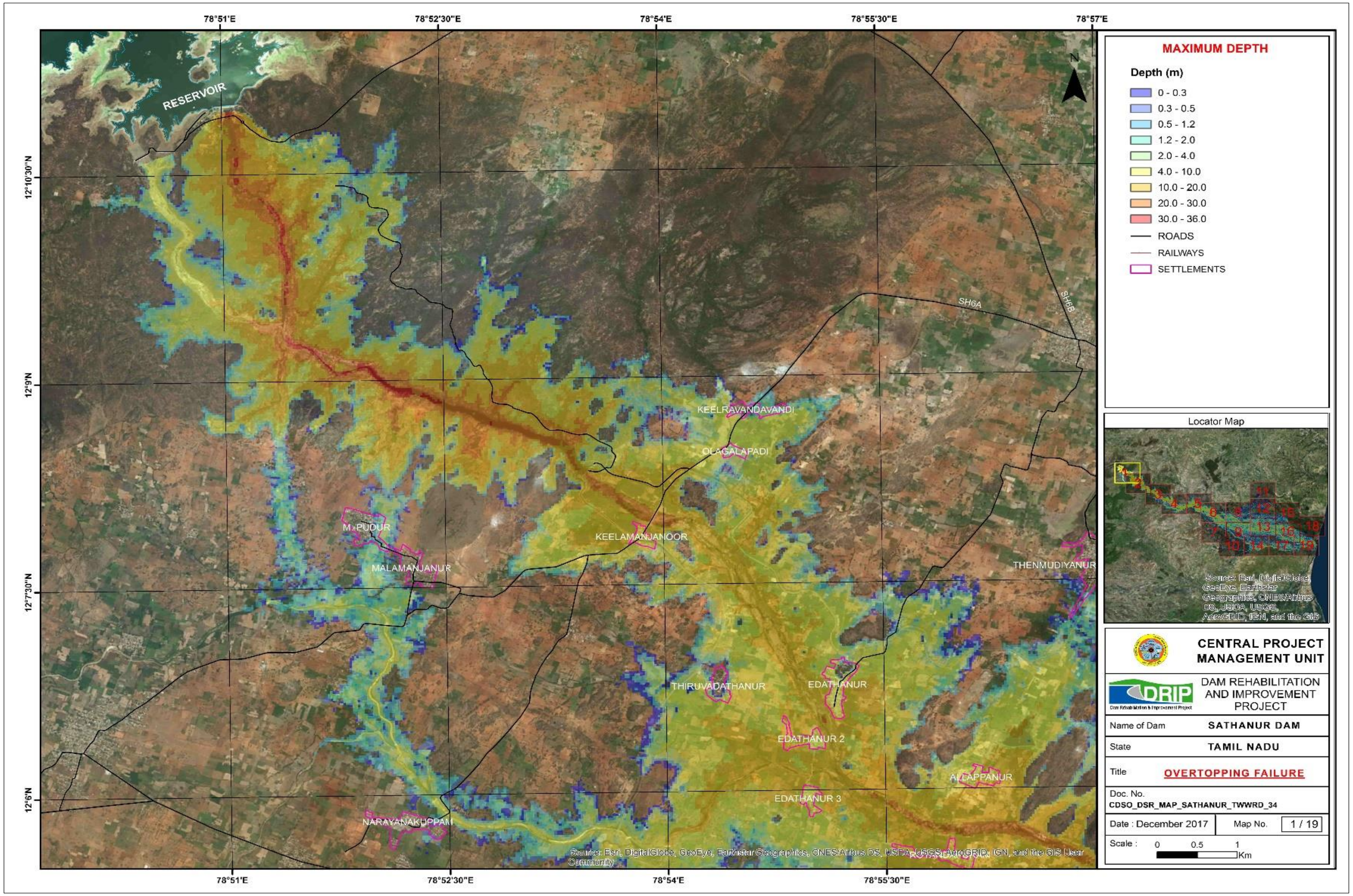


Figure 5-34: Map showing depth of inundation due to overtopping failure of Sathanur Dam of Tamil Nadu

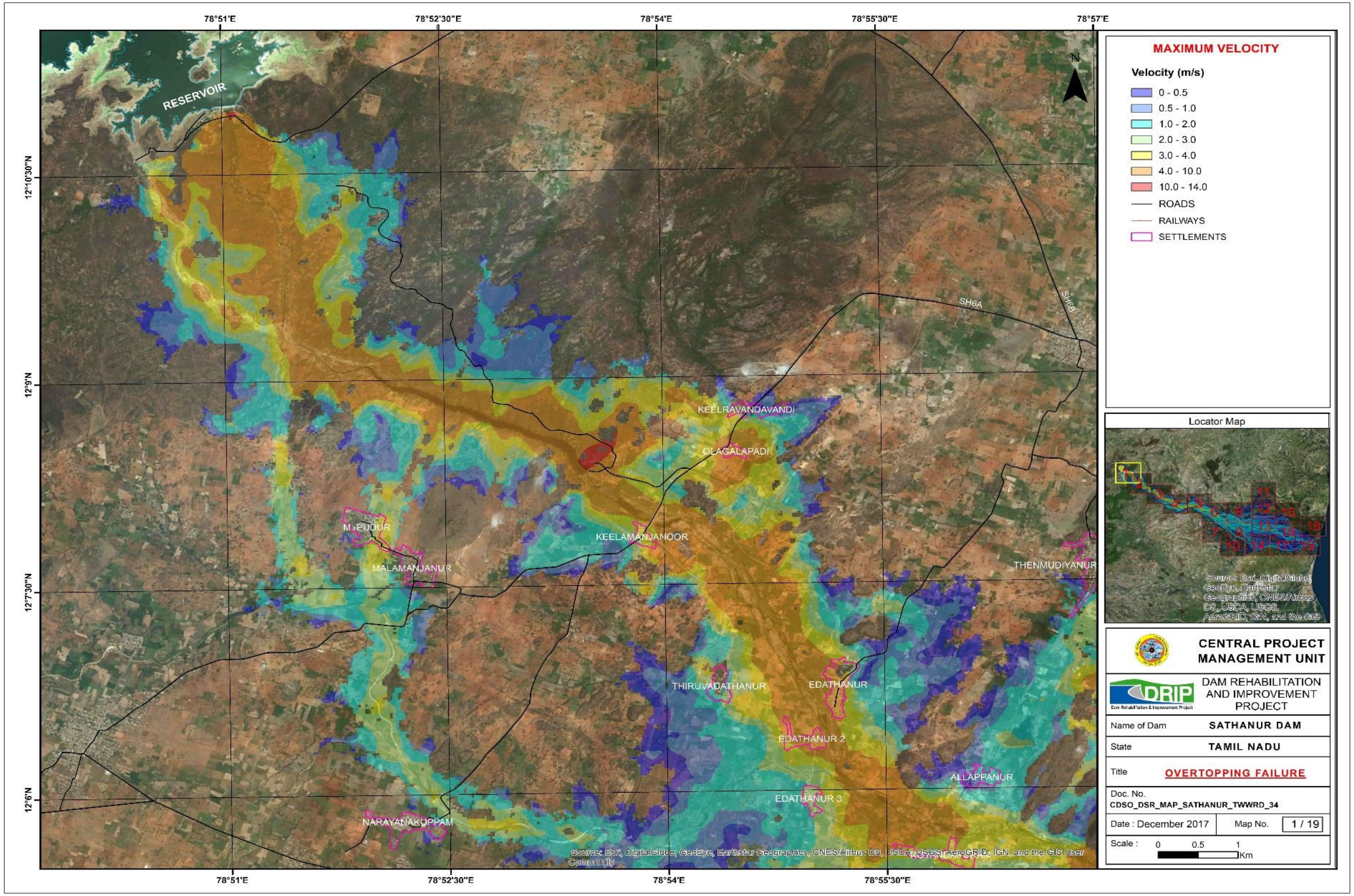


Figure 5-35: Map showing velocity of water flow due to overtopping failure of Sathanur Dam of Tamil Nadu

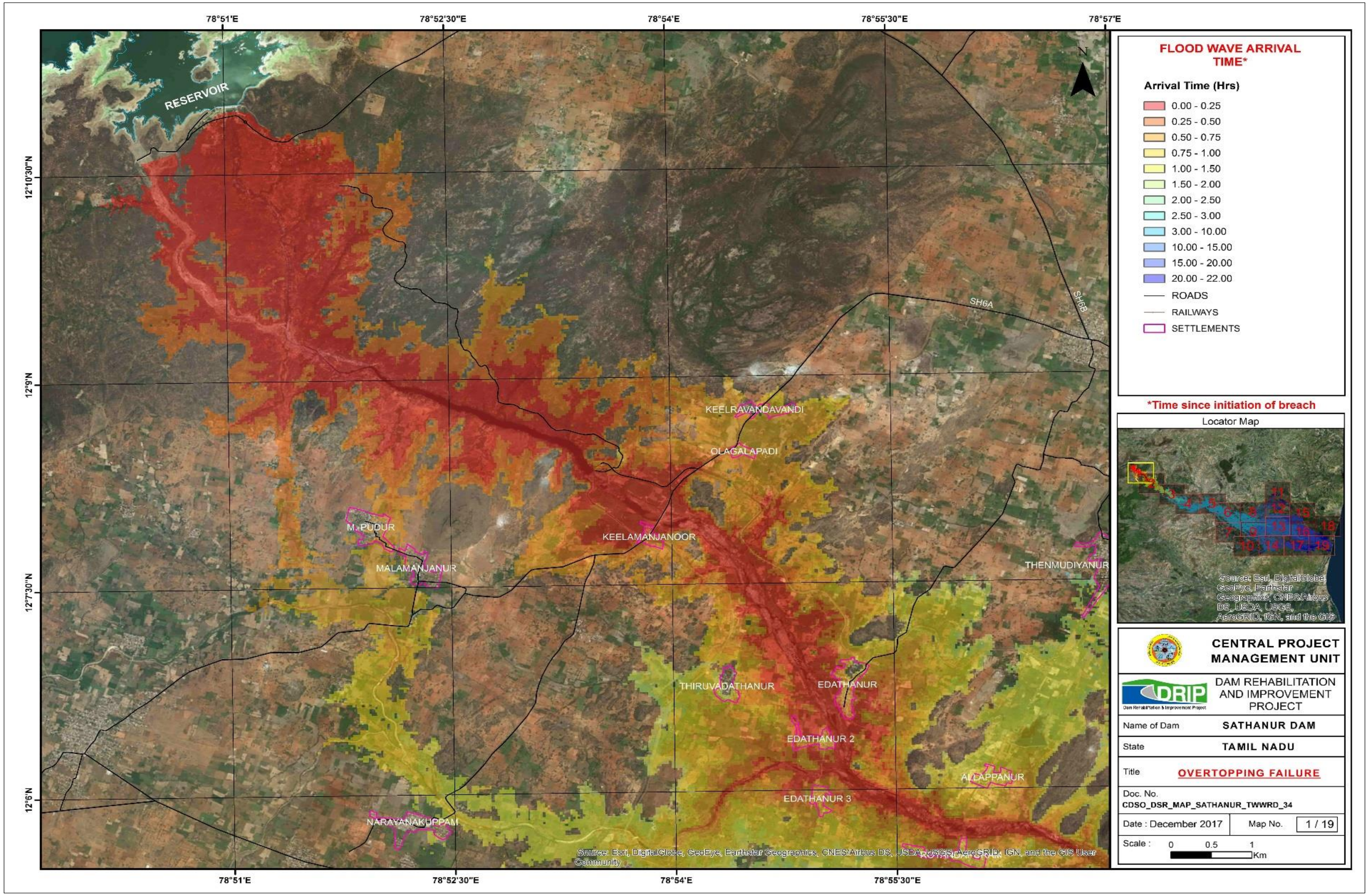


Figure 5-36: Map showing time of flood arrival due to overtopping failure of Sathanur Dam of Tamil Nadu

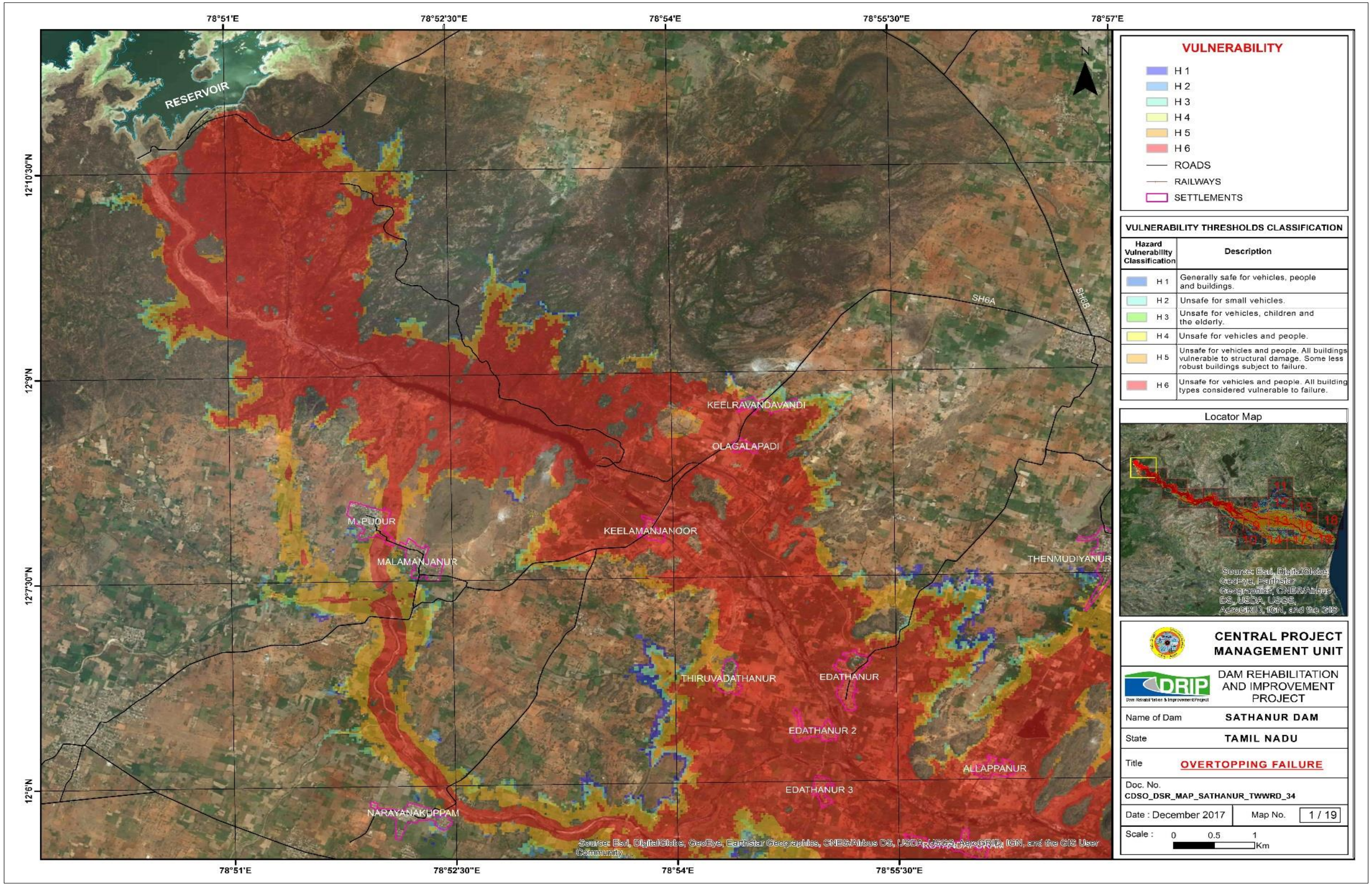


Figure 5-37: Map showing vulnerability due to overtopping failure of Sathanur Dam of Tamil Nadu

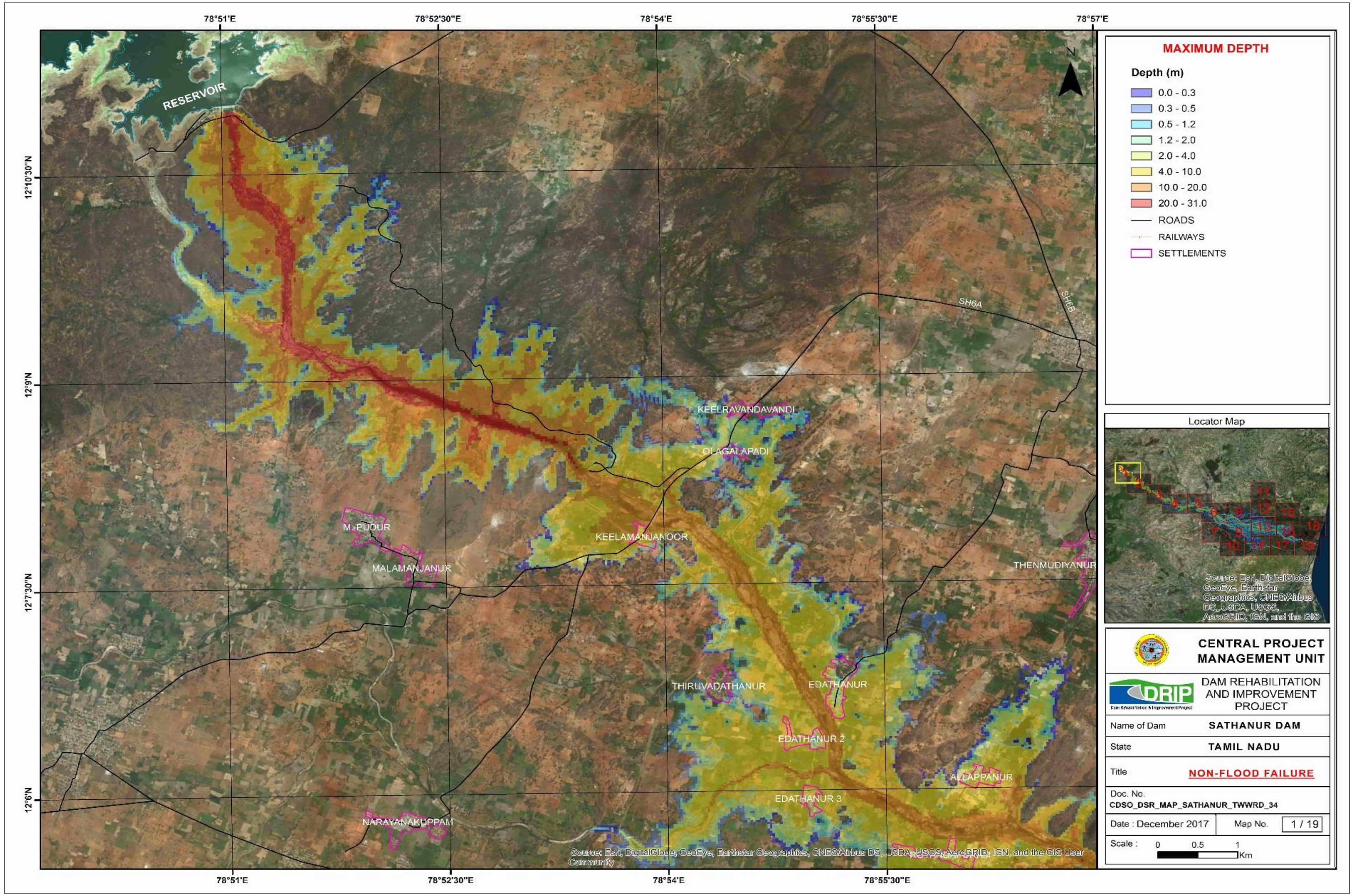


Figure 5-38: Map showing depth of inundation due to piping failure of Sathanur Dam of Tamil Nadu

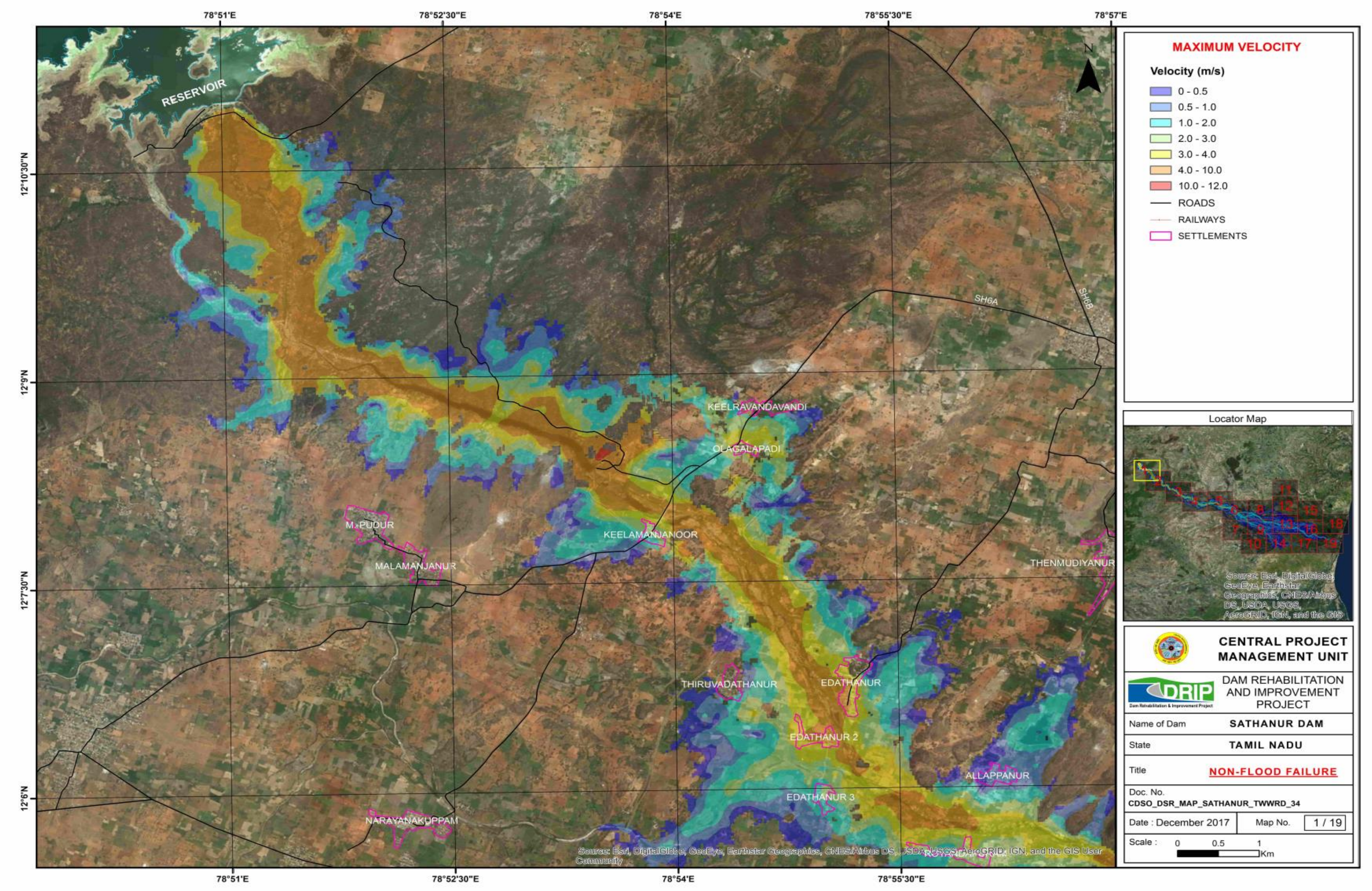
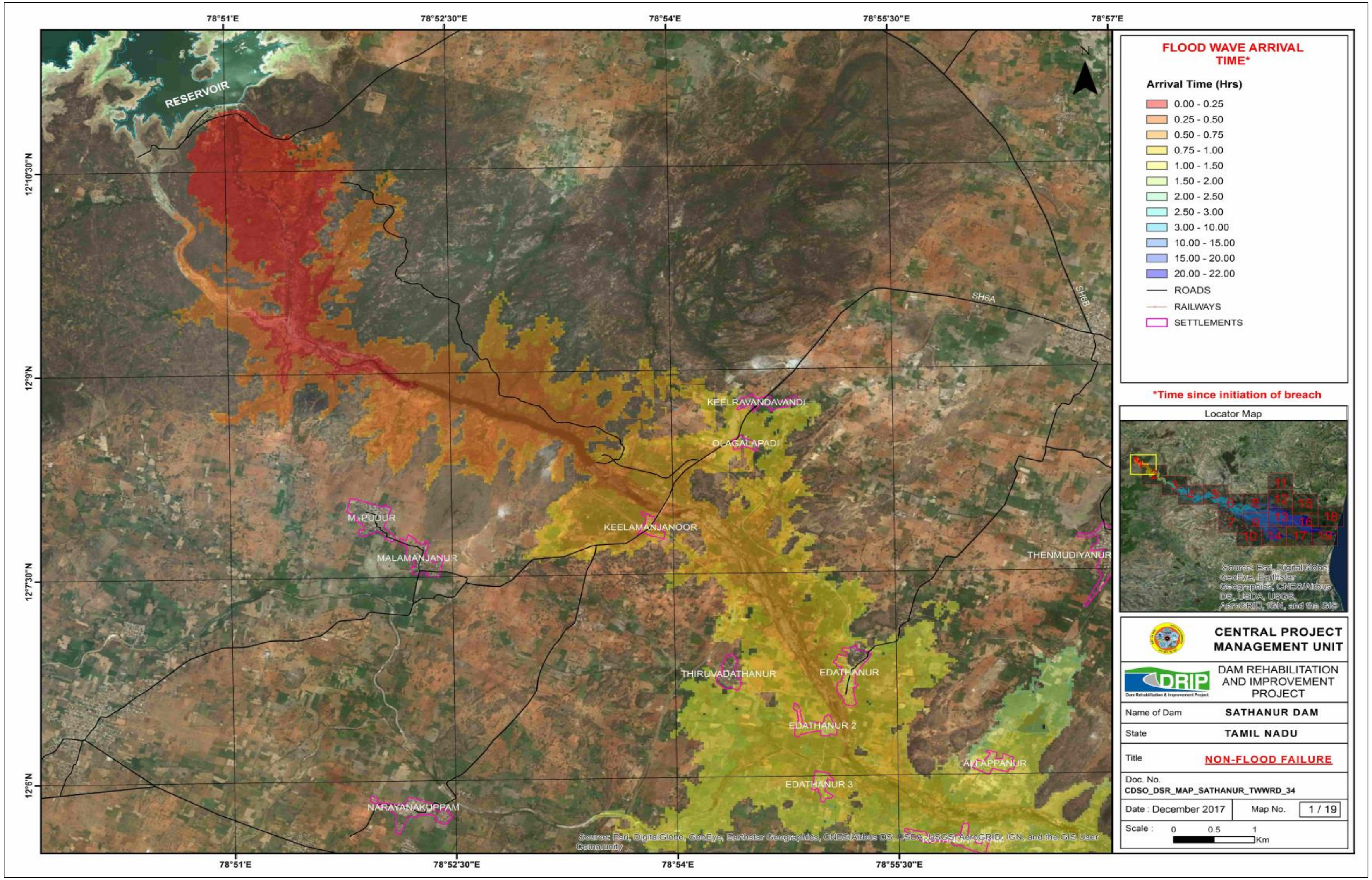


Figure 5-39: Map showing velocity of water flow due piping failure of Sathanur Dam of Tamil Nadu



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 5-40: Map showing time of flood arrival due to piping failure of Sathanur Dam of Tamil Nadu

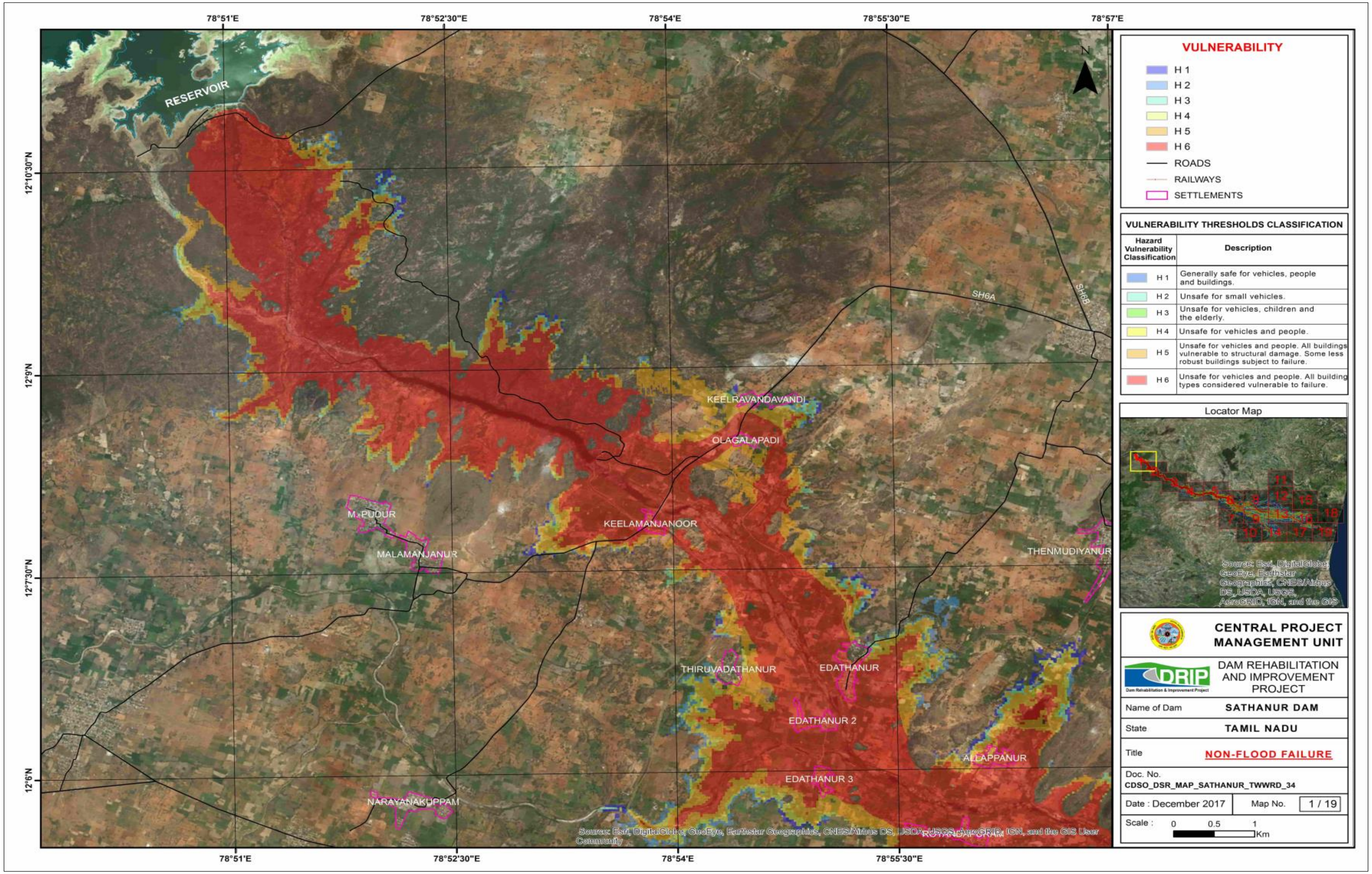
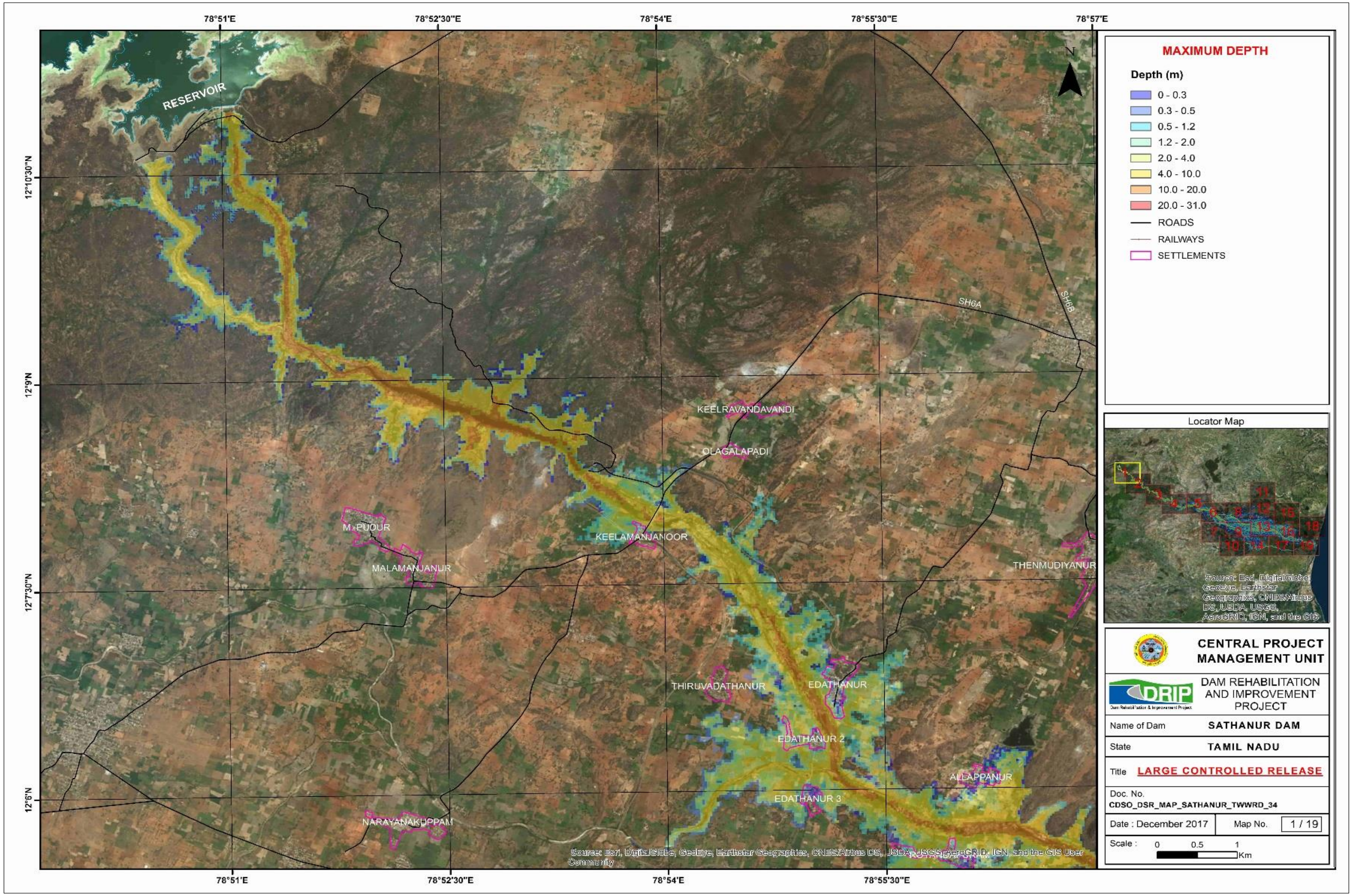
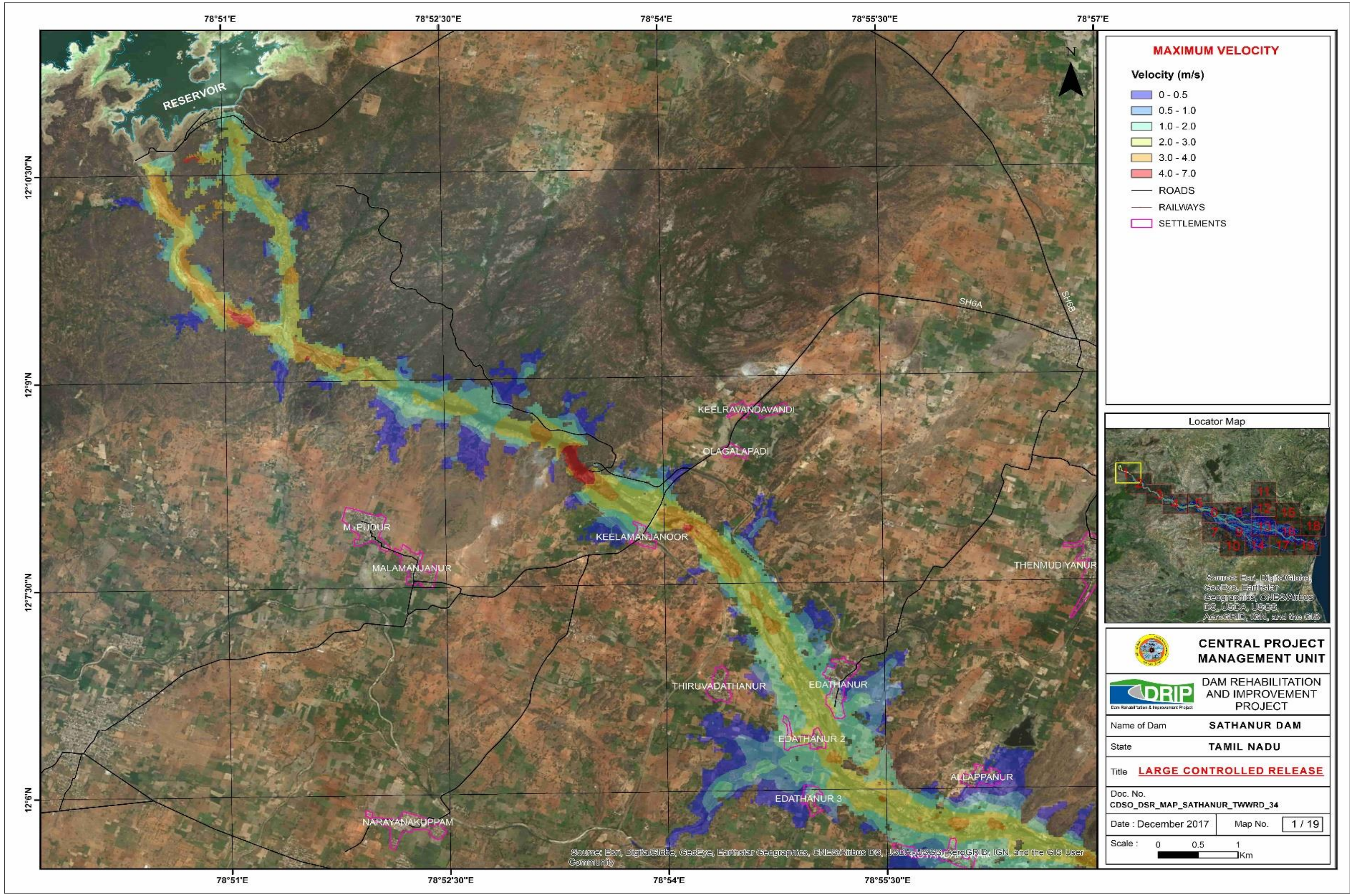


Figure 5-41: Map showing vulnerability due to piping failure of Sathanur Dam of Tamil Nadu



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 5-42: Map showing depth of inundation due to large controlled release from Sathanur Dam of Tamil Nadu



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 5-43: Map showing velocity of water flow due to large controlled release from Sathanur Dam of Tamil Nadu

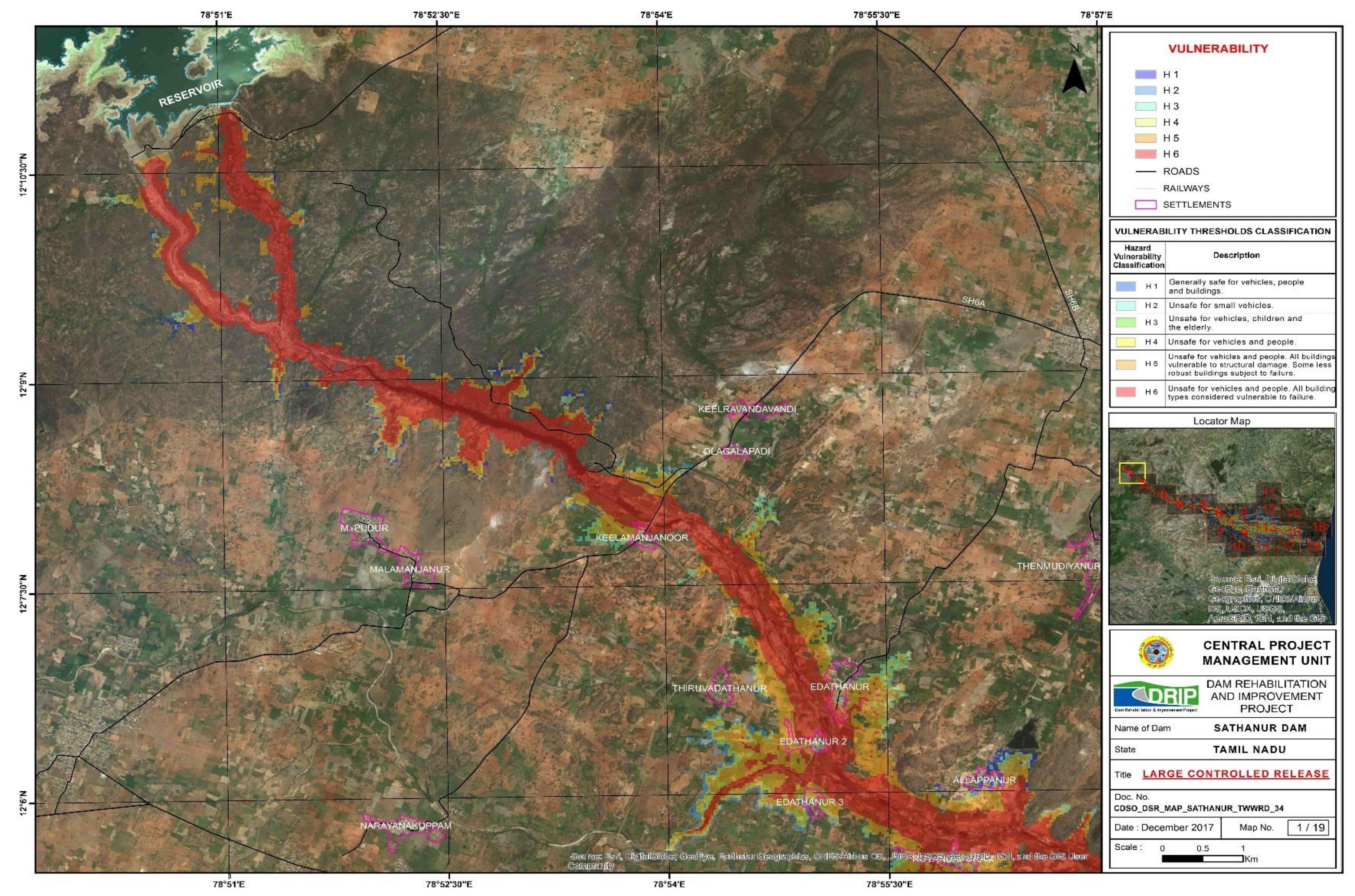


Figure 5-44: Map showing vulnerability due to large controlled release from Sathanur Dam of Tamil Nadu

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Chapter 6. FLOOD RISK MAPPING

6.1 Flood Risk

Risk is the uncertainty about the occurrence of a loss. The fact that a site may be flooded occasionally and be subject to a variety of flood hazards does not itself represent a problem. It is only with the occupation and utilisation of a floodplain that flood risks are invited. What becomes a risk to the lives and/or assets, and how great or small the risks are is a reflection of what development is allowed on the floodplain, how carefully it is planned and designed and how well or how poorly the flood hazards are understood before and after the site is developed.

The risk is generally thought of as having two components, which are the probability of a harmful event occurring and consequences of the event. A simple and commonly used definition of risk is risk = probability × consequence. Flood risk estimation involves assessment of hazard, vulnerability, and consequence due to flooding. Hazard is a condition that creates or increases the chance of loss. In this context, the hazard is the naturally occurring threat (flood). The vulnerability is the fragility of the construction (e.g. the embankment systems) to withstand/contain the hazard. This includes exposure, coping (short-term mitigation) and adaptation (long-term adjustment). The consequence is the adverse outcome of the combination of hazard and vulnerability (e.g. economic and property losses, loss of life or environmental damage). While infrequent events of very high magnitude may cause huge damage, but rarely, smaller events of much smaller magnitude may cause significant collective damage due to their high frequency of occurrence. The concept is shown graphically in Figure 6-1.

Flood risk estimation involves an assessment of the population and infrastructure that may be exposed to the flood hazard and the losses that may be incurred because of the exposure. The severity of the risks is directly proportional to the significance of the impacts of flooding i.e., the consequences of flooding. Limiting the flood hazards and reducing the degree of vulnerability to the flood impacts (such as proneness to water and velocity damage) may significantly reduce the consequences of flooding. Better management of future flood risk is required to reduce potential losses.

6.2 Flood Hazard to Flood Risk

Traditionally, floodplain management is dominated by the hazard-based method. By adopting structural measures such as embankments, this method aims to protect the community against the risks due to design flood (e.g. in case of dams: flood of a particular magnitude is chosen based on the gravity of the consequences that may arise due to the failure of the structure). Here, the focus is only on the hazard, intending to exclude the risk by controlling/containing the flood so that losses due to inundation are minimised. It is realized that the flood hazard based approach suffers from inefficiency due to the following limitations:

- Provision of protection against the design flood is only effective up to floods with a certain probability of occurrence. So, the residual risks, which

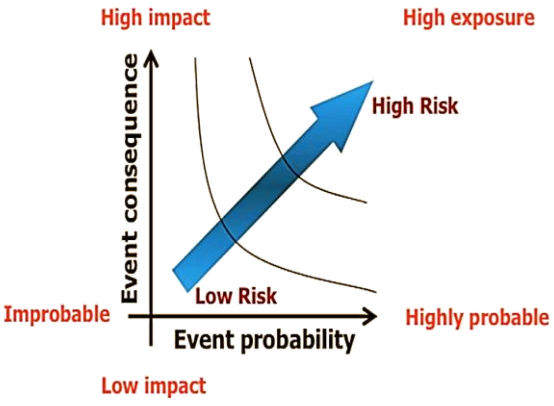

Figure 6-1: Risk conceptualised

may lead to unforeseen consequences, are ignored.

- The structural measures adopted are fragmented and designed separately, which fail to provide a holistic approach needed for managing flood risks.
- As the consequences of the flood are left open for interpretation in the decision-making, the adoption of risk-reduction measures is based on assumptions rather than testing, which is not scientific.

Therefore, current management strategies are more inclined towards the reduction of the risk through a reduction in vulnerability and consequences.

6.3 Management of Flood Risk

Risk management is a method of managing that concentrates on identifying and controlling the areas or events that have a potential of causing unwanted change. It is no more and no less than informed management. It is the process of weighing policy alternatives and selecting the most appropriate regulatory action, integrating the results of risk assessment with engineering data and with social, economic, and political concerns to reach a decision. It involves choosing among the options after the appropriate assessments have been undertaken and evaluated. The essence of risk management lies in maximising the areas where we have some control over the outcome while minimising the areas where we have absolutely no control over the outcome. The concept of risk management may be summarised as a process as shown in Figure 6-2. Within this broad framework of risk flood management, flood risk mapping forms the heart of risk identification, risk quantification, and risk mitigation planning. It may also help in risk monitoring and control.

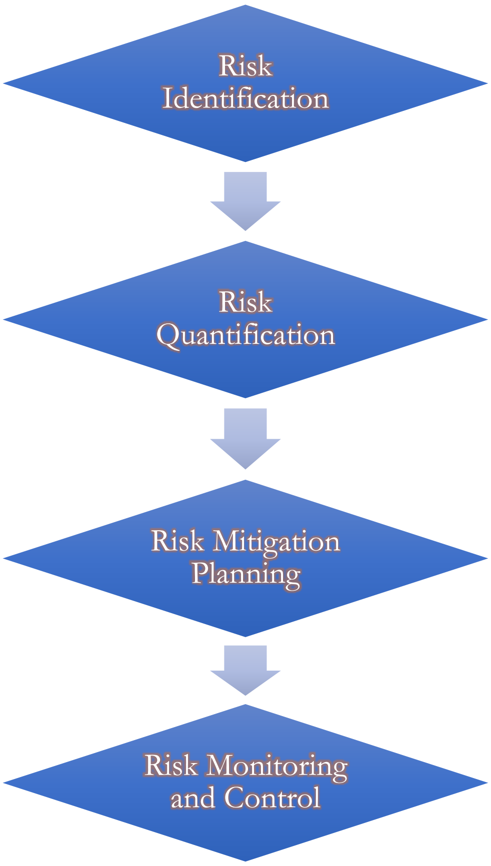

Figure 6-2: Managing flood rRisks

6.4 Assessment of Flood Risk

Flood risk assessment should identify who or what would be affected by adverse change due to the flood hazard (i.e. depths, velocities, rate of rise or duration of inundation), what these changes would mean to those directly affected and to the general community, and what mitigation measure(s) might be required to address the changes. Risk analysis has brought a paradigm shift that has allowed advancement in the evaluation and management of flood risks, which may affect people, the environment, and human development.

6.4.1 Risk Identification

Risk identification is an organized, thorough approach to find real risks associated. The identification of failure modes is paramount to all risk-based approaches. Risks cannot be assessed or managed until they are identified and described in an understandable way.

Flood risk identification may be handled under the categories of flood hazard identification and flooding consequence identification.

6.4.2 Hazard Identification

The flood hazard mapping discussed in the previous chapter paves the way for identification of the dam breach flood hazard to the downstream population, properties, and assets of special significance (because of their high hazard/huge loss involved). The localities and structures that would be inundated due to a dam breach may be marked, along with the maximum depth of inundation, the maximum velocity of water flow and maximum duration of inundation, enabling identification of the ones, that are under threat.

6.4.3 Consequence Identification

This involves prima facie estimation of damage to properties, disruption of critical infrastructures like road network, water supply network or electricity supply network and long-term health effects. The tools and techniques may include documentation reviews, information-gathering techniques, checklists, assumptions analysis and diagramming techniques.

Category of flood severity may be adjudged as low, medium or high (FEMA, 2012). Low flood severity is expected to occur when no buildings are washed off their foundation. This may be anticipated where most of the structures are exposed to depths of flood less than 3 metres. Medium flood severity may occur when homes are destroyed but trees or distorted homes remain in the nearby area where people can seek refuge. This may happen where most structures are exposed to flood depths of greater than 3 metres. High flood severity may occur when the flood sweeps the area clean and nothing remains in the area to shelter the persons from the fury of the flood. This may happen when very deep floodwater reaches its ultimate height in just a few minutes, as in the case of areas immediately downstream of large dams.

6.4.4 Risk Quantification

It is the effort to examine risk and assign values to flood risks for a project and for different components of a project. For estimating the efficiency of the measures targeting risk reduction, the estimation of the potential life loss and the economic loss are of great importance.

6.4.5 Consequence Magnitude Estimation

This entails estimation of the losses in economic and numeric terms like damages amounting to so many crores of rupees are anticipated, so many hospitals could be closed, so many people could suffer health problems. Ideally, this step should consider the spatial scale of the consequences, the duration, as also, where relevant, how quickly the harmful effects of a hazard would be felt.

The analysis of consequences consists of three parts: estimation of the failure discharge, the study of the flood and estimation of its consequences. The objective is to obtain a relation between the hydrograph in case of failure and non-failure with its consequences. Consequences are required to be analysed twice for each case of study: one due to the case of the failure of the dam and the other due to the case of non-failure. Thus, the incremental consequences required for the risk model may be obtained by subtraction. In general, consequences are analysed in economic terms and in terms of loss of life or population at risk. So, four curves are usually considered for the risk model (two parameters coupled with two cases). The process has been schematically shown in Figure 6-3. There are other intangible damages also, as discussed earlier. The values obtained for all these damages allow the definition of curves relating peak failure discharge to consequences.

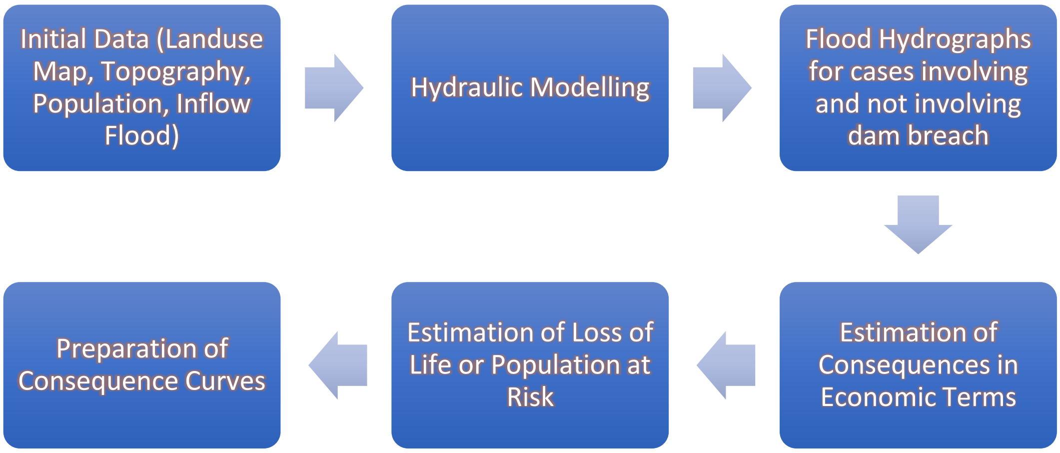

Figure 6-3: Schematic procedure to estimate flood consequences

Several floods with different maximum peak discharges should be studied to prepare these curves, the consequences of each flood defining a point on the curve. The number of points will depend on the desired level of detail of the risk analysis, better-defined curve and greater accuracy being associated with a larger number of points. Generally, it is advisable to use at least 4 or 5 points to avoid an incomplete definition of the curve. It is required to study the shape of the curve, considering that the changes in shape correspond to what effectively happens during a flood (e.g., overtopping of a flood embankment beyond a particular water elevation). Generally, two curves characterize consequences, one relating discharge with economic consequences and another one relating it to the loss of life or population at risk.

6.4.6 Failure Hydrographs

The estimation of the failure hydrographs is part of the analysis of consequences in the stage of risk analysis. The maximum discharge from a dam (the maximum routed discharge in the case of non-failure, or the peak dam break discharge in the case of a failure) is a key characteristic variable of the resulting flood, since larger discharges usually flood larger areas, with higher depths and higher associated costs. Therefore, the first step of the analysis of consequences is to estimate the failure hydrographs due to dam breach. Afterwards, these hydrographs are used in the estimation of the consequences curves.

The primary step in the estimation of failure hydrographs is to estimate the dam breach. This breach may be different for different failure modes and its progression will also vary with the changing water level in the reservoir. Consequently, as opposed to the studies for an emergency action plan in which only a few failure scenarios are studied (e.g., dam breach with the reservoir at its crest level), risk analysis considers the failure hydrographs corresponding to the whole range of possible pool levels in the reservoir and each of its different failure modes.

In risk models, failure hydrographs are usually characterised through a significant variable, which is usually the peak discharge. A curve relating the maximum pool level with any representative variable of the failure diagram (e.g., peak discharge due to dam breach) for each failure mode may be included in the risk model. Alternatively, curves of consequences due to peak discharge calculated using the complete failure hydrograph may also be included in the model.

The failure hydrographs for several pool levels of the reservoir may be obtained for each failure mode. The curve of peak discharge vs. pool level is obtained by correlating the peak discharge of the hydrograph with the maximum pool level to which it corresponds. Alternatively, a single failure hydrograph may be obtained and increased for larger peak discharges. The dam break peak discharge vs. pool level curve may be obtained through use of empirical relations like Froehlich (1995, 2016).

The basic level of detail may be used when one or several failure hydrographs are already available, e.g., the ones developed for the Emergency Action Plan. In this case, the required results may be obtained with little effort. The flood hydrographs may be obtained by using numerical hydraulic models like the HEC-RAS. Whenever hydrograph obtained using numerical calculations is available, its peak discharge may be used to scale the relation obtained through the application of empirical relations.

6.4.7 Population at Risk

The population at risk is defined as the population within the flooded area when the dam fails. In order to estimate, it is important to study the population located in each of the locations affected by the considered situation. It is possible to resort to census data as also to population studies performed by public institutions that reflect seasonal variations. Other data, such as the number of working people in the commercial and industrial areas along with their residence are also important to estimate the daily variations of the population.

Once the area that would be inundated due to dam breach event is estimated through modelling, the population at risk (PAR) may be estimated for various locations downstream of the dam. PAR may be estimated as groups or as individuals. Groups may be families, classrooms of students, busloads of people, groups of people located in a single building or an apartment, etc. The population at risk groups may be either separable or inseparable. The inseparable group would stay together during the evacuation, meaning that they would travel in the same vehicle or together on foot. When traveling by foot, a group will move only as fast as its weakest member.

It is suggested that the PAR be estimated for different reaches based on their distances from the dam and hydraulics of flood flow or type/value/intensity of the developments. PAR may be estimated either using the population of communities and the percentage of the community that is flooded, or by obtaining the number of houses from maps, or from a site visit, and then multiplying the number of houses or residences by an average number of residents per house for the area. Seasonally occupied locations or sites that have significant differences in population between weekdays and weekends (e.g., campgrounds) may need special consideration.

The larger the population at risk, the greater is the number of people that need to be warned and evacuated. Vulnerability increases if people need additional support to evacuate. This may include those in hospitals, nursing homes, corrective facilities, people with mobility limitations, older people, and children in schools and childcare facilities. Vulnerability also increases as emergency-response logistics become more difficult – that is, less warning time and time to evacuate, fewer resources to assist and more limitations on evacuation routes.

It may be appreciated that there always remains a part of the population who cannot be evacuated. With regard to the movement towards refuges/safe havens or protected places, it is a function of the warning time and the population living in high buildings. Moreover, to estimate the exposed population, the population already rescued during the flood must also be removed.

6.4.8 Potential Loss of Life

For comparing risk results with international recommendations on risk tolerability, it is particularly important to estimate the loss of life. Loss of life is an intangible consequence that cannot be estimated directly in economic terms. It is in the category of direct consequences since it is generally a direct result of the flood wave. The severity of the flood and the warning and evacuation times are also important factors. Sometimes, the indirect loss of life due to diseases or lack of drinkable water may assume serious proportions.

Following USDHS (2011), the three groups of factors that influence loss of life due to a dam failure are dam failure flood event, number and location of people exposed to the dam failure flood event, and loss of life amongst the threatened population.

The factors under the dam failure flood event are cause and type of dam failure, the location of the dam breach, breach geometry and its rate of development, water storage in the reservoir at the initiation of failure, time of the day, day of the week, and time of the year. Other important factors include weather and pre-failure flood conditions in the downstream inundation area, extent, velocity, depth, rate of rising of the water levels, arrival time in the downstream inundation area, and detection time of the dam failure event relative to failure initiation.

Considerations under the category number and location of people exposed to the dam failure flood event include initial spatial distribution of people in the downstream area inundated, general health conditions of the people threatened by floodwater, quantity, quality, accuracy, forcefulness and effectiveness of warnings, availability of sensory signals (sight or sounds of floodwater) to people at risk. It also includes readiness to evacuate for those at risk, the response of people to flood warnings, the opportunity for, and effectiveness of, evacuation measures undertaken, obstructions to evacuation (washed-out bridges, traffic jams, etc.).

Loss of life amongst the threatened population will depend on the number of persons who would remain in the inundation area at the time of arrival of the dam failure flood wave and severity of the flood (physical characteristics of the flood event). Further, the degree of shelter available at the place where people are located (structure, vehicle, on foot, etc.) at the time of arrival of the dam failure flood wave, and the same after the flood wave has passed (for those who survive it) also needs consideration.

6.4.8.1 Current Modelling Approaches

A couple of the recent models used for estimation of potential loss of life are being discussed underneath.

The LSM Model

Life Safety Model (LSM, Lumbroso et. al. 2011) developed by the BC Hydro in collaboration with HR Wallingford and the United States Bureau of Reclamation (USBR) is amongst the best of recent approaches for estimation of life lost due to a dam breach simulated using a two-dimensional model. It is a dynamic, agent-based, model for estimation of the flood risk to people in terms of loss of life and injuries. It also considers evacuation times and how improvements in emergency planning may help to reduce the loss. It allows for a dynamic interaction between people, vehicles, buildings and the flood wave. This model is based on the latest available physical equations rather than empirically deduced mortality rates and evacuation times. It estimates the loss of life due to drowning, exhaustion, building collapse and cars being swept away. It includes traffic and pedestrian models and also has the ability to simulate the effectiveness of the dissemination of flood warnings on the behaviour of the persons affected.

The model simulates the “fate” of a set of receptors (like people, vehicles, and buildings), which are described by their position at each time step through the simulation.

Each receptor may have a set of properties that describe its normal location/condition during a week, such as travel times, school/work hours and weekend activities. Other time-varying properties include the ability of the receptor to withstand the effect of the flood wave, and its anticipated reaction to the approaching wave, with and without a formal evacuation warning.

A loss function related to each receptor specifies its ability to resist the impact of the flood wave in terms of depth and velocity, and its possible change during an event. There may be an instantaneous loss when an individual encounters fast-flowing water, or a group who have sought safety in a building may suffer cumulative loss if the building collapses or a slow deterioration in health if they are exposed to the floodwater for a significant length of time, because of hunger or cold.

As a flood event progresses, the interaction of receptors with the flood wave affect the ultimate loss of life. The timing of the event and the decisions made by individuals determine their ability to escape the flood wave. As the flood advances, escape routes may be damaged or even destroyed by rising water and with advancing time roads may become congested with evacuees. The model has been successfully applied to a number of case studies, with estimated of loss of life of the same order as an actual flood event. The visualisation in the software helps to communicate with the community at risk, planners, and decision-makers, enabling them to improve emergency response plans for such situations. The Life Safety Model helps to fulfil broader sets of objectives than producing one loss estimate. It may be argued that under the present context of data availability in the country, carrying out the modelling exercise using LSM is difficult. However, for implementation of an emergency action plan based on scientific rationale, this shows the way forward.

The LIFESim Model

For detailed analysis, where the results are required to represent the physical reality and the development of the flooding process more faithfully, LIFESim is another model of choice (SPANCOLD, 2012). It simulates the behaviour of the people affected by flood and provides results at a micro-scale (Aboelata and Bowles, 2008).

Three different modules are used for the purpose:

- Warning and evacuation module: redistributes the population considering a curve of warning propagation that depends on the time of the day and a mobilization curve that simulates the escape of the population through the existing road network. Data on type of warning, evacuation methods, distance to safe areas and the characteristics of the roads are used. Characteristics of the traffic and the blockage of roads are also considered.
- Loss of shelter module: estimates the consequences of the flood on the buildings, depending on the characteristics of the flood and the building construction. Data on the type of construction of the buildings and the distribution of the population with respect to the buildings high enough to act as potential refuge are required.
- Loss of life module: estimates fatalities by applying mortality rates (corresponding to three categories of flood severity) on the population staying back in the flooded area with their shelter destroyed. The rates for each area are obtained through studies of historic floods.

The method is more suitable for city-centres, where the capacity of roads and the propagation of warning messages influence the number of victims significantly. It demands data on population distribution, roads, warning systems, etc. It also requires considerable modelling efforts.

A Simplified LIFESim, more adapted to the simulation of loss of life within the context of infrastructure risk management (Needham et al., 2010), reduces the data requirement for hydraulic modelling considerably by discounting the flow speed in the loss of refuges. It also simplifies the evacuation processes assuming a fixed speed of evacuation and a straight line evacuation path to the closest safe area.

Even though these models may be considered as state-of-the-art, the use of LSM or LIFESim in India at a large scale may become practicable only with time, because of their huge data requirement. At most, this may be suitable for Tier 3 level EAP, but for the two other levels, simpler techniques are warranted.

The SUFRI Model

Sustainable Strategies of Urban Flood Risk Management (SUFRI) is a tool developed in Europe recently (Escuder-Bueno et al., 2012). It considers the effect of non-structural measures on the reduction of the consequences, and thus the flood risk. It is based on the development of FN curves (depicting frequency of events that causes at least N number of fatalities) for each urban environment. It enables the quantitative classification of the risk with the application of tolerability guidelines for the existing risk. Fatality rates are estimated separately for each of the three categories (of implementation of flood warning systems), and level of flood severity.

Based on the existence of warning systems, coordination between the emergency systems and the local authorities, mass media, training of the population, etc., the population is classified into ten categories. Reference fatality rates for each category are available, depending on the warning time and the degree of severity of the flood. This table, adopted from Escuder-Bueno et al. (2012) has been shown as Table 6-1. It focuses on the affected population, acting in a way to reduce probable consequences of flooding. Risk communication plays a crucial role in the model. A sample map showing the estimated potential loss of life using the SUFRI model for areas downstream of Vazhani Dam, Kerala due to overtopping failure has been presented in Figure 6-4. It assumes that no warning systems are available.

Under the average Indian conditions, the data required for using SUFRI may not be easily met with. In addition, the time available may not permit following such extensive approach. Even though this type of analysis is mandated, some early results of even less accuracy may be needed for the planning purposes. In such cases, use of simpler methodology suggested by Graham (1999) may be adopted.

The Graham (1999) Methodology

Graham's method developed in 1999 (Graham, 1999) uses fixed mortality rates to estimate the loss of life from the population in the locations flooded due to dam failure. The method has been widely used.

The fatality rates are dependent on:

- Severity of the flood: A function of the depth of the flood representing the degree of destruction of buildings and refuges.
- Warning time: An indicator of the time available to evacuate or protect people. The time between the issue of first warning and the arrival of the flood.
- Understanding of the severity of the flood: Parameter representing the understanding of the potential consequences and dangers by the public and their alertness with regard to a possible flood.

Table 6-1: Fatality rates in case of river flooding (adopted from Escuder-Bueno et al., 2012)

ID	Category for the Case Study (C)	Warning Time TW(h)	Flood severity (Sv)		
			High (3)	Medium (2)	Low (1)
1	There is no public education on flood risk terms. No warning systems, no EAP. There is no coordination between emergency agencies and authorities. No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.7	0.08	0.015
		1	-	0.06	0.0006
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
2	There is no public education on flood risk terms. There is no EAP, but there are other warning systems. There is no coordination between emergency agencies and authorities. No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.675	0.075	0.014
		1	-	0.055	0.00055
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
3	There is no public education on flood risk terms. There is EAP, but it has not been applied yet. Some coordination between emergency agencies and authorities (but protocols are not established). No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.85	0.2	0.015
		0.625	0.6	0.07	0.012
		1	-	0.05	0.0005
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
4	There is no public education on flood risk terms. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols). No communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.04	0.007
		1	-	0.03	0.0003
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
5	There is no public education on flood risk terms. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols). Communication mechanisms to the public (not checked yet).	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.0375	0.0065
		1	-	0.0275	0.000275
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
6	There is no public education on flood risk terms. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols). Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.475	0.035	0.006
		1	-	0.025	0.00025
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
7	Public education. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols). Communication mechanisms to the public. Or Dam break with no hydrologic scenario.	0	0.9	0.3	0.02
		0.25	0.65	0.1	0.0075
		0.625	0.4	0.02	0.002
		1	-	0.01	0.0002
		1.5	-	0.0002	0.0002
		24	-	0.0002	0.0001
8	Public education EAP is already applied. It has been proved or used previously. Coordination between emergency agencies and authorities (there are protocols). Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.01	0.0015
		1	-	0.005	0.00015
		1.5	-	0.0002	0.00015
		24	-	0.0002	0.0001
9	Public education. EAP is already applied. It has been proved or used previously. High coordination between emergency agencies and authorities (there are protocols). Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.55	0.06	0.006
		0.625	0.35	0.008	0.0015
		1	-	0.004	0.000125
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001
10	Regular activities and plans for public education. EAP is already applied. It has been proved or used previously. High coordination between emergency agencies and authorities (there are protocols). Communication mechanisms to the public.	0	0.9	0.3	0.02
		0.25	0.5	0.03	0.005
		0.625	0.3	0.005	0.001
		1	-	0.002	0.0001
		1.5	-	0.0002	0.0001
		24	-	0.0002	0.0001

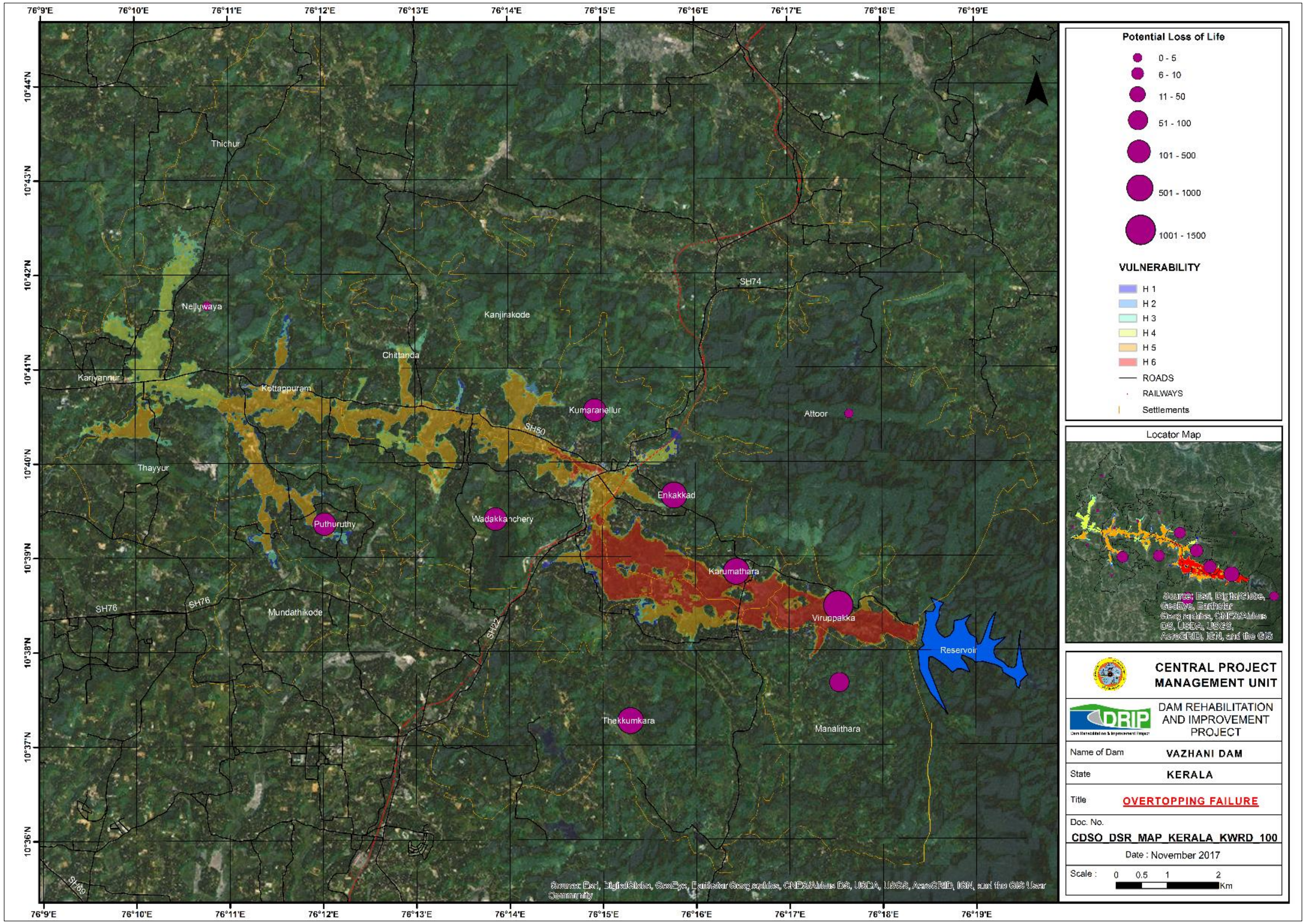

Figure 6-4: Potential loss of life due to overtopping failure of Vazhani Dam, Kerala

The probable fatality rates on the basis of these three parameters, as adopted from FEMA (2011) are presented in Table 6-2.

The first step of application is the estimation of the population at risk, defined as the inhabitants of the flooded area when the dam fails. This is carried out using census data or population studies dealing with seasonality. Number of working people in the commercial and industrial areas are also considered for diurnal variation.

Next, the severity of the flood is defined considering the degree of destruction of the buildings and the threats to the population. Flood severity is classified into three categories:

- High severity: A total destruction of the buildings and structures, killing most of the people inside.
- Medium severity: Some buildings like homes suffer serious damages, trees and buildings remain for people to seek refuge.
- Low severity: No building destroyed and damages are superficial.

High severity applies to areas located very close to the dam, affected by high flood depths within few minutes, a sweeping trace of life. It depends on the product of floodwater velocity and depth of flood, as also the construction material of the buildings and their height. Must be used for concrete dams that fail instantaneously (except for liquefaction produced by an earthquake, earth dams fail gradually).

Then, warning time or the time available for people to seek refuge or be evacuated is estimated for each group of houses or populations within the flooded area. It is also grouped into three categories:

- No warning: Warning time less than 15 minutes. The population is only

Table 6-2: Probable fatality rates for estimating life loss due to dam failure (adopted from FEMA, 2011)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk that died)	
			Average	Range
HIGH	No warning	Not applicable	0.75	0.3 to 1.00
	15 to 60	Vague	The values shown above are to be used and applied to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		Precise		
	More than 60	Vague		
		Precise		
MEDIUM	No warning	Not applicable	0.15	0.03 - 0.35
	15 to 60	Vague	0.04	0.01 - 0.08
		Precise	0.02	0.005 - 0.04
	More than 60	Vague	0.03	0.005 - 0.06
		Precise	0.01	0.002 - 0.02
LOW	No warning	Not applicable	0.01	0.0 - 0.02
	15 to 60	Vague	0.007	0.0 – 0.015
		Precise	0.002	0.0 – 0.004
	More than 60	Vague	0.0003	0.0 – 0.0006
		Precise	0.0002	0.0 – 0.0004

warned when they see or listen to the in-coming flood.

- Some warning: Warning time between 15 and 60 minutes. Official warnings circulated to some people through different communication channels; not everybody is warned properly.
- Adequate warning: Warning time greater than 60 minutes. Proper warning disseminated; most people at risk know about the in-coming flood.

Linear interpolation between the fatality rate with no warning and the rate with enough warning is suggested. As a first approximation, the time lapse between the dam failure and the arrival of the flood wave may be used as warning time.

For more detailed study, the time taken by the process of breach formation is taken into account. For large dams, this will be significant while for smaller damss it will be much less. Internal erosion failure may provide a few hours of warning time. Seismic events allow shorter warning times. The time of the day is important as observations are clearer and the transmission of the warning works better during the day. For failure of earth dams, Graham (1999) provides guidance on estimation of starting time of the warning, which has been presented in Table 6-3. Warning time is considered as the difference between the arrival time of the flood and the moment of the start of the warning.

Thereafter, the parameter on an understanding of the severity of the flood is assessed. It depends on the type of warning messages issued and the manner the population assimilates them. It is classified into two categories:

- Vague understanding: Population receiving the warning has never seen a flood or does not comprehend the magnitude of the imminent flood.
- Precise understanding: Population understands the warning messages properly and realises the flood magnitude.

Time available between the dam failure and the arrival of the flood is critical, as a population can learn about the consequences of the flood in other settlements through media if such time is available. In addition, clear, direct and decisive messages generate a better understanding of flood severity. With memories of past floods, people react more quickly to the warning messages. An emergency action plan of the dam helps authorities to know how to transmit message properly, and population understands the severity of the event.

After estimating warning time, the population at risk, the severity of the flood and understanding of severity for each settlement, the number of victims is assessed using the table of fatality rates mentioned earlier. The sum of the number of victims for all the settlements represents total for the flood event. Depending on the available data of population distribution, the method can be applied for obtaining the approximated number of victims at different levels- from isolated homes to large areas. Average values of the fatality rates for both categories may be applied for categories like medium- low severity or intermediate understanding of the flood. With digital maps of population distribution and its temporal variation, it is also possible to use GIS software to calculate the loss of life.

The Graham (1988) Methodology

This method (Brown and Graham, 1988) recognises that for the estimation of potential loss of life, the importance of factors like time available after the warning is received is more than that of the height of the dam or the volume of the reservoir stored behind. The loss of life estimation has been classified into three categories based on the time available after the issue of warning. By

Table 6-3: Estimation of starting time of warning for earth dam failure (adopted from Graham, 1999)

Cause of Failure	Special Considerations	Time of Failure	When Would Dam Failure Warning be Initiated?	
			Many Observers at Dam	No Observers at Dam
Overtopping	Drainage area at dam less than 260 km²	Day	0.25 hrs. before dam failure	0.25 hrs. after floodwater reaches populated area
	Drainage area at dam less than 260 km²	Night	0.25 hrs. after dam failure	1.0 hrs. after floodwater reaches populated area
	Drainage area at dam more than 260 km²	Day	2 hrs. before dam failure	1 hr. before dam failure
	Drainage area at dam more than 260 km²	Night	1 to 2 hr. before dam failure	0 to 1 hr. before dam failure
Piping (full reservoir, normal weather)		Day	1 hr. before dam failure	0.25 hrs. after floodwater reaches populated area
		Night	0.5 hr. after dam failure	1.0 hr. after floodwater reaches populated area
Seismic	Immediate Failure	Day	0.25 hr. after dam failure	0.25 hr. after floodwater reaches populated area
		Night	0.50 hr. after dam failure	1.0 hrs. after floodwater reaches populated area
	Delayed Failure	Day	2 hrs. before dam failure	0.5 hrs. before floodwater reaches populated area
		Night	2 hrs. before dam failure	0.5 hrs. before floodwater reaches populated area

this method, the loss of life is estimated on the basis of the people at risk as:

For areas receiving less than 15 minutes of warning: loss of life = 0.5(people at risk)

- For areas receiving between 15 and 90 minutes of warning: loss of life = $(\text{people at risk})^{0.6}$
- For areas receiving more than 90 minutes of warning: loss of life = 0.0002(people at risk).

6.4.8.2 Choice of Method for Different Tiers of EAP

The preferred choice of methods for preparation of EAP at Tier 1, Tier 2 and Tier 3 levels are provided in Table 6-4. This is indicative in nature, introduced for the sake of providing guidance to the varying levels of details that must be taken into consideration for each tier of EAP. Any other model that considers input at the similar level of details and yields results with comparative accuracy are equally acceptable.

6.4.8.3 Limitations of the Potential Life Loss Estimation

The methods to estimate the potential loss of life may provide an indicative value of the magnitude of this parameter, but an accurate figure cannot be expected from them. This is because variables involved in this process are difficult to model properly (e.g., behaviour of the people). Further, a large number of complex processes are to be modelled for the estimation, and the database on the loss of life is limited.

In any loss of life estimation procedure, there is uncertainty associated with natural variability, as well as uncertainty associated

Table 6-4: Choice of method for estimation of potential life loss

Tier of EAP	Preferred Method of Estimation
Tier 1	Graham (1988)
Tier 2	SUFRI, Graham (1999)
Tier 3	LSM, LIFESim

with the knowledge about the behaviour of the system (USDHS, 2011). Uncertainty about natural variability include mode of failure, water level in the reservoir at the time of failure, depth of dam overtopping that causes failure, timing of failure of the dam, prevailing conditions (darkness, rain, etc.) and its synchronisation with special event involving public gathering, issue, and receipt of warnings before dam failure as well as its effectiveness. It also includes the capacity of the roads to allow movement at the time of arrival of dam failure flood, due to prior inundation.

Knowledge uncertainty may include information about breach shape, ultimate size, and rate of breach development, the velocity of flow of floodwater downstream and presence of floating debris and its effect on flood flow. It also includes the factors that motivate/demotivate a person to evacuate, the time taken by a person to move for evacuation after the dissemination of flood warning, the percentage of people who do not evacuate, and flood depths and velocities that destroy structures of different kinds either fully or partially.

For example, there are various methods available for estimation of breach characteristics like the breach shape, ultimate size, and rate of breach development, each yielding a different estimate of the peak breach outflow. In addition, overtopping and the formation of a breach at one end of a dam may result in a different peak breach outflow than the case when the breach forms at a different location along the dam crest. Combined together, natural variability and knowledge uncertainty may result in a significant variability in loss of life estimates produced by the various methods.

6.4.9 Economic Losses

Economic loss assessment provides essential support for analysing and developing mitigation proposals. It helps decision makers to develop new policies, programs or development plans, and to identify issues that may require further consideration. The direct economic losses may include damage to building a structure (residential or commercial), gardens and contents, damage to equipment and supplies at an industrial site, damage to facilities that provide services.

It also include damage to vehicles, damage to public buildings and contents, damage to infrastructure (transportation, water supply, sanitation, electrical and communication infrastructure and riverbank damage due to flooding), loss of livestock, aquaculture stock and loss of standing crops, damage to fencing and equipment, damage to vegetation - loss of carbon credits and clean-up costs for removal of debris and sediment.

It may further include loss incurred due to reduction in agricultural output due to loss of irrigation, loss of municipal and industrial water supply, loss of recreation opportunities, loss of hydropower generation, cost due to increase in flood damage because of loss of flood moderation by the dam, cost due to loss of navigation (FEMA, 2011). Cost due to reduction in fish production from the reservoir, cost to rebuild/repair assets (the dam and the properties in the downstream area), cost to respond and recover along with cost of temporary structures, and cost of downstream damages, long-term costs due to environmental damage should also be considered under direct economic losses.

The indirect costs may comprise disruption of transport when roads are cut by floods, loss of value-added from affected businesses, loss of value-added due to manufacturing disruption and loss of value-added in retail, distribution and services (including networks), where not taken up elsewhere in the specified economy, costs due to reduction in agricultural yield if not due to direct damage. It also includes additional costs of maintaining production or service incurred by businesses, marginal costs of providing alternative public services, disruption to public utility systems outside the hazard-affected area, increased travel and congestion costs including food spoilage during transport. It may also involve loss of capital and labour.

Costs due to the interrupted water supply to municipal areas and factories, sewerage treatment or power generation and deteriorated groundwater quality caused by pollution or salinisation in coastal areas, additional costs of emergency services in a hazard event and additional costs borne by volunteer groups are also to be included under the indirect costs.

Losses in or beyond the flooded areas such as socio-economic challenges in the form of lower productivity, failure of services, loss of jobs and income sources pose additional problems. Examples may be unemployment caused by the closure of a damaged business inside the inundation area, or closed industry/hospital outside the inundation area due to wanting of water that was originally supplied from the reservoir, or additional cost of transport due to the adoption of the longer alternative route because of damage/flooding of roads. Indirect losses are more complex to evaluate, particularly because of the need to avoid double counting losses which have already been assessed as direct losses.

In addition, economic impacts may also include the amount of time and expenditure required to repair or replace and reopen businesses, governmental and non-profit organisations, and industrial facilities damaged by the dam failure.

The economic loss corresponding to a particular peak outflow discharge from the dam is obtained by adding direct economic consequences, indirect ones, damage due to the absence of the dam and the cost of rebuilding the dam. For risk analysis, it is generally necessary to obtain incremental consequences (i.e., the difference between the consequences in the case of failure of the dam and non-failure). Damage to the structure is included in the economic consequences associated with the failure of the dam.

Combined with information on people, assets, and activities, hazard information provides the basic data for loss assessment. Information on hazard size and its occurrence probability is essential for calculating average annual damages, which are required for cost-benefit analysis of alternative mitigation options. Based on maps showing the extent of the affected area, time of occurrence and duration of flooding, flood depths, and flow rates, an estimation of people, things, and activities that would be affected is carried out.

For residential and commercial areas knowledge about the depth of the floodwater in relation to the the floor levels are important. For agricultural areas, the duration of flooding is important because many crops may be destroyed after a certain period under water. In addition, agricultural machinery may not be able to operate potentially resulting in a lost asset. The information may be gathered through surveys, census data reports on previous events etc.

There should be a defined boundary within which the impact of the event on the economy of that area may be defined and evaluated. It should be clear whether the losses are being calculated for the town, the region or the state, as the results will depend on the boundary definition. In general, the more isolated the disaster-affected economy, the greater indirect losses are likely to be since there will be greater costs incurred in making up losses, exports will be lost or imports will increase.

There may be some information needed beyond that area, and the originally defined study zone may enlarge or contract as adjusting information comes in. The nominated area may be subdivided for detailed study of some specific loss components. There also should be a timeframe set to define how long after the disaster event the assessment will be considering losses associated with it. An extended timeframe of at least 3 - 6 months may be used to assess indirect and intangible losses. The commonly used approaches in assessing losses are:

i. The averaging approach, based largely upon pre-existing data on losses from similar previous events.
ii. The synthetic approach, based upon predictions of losses technically derived-rather than historical data.

To get a quick result with limited resources the averaging approach is appropriate but where accuracy is important, the synthetic method is generally preferred. The synthetic method also offers the best balance between consistency and local accuracy. The synthetic approach is probably the most flexible and currently the most widely used approach. It makes use of a variety of existing computer packages with their own stage-damage curves for calculating residential and small business direct losses. However, this extensive use and availability of calculation packages disguise considerable debate over the accuracy of the stage–damage curves and resulting figures.

Synthetic damage assessment involves compiling detailed average inventories of property contents for different structure types. It is required to measure hazard severity by potential loss tables or curves (stage– or depth–damage curves for floods) that are devised or synthesised for properties having similar susceptibility to flooding damage.

The contents component of commercial and residential damage curves may be constructed by estimating the flood susceptibility of all main items and then the ownership pattern and typical height above the floor for each item in each building type, as shown schematically in Figure 6-5 (adapted from AIDR-27, 2002).

The losses may be categorised as residential (including memorabilia and ill health), vehicles and boats, commercial (including tourism and hospitality), industrial, infrastructure, cultural heritage, environmental, and other. At a minimum, key local and state authorities, residents' representatives (if active or likely to become active), local business representatives, and others as locally appropriate (for example, producers, environmental organisations), should be consulted formally as assessment for the area is being finalised. Framework of a sample report on mapping flood risks associated with a dam has been presented in Appendix D for reference.

The impacts of disaster mitigation measures must also be modelled in physical and economic terms. Investment in disaster mitigation may be economically justified in terms of losses avoided in an average year, using an estimate of average annual damage. Average annual damage may be calculated by plotting loss estimates for a given hazard at a range of magnitudes, against the probability of occurrence of the hazard event. This may also be obtained mathematically by integration. The high damages resulting from an extreme event gets multiplied by a very low probability so that its average annual contribution is small although the event loss is very large. The opposite applies for frequent events.

The accuracy of the synthetic method depends on the reliability of the available datasets like the way the hazard severity is reflected by loss data and the extent and accuracy of the inventory of affected property. The actual loss experienced will vary greatly depending on the aspects of the hazard, exposure to the hazard and the vulnerability of the property, activities, and people exposed. However, it may be appreciated that the difference between actual and po-

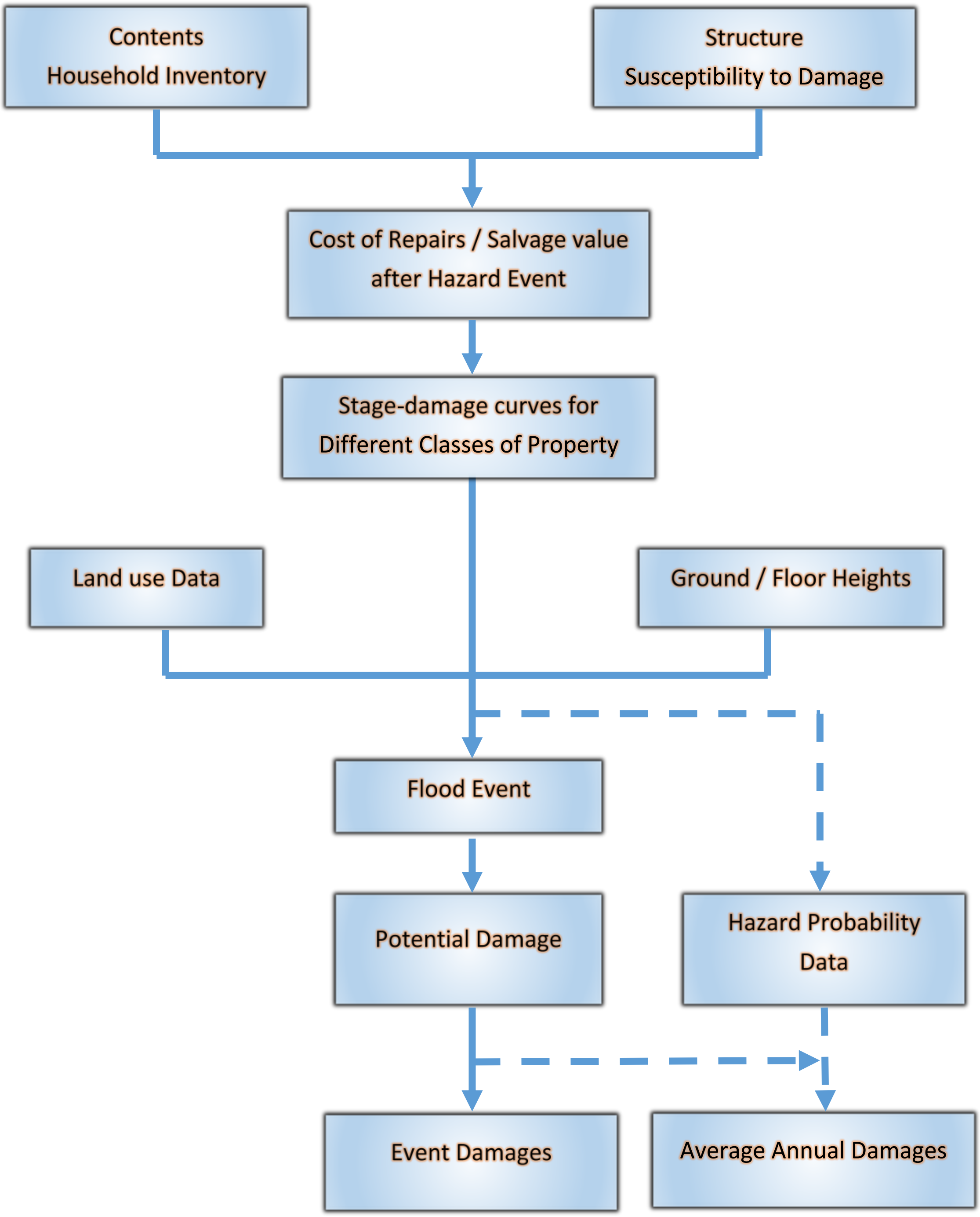

Figure 6-5: The Synthetic Approach (adapted from AIDR-27, 2002)

tential losses will change a lot over time as people move and as other circumstances change.

6.5 Risk Mitigation

It is the process of taking specific courses of action to reduce the probability and/or to reduce the impact of risks. This may be categorised into avoidance, loss prevention, and loss reduction. Avoidance implies that an existing loss exposure is abandoned. Loss prevention refers to measures that reduce the frequency of a particular loss. Loss reduction refers to measures that reduce the severity of a loss after it occurs. Risk mitigation may involve the use of reviews, risk reduction milestones, novel approaches, and similar management actions.

Occupying the floodplains and management of the associated risks is a balancing act. It involves acknowledging that living on the floodplain comes with an inherent risk and understanding what adverse impacts the community should be prepared to accept in return for the benefits of living on the floodplain. Knowing the consequences of the full range of losses due to flooding may help decision-makers on limiting the growth of risk resulting from new developments and ensuring risk reduction to the existing community.

Effective flood risk management entails working at the catchment scale, city scale, neighbourhood scale and the building scale. At higher levels, flood risk management is linked to planning and management, including land administration, land use planning, housing provision, infrastructure delivery and basic service provision. The need for improving drainage systems in the existing settlements, developing new settlements that incorporate integrated flood management techniques from the outset, as also reconstructing safer and stronger communities that have the capacity to withstand future flooding in a better way has to be addressed.

6.5.1 Flood Risk Reduction through Structural Measures

Flood risk reduction may be realised by having some structural measures. DRCFHMP (2009) and AIDR-7 (2017) provides details on many of such measures like relocating a structure, elevating/raising a structure, encapsulating/waterproofing below flood level/flood proofing, constructing embankment/levee/floodwall/berm/dike, erecting temporary barriers, constructing floodgates.

Some more measures are constructing off-stream retarding or detention pond, restoring abandoned channel/constructing split channel, maintaining floodway, reducing bank slope, reinforcing bank, laying gabion, laying concrete-block mattresses, laying riprap/geotextiles, placing cable trees, placing anchor logs/root wads, placing geogrids, replacing bridges, carrying out embankment/levee and dike setback, constructing reservoirs, establishing sediment trap. Constructing deflector structures, realigning flow, dredging channel/bed, constructing chevron dams, scalping gravel bar, improving evacuation route, rezoning with the the relocation of existing urban development, constructing shelter in place comprises some additional measures.

A few modern techniques of structural flood risk reduction (Kumar, 2009) include Rapidam, Flood Break Autogate, flood barrier, Floodgate door and vent seals, water inflated dams, water absorbent bags.

6.5.2 Flood Risk Reduction through Non-structural Measures

An important driver of the increasing losses from floods is the accumulation of assets in flood-prone areas. By 2030, developing countries are expected to have a large share of vulnerability to flooding because of more rapid urbanisation in high-frequency flood zones (OCED, 2016). Floodplain regulatory management assumes the critical role to provide risk reduction in a sustainable manner. A host of literature is available on the subject. A few important ones that merit consideration include AEMI (2013), Santato et al., (2013), FEMA P-259 (2012), NFIP (2011), PPS25 (2010), AIDR-21 (1999) and INCID (1993). Some other measures to reduce flood risk at a community scale may include the development of flood forecasting and warning system, preparing community-scale emergency response plans, increasing community preparedness and developing community recovery plans.

6.5.3 Integrated Flood Risk Management Strategy

An integrated strategy for flood risk management may involve a host of structural and non-structural measures to mitigate and manage existing and future flood risks as indicated in flood risk management plans. These plans should outline short-term and long-term actions for implementation. The plans should incorporate land use planning and development controls, creation, maintenance and management of infrastructure for flood mitigation, raising flood awareness through the implementation of efficient flood forecasting and warning system as well as flood emergency management responses. With the consideration that structural and non-structural measures are complementary, an optimal balance is envisaged that meets the expectations of safety while ensuring affordable costs and environmental protection. Urbanisation warrants the integration of flood risk management into regular urban planning and governance activities. In addition, consideration of social and ecological consequences of land use planning scenarios is necessary.

6.5.3.1 Planning Smartly

Planning should be carried out in a way that ensures that new developments are increasingly resilient to flood risk. This may be achieved through the judicious allocation of land use based on the location of the place, along with its strict enforcement, in order to make them better suited to tolerate flood hazards. New urban growth may be established in areas beyond the reach of the flood, or in areas where the effects of flooding may be managed properly. Buildings in the flood-prone zone may be constructed as flood resilient. Planning may be carried out in a way that ensures safe movement of emergency workers, evacuees, and supplies during floods, thereby maximising the efficiency of the disaster response capability and efficiency.

6.5.3.2 Ensuring Timely Response and Effective Recovery

Capacity to respond to and recover from flood events should be under continuous review and consequent development. Best practice in disaster management follow the pathway of prevention, preparedness, response, and recovery. With the help of India Meteorological Department, public notification and early warning systems for flood should be developed based on the meteorological forecast. Warnings before and during flood event should be disseminated using all channels of communication (including not only radio and TV but also mobile phone and the social media platforms). Easy to use guidelines on the procedure for development of emergency action plans and preparation of emergency action kits should be made widely available. Measures to follow during an emergency should be well known to all. A local group may be established for coordination of operations during flood events. Review and update of the local disaster plan should take place at least once a year.

6.5.3.3 Maintaining Flood Mitigation Infrastructure

For ensuring the protection of the community and supporting economic growth, critical infrastructure should be maintained in a way that makes them robust against flood (e.g., highways should remain operable even during the flood). Flood mitigation structures (e.g. guide bunds and embankments, stormwater drains and pumping arrangements in low-lying urban/semi-urban areas) should be constructed/arranged and maintained in a state that it functions effectively when required.

6.5.3.4 Educating to Make a Resilient Community

The community should be able to understand flood behaviour and risk. They should be more resilient and able to prepare for floods and minimise impacts on homes and businesses. This may be achieved through flood hazard information and planning, based on flood maps prepared on the basis of flood studies.

6.6 Towards Risk Resilience

The strategy of risk resilience provides the foundation for governments to shift the traditional emphasis of emergency management efforts from response and recovery from natural disasters to preparedness and prevention. Safer and more resilient communities are expected to be flexible and resourceful, with the capacity to accept uncertainty and proactively respond to change. Risk resilience relies on shared responsibility between governments, business, and industry, non-government organisations, community groups, emergency management volunteer organisations and the community. It acknowledges that all levels of government (Central, State and Union Territory, and Panchayat/local) have a role in driving systemic change for a more disaster resilient country.

The objective is to have safer and more resilient communities with strong, united leadership, underpinned by shared values and positive behaviours. The importance of the sector, community, and businesses continuing to work collaboratively to develop adaptive and agile strategies for emergency management needs to be acknowledged. This will lead to increased community safety and self-reliance.

Engaging with young people as both learners and educators, leadership programs that support diversity and inclusivity, developing workforce and training frameworks, providing support and promoting innovative approaches to water safety education for enhancement of the skills across communities during an emergency and stronger planning for investment across sectors are some actions towards its achievement. All will need to work together to drive sector reform and ensure that this momentum continues.

As the population increases and demographics change, the emergency management sector will continue to be challenged on how to engage with communities whose capabilities, capacities, needs, and expectations vary. The emergency management action plan should emphasise the impact of gender, inclusion, ethnicity (including aboriginal communities), religion and linguistics. Disability and socio-economic diversity should be taken into account, wherever applicable.

Roles and responsibilities across Central, State and Local Governments and agencies should be clearly defined and understood. It should be translated into in modernised and simplified legislation, operating arrangements and plans to meet the current and future needs of metropolitan, regional and rural residents. Emergency management should be properly reflected in land use and infrastructure planning and implementation of efficient operational arrangements to improve community safety.

Across the vast expanse of the country, flood disaster resilience is highly variable, with varying expectations of the role of the Government before, during and after emergencies. Following EMV (2016), building and empowerment of community leadership and development of awareness, shared responsibility and self-reliance to strengthen resilience should be taken on priority.

Roles and responsibilities of the Local Government in emergency management are varied and inconsistent. It is needed to better understand their capability and capacity to meet these roles and responsibilities. The capability and capacity of Local Governments need to be enhanced to meet their obligations in the management of emergencies.

There are varied workforce cultures across the emergency management sector that have different levels of diversity, inclusivity, and organisational values. It is required to develop sector leadership that instils a positive workforce culture and promotes respect, cooperation, innovation, and diversity.

A consistent, collaborative and innovative approach towards workforce management across the emergency management sector is needed. A diverse, inclusive and skilled workforce is required for the future sustainability of the sector. Therefore, a long-term emergency management employee and volunteer workforce development strategy needs to be created.

Even with the evolution of the emergency management sector, there is a need of clarity and understanding across government and non-government organisations about their roles and shared responsibilities. Existing arrangements do not support the future needs for the direction of the reform. Emergency management roles and responsibilities across all tiers of government, non-government organisations, agencies, businesses and the community are to be defined and made sure that they are understood by all involved.

There is a need of integrated, consistent, collective, transparent planning and governance processes and decision-making to mitigate the consequences of emergencies in communities with high-risk. A process for understanding and mitigating the consequences for communities that are at high risk of experiencing an emergency, such as those in semi-urban areas is to be defined and made sure that the process is understood by all involved.

Across the emergency-management sector service-delivery, governance, resources, people, and systems and processes vary. Additionally, there is a need of clarity about the future requirements of an integrated service delivery model for the emergency management sector to support collaboration, community safety, and self-reliance. An integrated emergency-management service-delivery model that facilitates community safety and self-reliance, and supports the people and systems to deliver in an integrated and coordinated manner needs to be formalised.

There is a limited amount of shared infrastructure and common terminology, with varied systems, inconsistent data, and information that does not support a common operating picture for the sector or the community, before, during and after emergencies. Systems and platforms to deliver integrated services are required to be enhanced.

A national, coordinated and cooperative effort is required to enhance the capacity to withstand and recover from emergencies and disasters. Community resilience can be achieved only by ensuring that communities are cognizant of the risks they face and the limitations of emergency service organisations. Communities that are involved in the development and have the feeling of ownership of plans for their safety have a greater capability and capacity to look after themselves. The need for constitutional and administrative responsibility for risk reduction is to be vested at the highest possible level of government, in order to have the necessary political authority and resources to influence development policy.

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Appendix A. GLOSSARY OF TERMS FOR MAPPING FLOOD RISKS ASSOCIATED WITH DAMS

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GLOSSARY OF TERMS FOR MAPPING FLOOD RISKS

The purpose of this glossary is to establish a common vocabulary of terms on flood risk mapping related to dams for use within and among Central and State Government agencies. Terms have been included that are generic and apply to all dams, regardless of size, owner or location.

Acceptable risk - A broadly acceptable risk is in general one that may be considered as negligible and properly controlled. However, risks associated with dams will rarely be classified into this category due to the huge destructive potential of this infrastructure.

Action plans - Plans that reflect the overall incident goal or objectives and strategy for the designated operational period, specific tactical actions and assignments, and supporting information for the designated operational period. Provide designated personnel with knowledge of the objectives to be achieved and the strategy and steps to be used for achievement, thus improving coordination across different levels of government and other stakeholders. Action plans not only provide direction but also provide a metric for evaluating achievement of objectives and overall system performance.

ALARP - The criterion ALARP (As low as reasonably practicable) is a concept related to tolerable risks. It means that in order to accept a risk as tolerable, all mitigation measures must be applied as long as their cost is not disproportionably high with regard to the risks they reduce.

Alert - A notification category that provides urgent information and indicates that system action may be necessary. An alert can be used for initial notification that incident activation is likely, and for ongoing notification throughout an incident to convey incident information and directed or recommended actions.

Analysis - A method of study on the nature of something, or for assessing its essential features and their relationships.

Annual exceedance probability - The probability that flooding will occur in any given year considering the full range of possible annual flood discharges.

Auxiliary/Emergency spillway - A spillway that provides additional discharge capacity to the principal spillway's design discharge in the event of extreme weather or other emergency conditions.

Base flood - The median flood discharge having a 1 percent chance of being equalled or exceeded in any given year.

Bathymetric survey – An underwater survey of the reservoir floor normally conducted for estimation of siltation.

Breach - An opening through a dam that allows the uncontrolled draining of a reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening caused by discharge from the reservoir. A breach is generally associated with the partial or total failure of the dam. Often used interchangeably with "failure" in the document.

Breach depth - The vertical extent of the breach measured from the dam crest down to the invert of the dam breach. Some publications cite the reservoir head on the breach, measured from the reservoir water surface to the breach invert.

Breach formation time or time-to failure - The time of failure is the duration of time between the first breaching of the upstream face of the dam until the breach is fully formed. For overtopping failures, the beginning of breach formation is after the downstream face of the dam has eroded away and the resulting crack has progressed back across the width of the dam crest to reach the upstream face.

Breach hydrograph - A graph showing the discharge from a dam breach over time.

Breach parameter - Parameters that define the breach geometry and formation time. Common breach parameters include breach depth, breach height, breach side slopes and breach formation time.

Breach progression - Progression in which dam embankment material is removed from the structure due to dam failure.

Breach side slope - The breach side slope is a measure of the angle of the ultimate breach sides and is typically described as horizontal to 1 vertical (H:1V)

Breach width - The average ultimate breach width typically measured at the vertical centre of the breach.

Casualty - Any person accessing health or medical services, including mental health services and medical forensics/mortuary care (for fatalities), because of a hazard impact.

Catastrophe - An event in which a society incurs, or is threatened to incur, such losses to persons and/or property that the entire society is affected and extraordinary resources and skills are required, some of which may come from other nations.

Catchment flooding - Flooding due to prolonged or intense rainfall (e.g. severe thunderstorms, monsoonal rains in the tropics, tropical cyclones). Types of catchment flooding include riverine and local overland flooding.

Catchment/Watershed - The area of land drained by a river or river system up to a particular site. It is related to a specific location and includes the catchment of the main river as well as any tributary streams.

Chance - The likelihood of something with beneficial consequences happening (e.g. the chance of a win in a lottery).

Community - An entity that has the authority to adopt and enforce laws and ordinances for the area under its jurisdiction. In most cases, the community is an incorporated town, city, township, village, or unincorporated area of a county. Maybe different for rural and urban areas.

Competency - A specific knowledge element, skill, and/or ability that is objective and measurable on the job. It is required for effective performance within the context of responsibilities for a job and leads to achieving the objectives of the organization. Competencies are ideally qualified by an accompanying proficiency level.

Concrete dam - A dam constructed from concrete. There are several types of concrete dams ranging from conventional design styles such as gravity, arch, multi-arch, and buttress dams to newer approaches in design such as roller compacted concrete.

Concurrent inflows - Flows expected on tributaries to the river system downstream of the dam at the same time a flood inflow occurs.

Conditional non-exceedance probability - The probability that failure will not occur during a flood of a given frequency. For example, an embankment may have a 90 percent chance of not being overtopped when exposed to a 100-year flood.

Consequence - The outcome of an event or situation affecting objectives, expressed qualitatively or quantitatively. Consequences may be adverse (e.g. death or injury to people, damage to property and disruption of the community) or beneficial. Several adverse effects or consequences may follow a dam failure

Consequence management - Measures to protect public health and safety, restore essential government services, and provide emergency relief to governments, businesses, and individuals affected by the consequences.

Crisis - A crucial point or situation in the course of anything; a turning point; an unstable condition in which an abrupt or decisive change is imminent.

Crisis management - The coordination of efforts to control a crisis event consistent with strategic goals. Although generally associated with response, recovery and resumption operations during and following a crisis event, crisis management responsibilities extend to pre-event awareness, prevention, preparedness, post-event restoration, and transition.

Cross-section - A section formed by cutting a plane through an object, usually perpendicular to an axis.

Dam - An artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water.

Dam failure – A catastrophic type of failure characterized by the sudden, rapid, and uncontrolled release of impounded water or the likelihood of such an uncontrolled release. There are lesser degrees of failure and any malfunction or abnormality outside the design assumptions and parameters that adversely affect a dam's primary function of impounding water is properly considered a failure. These lesser degrees of failure may progressively lead to or heighten the risk of a catastrophic failure. They are, however, normally amenable to corrective action.

Dam size classification system - A system that categorizes dams according to the storage capacity and/or height of the dam.

Damage assessment - An appraisal or determination of the effects of the disaster on human, physical, economic, and natural resources.

Damage to people - In principle, apart from the loss of life, damage to people could also consider other aspects such as people injured with different degrees of gravity. However, due to the difficulty of quantification of wounded numbers, quantitative analysis usually focuses only on the first aspect.

Design flood - The flood that a hydraulic structure (e.g. a dam/barrage/embankment), is based upon.

Deterministic methodology - A method in which the chance of occurrence of the variable involved is ignored and the method or model used is considered to follow a definite law of certainty and not probability.

Development - Development may be defined in jurisdictional legislation or regulation. This may include erecting a building or carrying out of work, including the placement of fill; the use of land, or a building or work; or the subdivision of land. Infill development refers to the development of vacant blocks of land within an existing subdivision that is generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. New development is an intensification of use with the development of a completely different nature to that associated with the former land use or zoning (e.g. the urban subdivision of an area previously used for rural purposes). New developments generally involve rezoning, and associated consents and approvals. It may require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. Redevelopment refers to rebuilding in an existing developed area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.

Direct Economic Consequences - Direct economic consequences are the costs of lost project benefits, downstream property damages, and repair/replacement costs.

Direct economic damage - Damage caused directly by the impact of the flood and the most visible type. It includes the cost associated with the damage suffered by the dam itself.

Direct Economic Effects - Direct effects are the initial changes in the industry to which there is a change in final demand. The direct effects are equal to the value of the change in final demand used to estimate regional impacts. For example, the direct effects of a management action resulting in water delivery changes may be changes in the value of agricultural production due to changes in irrigated acreage.

Disaster - A hazard impact causing adverse physical, social, psychological, economic or political effects that challenges the ability to respond rapidly and effectively. Despite a stepped-up capacity, capability, and change from routine management methods to command/management process, the outcome is lower than expected compared to a smaller scale or lower magnitude impact.

Disaster risk reduction - The systematic development and application of policies, strategies, and practices to minimize vulnerabilities and disaster risks throughout a society, to avoid or to constrain the adverse impact of hazards, within the broad context of sustainable development.

Discharge exceedance probability - The relationship of peak discharge to the probability of that discharge being exceeded in any given year.

Drainage area - The area that drains to a particular point on a river or stream.

Drill - A training application that develops a combination or series of skills (for example - a drill for evacuation). May also be referred to as an instructional drill. A drill conducted primarily for evaluation rather than training may be referred to as an evaluative drill.

Duration of the flood - It is important since damages increase with the deterioration induced by water.

Dynamic routing - Hydraulic flow routing based on the solution of the St. Venant equation(s) to compute the changes in discharge and stage with respect to time at various locations along a stream.

Ecologically sustainable development - Using, conserving and improving natural resources so that ecological processes on which life depends are maintained, and the total quality of life – now and in the future – may be maintained or increased.

Economic Consequences - Economic consequences are the direct and indirect economic impacts associated with a dam failure.

Education - Education is instruction, structured to achieve specific competency-based objectives, that imparts primarily knowledge. This may be general knowledge or it may be job specific but extend to higher order knowledge not specifically included in the job description of a person but of great value during emergency management activities. Educational material should be competency - based and specify a level of proficiency that relates to the competencies.

Effective – Able to achieve the established organization-wide and/or unit-level strategic and tactical objectives.

Effective warning time - The effective warning time available to a flood-prone community is equal to the time between the delivery of an official warning to prepare for imminent flooding and the loss of evacuation routes due to flooding. The effective warning time is used for people to self-evacuate, to move farm equipment, move stock, raise furniture, and transport their possessions.

Efficient – Ability to achieve objectives with a minimum of resources compared to past or standard methods. Resources include time, effort, personnel, equipment, supplies, facilities, and expense.

Embankment dam - Any dam constructed of excavated natural materials (includes both earth-fill and rock-fill dams).

Emergency - A hazard impact causing adverse physical, social, psychological, economic or political effects that challenge the ability to respond rapidly and effectively. It requires a stepped-up capacity and capability to meet the expected outcome and commonly requires a change from routine management methods to command process in order to achieve the expected outcome.

Emergency Action Plan - A plan of actions to be taken to reduce the potential for property damage and loss of life in an area affected by a dam failure or large flood.

Emergency assistance - Assistance that may be made available under an emergency declaration. In general, support from Centre to State and local efforts to save lives, protect property and public health and safety and reduce or avoid the threat of a catastrophe. Emergency assistance may take the form of coordinating all disaster relief assistance (including voluntary assistance) provided by Central agencies, private organizations, and State and local governments. The Central Government may also provide technical and advisory assistance to affected State and local governments for assuring the continuity of performance of essential community services, issuance of warnings of risks or hazards, public health and safety information including dissemination of such information. It may also include the provision of health and safety measures, management, control, and reduction of immediate threats to public health and safety, debris removal, temporary housing; and distribution of medicine, food, and other consumable supplies.

Emergency management - Organized analysis, planning, decision-making, and assignment of available resources to mitigate, prepare for, respond to, and recover from the effects of any hazard. The goal of emergency management is to save lives, prevent/reduce injuries, and protect property in case of an emergency.

Emergency management program - A program that implements the mission, vision, management framework, and strategic goals and objectives related to emergencies and disasters. It uses a comprehensive approach to emergency management as a conceptual framework, combining mitigation, preparedness, response, and recovery into a fully integrated set of activities. The program applies to all departments and organisational units, who have roles in responding to a potential emergency.

Emergency operation plan - The description of organizational authorities, relationships, functions, processes, and procedures, which are used to manage the response to, and recovery from, actual or potential incidents that may exceed the regular or routine response capability of the jurisdiction. It includes a standardised format, providing useful guidance and tools for promoting effective, coordinated response. It is a document that specifies actions to be taken in the event of an emergency or disaster; identifies authorities, relationships, and the actions to be taken by whom, what, when, and where, based on predetermined assumptions, objectives, and existing capabilities.

Emergency preparedness - Activities and measures designed or undertaken to prepare for or minimise the effects of a hazard on the civilian population, to deal with the immediate emergency conditions which would be created by the hazard, and to carry out emergency repairs to, or the emergency restoration of, vital utilities and facilities which are destroyed or damaged by the hazard.

Emergency services - The preparation for and the carrying out of functions to prevent, minimise and repair injury and damage resulting from disasters, together with all other activities necessary or incidental to the preparation for and carrying out of the functions. These functions may include firefighting services, police services, medical and health services, rescue, engineering, warning services, communications, radiological, chemical and other special weapons defence, evacuation of persons from stricken areas. It also includes emergency welfare services, emergency transportation, emergency resource management, existing or properly assigned functions of plant protection, temporary restoration of public utility services, emergency shelter, and other functions related to civilian protection. These functions also comprise the administration of approved regional, state and central disaster recovery and assistance programs.

Epistemological uncertainty - Epistemological uncertainty is related to the lack of knowledge resulting from either insufficient data or from the incapacity to understand the operating mechanisms of a given phenomenon. This uncertainty may be reduced through the collection of additional information, the gathering of more data and an in- crease of knowledge. On the contrary, this uncertainty is very difficult to quantify.

Erosion - The wearing away of a surface (bank, streambed, embankment) by floods, waves, wind, or any other natural process.

Evacuation - Organised, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and their reception and care in safe areas.

Evaluation - A systematic assessment process that leads to judgments and decisions about plans, programs or policies. Informal evaluation, which may be formalized by objective documentation of the assessment activity and its findings later, is also recognized as an ongoing and important activity of an emergency management program. It can also be described as one or more processes for interpreting the data and evidence accumulated through assessment practices. Evaluation is used to decide the extent to which program outcomes or program objectives are being achieved and results in decisions and actions to improve the program.

Event - An event may be used to differentiate any unusual activity from an incident where an emergency operation plan and its response system are activated.

Event tree - An event tree is a representation of a logical model that includes all the possible chains of events resulting from an initiating event. As its name indicates it is based on the mathematical structure known as a tree that is widely used in many other contexts.

Exceedance probability event - The probability that a specific event will be equalled or exceeded in any given year. For example, the probability of occurrence of 0.01 exceedance event in any given year is 1 in 100.

Exceptional - Refers to unusual numbers or types of victims, impacted medical care systems, or other very adverse conditions.

Exercise - A documented, scenario-based activity designed to evaluate the capabilities of the system and capacity to achieve overall and individual functional objectives, and to demonstrate the competencies for relevant response and recovery positions. The purpose of the exercise is to ensure the performance of the system under similar conditions in future and to identify potential system improvements.

Existing flood risk - The risk a community is exposed to as a result of its location on the floodplain.

Expected annual damage - In the risk-based analysis, the average or mean of all possible values of damage determined by Monte Carlo sampling of discharge–exceedance probability, stage–discharge, and stage–damage relationships and their associated uncertainties. Calculated as the integral of the damage–probability function.

Experience - Adequate participation in a prior response, signified by satisfactory performance evaluations from previous deployments in the position or function being considered.

Expert - An individual who meets some defined level of knowledge, skills, and abilities that usually have been demonstrated by his experiences.

Expert judgment - Information and data are given by qualified individuals in response to technical questions. It is generally used when test/observational data are difficult or expensive to obtain and when other sources of information are sparse, poorly understood, open to differing interpretations, or requiring synthesis. It may be an integral part of most problem solving and analysis. In the performance-based evaluation, expert judgment is essentially the assessment made by a qualified individual comparing performance measures, often approximated, to his understanding of an optimal yet realistic metric.

Exposure - The condition of being subjected to a source of risk.

Extreme event - A term used commonly in the field of risk management for collectively describing emergencies and disasters. These are events with low probability and high consequence.

Failure mode - A failure mode is the particular sequence of events that may cause failure or disrupt the function of the dam-reservoir system or part of it. This series of events is associated with a determined loading scenario and has a logical sequence, which starts with a main initial triggering event, is followed by a chain of development or propagation events and culminates in dam failure. A potential failure mode is a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or ageing process, which may lead to an uncontrolled release of the reservoir.

Failure probability - Within the scope of Risk Analysis applied to dam safety, the concept failure is not limited exclusively to the catastrophic breakage of the dam but includes any event that might produce adverse consequences. In this sense, the terms failure and breakage are interchangeable.

Fault tree – A fault tree is a top-down, deductive logical tool in which a major undesired event (failure) is postulated and then analysed systematically. The goal of Fault Tree Analysis is to develop all events or combination of events that might cause failure. These events may be of any nature: mechanical faults, human faults, external conditions, etc. The failure or undesirable event analysed in the tree is called top event and it is drawn in the top part of the diagram. Under it, all the events that might induce the top event to happen are drawn. This is done successively until reaching the lowest level where the basic events are found.

Flash flood - Flood that is sudden and unexpected. It may be caused by sudden local or nearby heavy rainfall. It is generally not possible to issue detailed flood warnings for flash flooding. However, generalised warnings may be possible. It may be defined as flooding that peaks within six hours of the causative rain.

Flood - Flooding is a natural phenomenon that occurs when water covers land i.e. normally dry. It may result from coastal or catchment flooding, or a combination of both. It is a temporary rise in water surface elevation that results in inundation of areas. Hypothetical floods may be expressed in terms of average probability of exceedance, such as the 100-year flood.

Flood awareness - An appreciation of the likely effects of flooding, and a knowledge of the relevant flood warning, response and evacuation procedures. In communities with a high degree of flood awareness, the response to flood warnings is prompt and effective. In communities with a low degree of flood awareness, flood warnings are liable to be ignored or misunderstood, and residents are often confused about what they should do when to evacuate, what to take with them and where it should be taken.

Flood damage - The tangible (direct and indirect) and intangible costs (financial, opportunity costs, clean-up) of flooding. Tangible costs are quantified in monetary terms (e.g. damage to goods and possessions, loss of income or services in the flood aftermath). Intangible damages are difficult to quantify in monetary terms and include the increased levels of physical, emotional and psychological health problems suffered by flood-affected people that are attributed to a flooding episode.

Flood damage reduction actions - Measures and actions taken to reduce flood damage. These may include implementation of reservoirs, detention storage, channels, diversions, embankments and floodwalls, interior systems, flood-proofing, raising, relocation, and flood warning and preparedness actions.

Flood education - Education that raises awareness of the flood problem, to help individuals understand how to manage themselves and their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.

Flood emergency management - Emergency management is a range of measures to manage risks to communities and the environment. In the flood context, it may include measures to prevent, prepare for, respond to and recover from flooding.

Flood emergency management plan - A step-by-step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations. The objective is to ensure a coordinated response by all agencies having responsibilities and functions in emergencies.

Flood fringe areas - The part of the floodplain where development could be permitted, provided the development is compatible with flood hazard and appropriate building measures to provide an adequate level of flood protection to the development. This is the remaining area affected by flooding after flow conveyance paths and flood storage areas have been defined for a particular event.

Flood hazard - Potential loss of life, injury and economic loss caused by future flood events. The degree of hazard varies with the severity of flooding and is affected by flood behaviour (extent, depth, velocity, isolation, the rate of rising of floodwaters, duration), topography and emergency management.

Flood hydrograph - A graphical representation of the flood discharge with respect to time for a particular point on a stream or river.

Flood planning level - The flood planning level is a combination of the defined flood levels (derived from significant historical flood events or floods of specific annual exceedance probabilities) and freeboards selected for floodplain management purposes, as determined in management studies and incorporated in management plans.

Floodproofing of buildings - A combination of measures incorporated in the design, construction, and alteration of individual buildings or structures that are subject to flooding, to reduce structural damage and potentially, in some cases, reduce contents damage.

Flood readiness - An ability to react within the effective warning time.

Flood risk - The potential risk of flooding to people, their social setting, and their built and natural environment. The degree of risk varies with circumstances across the full range of floods. Flood risk is divided into three types – existing, future and residual.

Flood routing - A process of determining progressively the amplitude of a flood wave as it moves past a dam and continues downstream.

Flood severity - A qualitative indication of the ‘size’ of a flood and its hazard potential. Severity varies inversely with the likelihood of occurrence (i.e. the greater the likelihood of occurrence, the more frequently an event will occur, but the less severe it will be). Reference is often made to major, moderate and minor flooding.

Flood storage - Storage volume in the reservoir exclusively allocated for regulation of flood inflows which is the storage in between the top of active storage (above normal reservoir operating level/Full Reservoir Level) and the top of conservation (top of dam/Top of the Bank Level) storage.

Flood storage areas - The parts of the floodplain that are important for temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage may increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.

Flood study - A comprehensive technical investigation of flood behaviour. It defines the nature of flood hazard across the floodplain by providing information on the extent, level and velocity of floodwaters, and on the distribution of flood flows. The flood study forms the basis for subsequent management studies and needs to take into account a full range of flood events up to and including the probable maximum flood.

Flood-frequency curve - A graph showing the average time interval (or recurrence interval) for the flood of a given magnitude being equalled or exceeded in any given year.

Floodplain - An area of land that is subject to inundation by floods up to and including the probable maximum flood event – that is, flood-prone land. It refers to the downstream area that may be inundated or otherwise affected by the failure of a dam or by large flood flows.

Floodplain - Lowlands adjoining the channel of a river, stream, or watercourse, which have been or may be inundated by floodwater, and those other areas subject to flooding.

Floodplain management - Floodplain management refers to the operation of an overall program of corrective and preventive measures for reducing flood damage, including but not limited to emergency preparedness plans, flood control works and floodplain management regulations.

Floodplain management plan - A management plan developed in accordance with the principles and guidelines in this handbook, usually includes both written and diagrammatic information describing how particular areas of flood-prone land are to be used and managed to achieve defined objectives. It outlines the recommended ways to manage the flood risk associated with the use of the floodplain for various purposes. It represents the considered opinion of the local community and the floodplain management entity on how best to manage the floodplain, including consideration of flood risk in strategic land-use planning to facilitate the development of the community. It fosters flood warning, response, evacuation, clean-up, and recovery in the onset and aftermath of a flood, and suggests an organisational structure for the integrated management for existing, future and residual flood risks. Plans need to be reviewed regularly to assess progress and to consider the consequences of any changed circumstances that have arisen since the last review.

Flood-prone land - Land susceptible to flooding by the probable maximum flood event. The flood-prone land is synonymous with the floodplain. Floodplain management plans should encompass all flood-prone land rather than being restricted to areas affected by defined flood events.

Flow - The rate of flow of water measured in volume per unit time – for example, cubic metres per second (m^3/s). Flow is different from the speed or velocity of flow, which is a measure of how fast the water is moving, for example, metres per second (m/s).

Flow conveyance areas - Those areas of the floodplain where a significant flow of water occurs during floods. They are often aligned with naturally defined channels. Flow conveyance paths are areas that, even if only partially blocked, would cause a significant redistribution of flood flow or a significant increase in flood levels. They are often, but not necessarily, areas of deeper flow or areas where higher velocities occur, and may also include areas where significant storage of floodwater occurs. Each flood has a flow conveyance area, and the extent and flood behaviour within flow conveyance areas may change with flood severity. This is because areas that are benign for small floods may experience much greater and more hazardous flows during larger floods.

Forecast - Statement or statistical estimate of the occurrence of a future event. This term has different meanings in different disciplines, including prediction.

Foundation - The portion of the valley floor that underlies and supports the dam structure.

Freeboard - The height above the defined flood events or design flood used, in consideration of local and design factors, to provide reasonable certainty that the risk exposure selected in deciding on a particular defined flood events or design flood is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, embankment crest levels and so on. Freeboard compensates for a range of factors, including wave action, localised hydraulic behaviour, and settlement, all of which increase water levels or reduce the level of protection provided by levees. Freeboard should not be relied upon to provide protection for flood events larger than the relevant defined flood event of a design flood. Freeboard is included in the flood planning level and therefore used in the derivation of the flood planning area.

Frequency - The measure of likelihood expressed as the number of occurrences of a specified event in a given time. For example, the frequency of occurrence of a 20% annual exceedance probability or five-year average recurrence interval flood event is once every five years on average.

Future flood risk - The risk that new development within a community is exposed to as a result of developing on the floodplain.

Gauge height - The height of a flood level at a particular gauge site related to a specified datum (generally the national datum).

Geographic Information System - A computerized system for the capture, storage, analysis and display of geographically/ spatially related information. Commonly, GIS shows a portion of the surface of the earth in the form of a map on which this information is overlaid.

Goal - A description of the end state – what should be achieved at the end of the activity or program for which the goal was defined.

Gravity dam - A dam constructed of concrete and/or masonry, which relies on its weight and internal strength for stability.

Habitable room - In a residential situation, a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom. In an industrial or commercial situation, it refers to an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.

Hazard - A source of potential harm or a situation with a potential to cause loss. In relation to this guideline, the hazard is flooding, which has the potential to cause damage to the community.

Hazard Analysis – A process of identification of all of the hazards that potentially threaten a jurisdiction and along with their analysis to determine the degree of threat posed by each.

Hazard Identification - The process of recognizing that a hazard exists and defining its characteristics.

Hazard Mitigation - Measures were taken in advance of a disaster aimed at reducing or eliminating its impact on society and environment

Hazard potential - The possible adverse incremental consequences that result from the release of water or stored contents due to the failure of the dam or misoperation (sudden unplanned release of water) of the dam or appurtenances. Impacts may be for a defined area downstream of a dam from flood waters released through spillways and outlet works of the dam or waters released by partial or complete failure of the dam. There may also be impacts for an area upstream of the dam from effects of backwater flooding or landslides around the reservoir perimeter.

Hazard potential classification - A system that categorizes dams according to the degree of adverse incremental consequences of a failure or misoperation of a dam. The hazard potential classification does not reflect in any way on the current condition of the dam (i.e., safety, structural integrity, and flood routing capacity).

Hazard probability - The estimated likelihood that a hazard will occur in a particular area.

Hazard risk - A quantitative product of the probability of a hazard occurring and the projected consequence of its impact.

Hazard vulnerability analysis - A systematic approach for identification of all hazards that may affect a community, assessing the risk associated with each hazard and analysing the findings for a prioritized comparison of hazard vulnerabilities. The consequence or vulnerability is related to both the impact on normal operations and the likely additional requirements arising out of the hazard impact.

Hydraulics - The study of water flow in waterways; in particular, the evaluation of flow parameters such as water level, extent, and velocity. It involves analysis of stream water surface profiles, flood inundation boundaries, and other technical studies of streamflow characteristics.

Hydrograph - A graph that shows how the flow or stage (flood level) at any particular location varies with time during a flood.

Hydrologic analysis - The study of the rainfall and runoff process, including the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.

Hydrologic breach - A dam breach associated with a rain event and/or flooding.

Hydrology - Hydrology involves the estimation of the amount and shape of the runoff– discharge hydrographs over the study area. It also includes estimation of the frequency of the events.

Incident - Activity resulting from an actual or imminent hazard, requiring action by emergency personnel to prevent or minimize loss of life or damage to property. Generally beyond the routine actions of the organisation for organizations other than public safety agencies.

Incremental hazard evaluation - The incremental hazard evaluation is used to determine the inflow design flood. The hazard potential is determined for incrementally larger flood flow conditions until the incremental increase in consequences due to failure is acceptable and it is apparent that a larger flood inflow would not result in an incremental increase in consequences due to failure, or up to a point where the hydrologic event is the probable maximum flood.

Incremental risk - It is the part of risk exclusively due to the dam failure. It is obtained by subtracting from the consequences of the dam failure the ones that would have happened anyway, that is, even if the dam had not failed.

Indirect Economic Consequences - Indirect economic consequences, which are also known as indirect impacts, refer to the changes in the valuation of business output and changes in employment from a failure scenario.

Indirect economic damage - Damage happening after the event as a result of the interruption of the economy and other activities in the area.

Indirect economic effects - Indirect economic effects are the secondary economic effects on regional and local economies that occur because of the direct impacts.

Inflow design flood - The flood flow above which the incremental increase in downstream water surface elevation due to the failure of a dam or other water impounding structure is no longer considered to present an unacceptable threat to downstream life or property. The flood hydrograph used in the design of a dam and its appurtenant works particularly for sizing the spillway and outlet works and for determining maximum storage, the height of the dam, and freeboard requirements.

Influence diagram - The influence diagrams are compact conceptual representations of the logic of a system. On its most generic form, an influence diagram is any representation including the relations between possible events, states of the environment, states of the system or subsystems, and consequences. An influence diagram offers a visual representation of a risk model. Each variable of the system is represented as a node and each relation as a connector or arc.

Intensity - Refers to the attributes of a hazard that causes damage (e.g., water depth and velocity are commonly used measures of the intensity of a flood).

Intolerable risk - A risk that, following understanding of the likelihood and consequences of flooding, is so high that it requires consideration of implementation of treatments or actions to improve understanding, avoid, transfer or reduce the risk.

Inundate - To overflow, to flood.

Inundation map - A map showing areas that may be affected by flooding from an uncontrolled release of a dam's reservoir.

Knowledge uncertainty - Uncertainty arising from imprecision in analysis methods and data.

Level of protection - A measure in years of the average interval between failures of a flood prevention system such as an embankment.

Level pool routing - Reservoir routing that assumes the water surface in the reservoir remains flat.

Life cycle costing - All of the costs associated with the project from the cradle to the grave. This usually includes investigation, design, construction, monitoring, maintenance, asset and performance management and, in some cases, decommissioning of a management measure.

Life-safety - In emergency response, this indicates safety issues that are important for prevention of injury or death for exposed responders or victims.

Likelihood - A qualitative description of probability and frequency.

Likelihood of occurrence - The likelihood that a specified event will occur.

Liquefaction - A condition whereby soil undergoes continued deformation at a constant low residual stress or with low residual resistance, due to the build-up and maintenance of high pour water pressures, which reduces the effective confining pressure to a very low value. Pore pressure build-up leading to liquefaction may be due either to static or cyclic stress applications and the possibility of its occurrence will depend on the void ratio or relative density of a cohesionless soil and the confining pressure.

Loading scenario - To obtain the risk associated with a dam, the calculation is usually disaggregated into various scenarios, depending on the event that originates failure. For instance, a dam may fail when subjected to a flooding or to an earthquake, and it is convenient to do those calculations in a separate way, each situation being called loading scenario.

Local overland flooding - Inundation by local runoff on its way to a waterway, rather than overbank flow from a stream, river, estuary, lake or dam. May be considered synonymous with stormwater flooding.

Lognormal distribution - A two-parameter probability distribution defined by the mean and standard deviation. An asymmetrical distribution applicable to many kinds of data sets where the majority (more than half) of values are less than the mean, but values greater than the mean may be extreme, such as that with streamflow data.

Logistics - Providing resources and other services to support disaster management.

Loss - Any negative consequence or adverse effect, financial or otherwise.

Major disaster - Any natural catastrophe (including cyclone, storm, high water, wind-driven water, tidal wave, tsunami, earthquake, volcanic eruption, landslide, mudslide, snowstorm, or drought) or, regardless of cause, any fire, flood, or explosion, that causes damage of sufficient severity and magnitude to warrant major disaster assistance. Requires efforts and resources of Central, State, and Local governments, as well as private and non-governmental organisations and other disaster relief organisations in alleviating the damage, loss, hardship, or suffering caused.

Major flooding - Major flooding refers to when appreciable urban areas and/or extensive rural areas are flooded. Properties, villages, and towns may be isolated.

Management - Decision making and decision-implementation to direct and coordinate activities to achieve a common goal. This is achieved by establishing objectives, assigning resources to the objectives and defining the parameters within which the resources are to achieve the objectives.

Mathematical and computer models - The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.

Meteorology - The science that deals with the atmosphere and atmospheric phenomena, the study of weather, particularly storms and the rainfall they produce.

Minor flooding - Minor flooding causes inconvenience such as minor roads closures and the submergence of low-level bridges. The lower limit of this class of flooding on the reference gauge may be the initial flood level at which landholders and townspeople begin to be flooded.

Mitigation - All activities that reduce or eliminate the probability of a hazard occurrence, or eliminate or reduce the impact of the hazard in case of its occurrence. Mitigation activities are undertaken during the period prior to an imminent or actual hazard. Once the hazard impact is recognized, subsequent actions are considered response actions and not mitigation.

Moderate flooding - Moderate flooding refers to the inundation of low-lying areas, which requires the stock to be removed and/or some houses to be evacuated. Main traffic routes may be covered.

Monte Carlo analysis - A method that produces a statistical estimate of a quantity by considering many random samples from an assumed probability distribution, such as a normal distribution. The method is used when experimentation is infeasible or when the actual input values are difficult or impossible to obtain.

Natural hazard - Any hazard produced primarily by forces of nature that result in human or property impact of sufficient severity to be deemed an emergency (see definition of an emergency). Natural hazards include hurricane, tornado, storm, flood, high water, wind-driven water, tidal wave, earthquake, drought, fire, infectious disease epidemic, or others.

Natural variability - Uncertainty arising from variations inherent in the behaviour of natural phenomena (e.g., the severity of the maximum flood in a year).

Non-structural measures - Measures that modify the existing and/or future damage susceptibility without modifying the structures associated. Non-structural measures are not designed to directly affect the flow of floodwaters.

Normal distribution - A two-parameter probability distribution defined by the mean and standard deviation. Symmetrical “bell-shaped” curve applicable to many kinds of data sets where values are equally as likely to be greater than and less than the mean. Also called the Gaussian distribution.

Normal reservoir level/Full Reservoir Level - The normal operating water elevation, when storage is at its maximum level (without any flood surcharge).

Normal reservoir storage - Reservoir storage volume when the water surface elevation is at normal reservoir level/Full Reservoir Level.

Notification - Information distributed to relevant personnel, containing important information about an actual or potential hazard impact and its response status. There are generally four categories of notification - update, alert, advisory, and activation.

Objective - The interim steps for achieving a goal.

Objective probability - It is the observed frequency of events that happen randomly. This probability is related to random or natural uncertainty.

One-dimensional hydraulic model - One-dimensional hydraulic modelling considers flow variations in one direction (i.e., the y-direction) at each river cross-section.

One-hundred-year flood - A median flood discharge having a 1 percent chance of being equalled or exceeded in any given year.

Other damages - Related to environmental damage, social disturbing, loss of reputation, attachment to historical or cultural heritage, etc. All of these aspects are difficult to quantify thereby they are usually treated in a qualitative way.

Overtopping failure - A hydrologic dam failure that occurs as a result of the water level in the reservoir exceeding the height of the dam.

Parametric regression equation - Equations that use case study information to estimate time-to-failure and ultimate breach geometry then simulate breach growth as a time-dependent linear process and compute breach outflows using principles of hydraulics.

Peak flow - The maximum instantaneous discharge that occurs during a flood. It is coincident with the peak of a flood hydrograph.

Physically based models - Models that predict the development of an embankment breach and the resulting breach outflows using an erosion model based on principles of hydraulics, sediment transport, and soil mechanics.

Piping failure - Dam failure caused when concentrated seepage develops within an embankment dam and erodes to form a "pipe." Piping typically occurs in two phases: formation of the "pipe" and the subsequent collapse of the dam crest. It is possible for the reservoir to drain before the dam crest collapses.

Plan - A proposed or intended method of progressing from one set of circumstances to another. It provides guidelines and/or directives for the movement from the present situation towards the achievement of one or more objectives or goals.

Predictor regression equations - Equations to empirically estimate peak discharge based on case study data, assuming a reasonable outflow hydrograph shape.

Preparedness - The range of deliberate, critical tasks and activities necessary to build, sustain, and improve the operational capability to prevent, protect against, respond to, and recover from disasters and emergencies. It is a continuous process, which includes all the activities, programs, and systems developed and implemented prior to a disaster/emergency. It involves efforts at all levels of government and between government and private sector and nongovernmental organizations to identify threats, determine vulnerabilities, and identify required resources. It may also comprise the establishment of guidelines, protocols, and standards for planning, training, and exercises, personnel qualification, and certification, equipment certification etc.

Preparedness plans - Plans addressing the preparedness for emergency response and recovery. These comprise training plan, exercise plan, and others. These also include developing, documenting and revising/ refining response and recovery plans and all their components.

Pre-plans - Guidelines that describe processes and procedures, and other response considerations, for specific hazards and/or for specific geographic locations. These may be included in the hazard-specific annexures of the emergency operation plan.

Prevention - Actions to avoid an incident or intervention to stop an incident from occurring. Prevention involves actions to protect lives and property.

Principal spillway - A spillway designed to pass normal flow conditions through a reservoir.

Probability - A statistical measure of the expected chance of flooding. It is the likelihood of a specific outcome, as measured by the ratio of specific outcomes to the total number of possible outcomes. Probability is expressed as a number between zero and unity, zero indicating an impossible outcome and unity indicating an outcome that is certain. Probabilities are commonly expressed in terms of percentage. For example, the probability of 'throwing a six' on a single roll of a die is one in six or 0.167 or 16.7%.

Probability function - A discharge–exceedance or stage–exceedance probability relationship for a reach developed by traditional, site-specific, hydrologic engineering analysis procedures.

Probable loss of life - The probable loss of life due to inundation caused by dam failure and is often determined based on how many habitable structures and roads are located in the inundated area.

Probable maximum flood (PMF) - The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that is possible in the drainage basin under study.

Probable maximum precipitation (PMP) - Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location during a certain time of the year.

Procedure - A series of activities, tasks, steps, decisions, calculations and other processes, when undertaken in the prescribed sequence produces the described result, product or outcome. Following a procedure should produce the same results for the same input conditions.

Process - A defined activity, related to planning and/or implementation, performed to achieve the objectives of the program. Commonly includes multiple linked or coordinated procedures.

Proficiency - Indicates the level of mastery of knowledge, skills, and abilities that are demonstrable on the job and lead to the achievement of objectives.

Program Evaluation - Activity based on collecting information about a program or some aspect of a program in order to make necessary decisions about the program.

Rainfall intensity - The rate at which rain falls, typically measured in millimetres per hour (mm/hour). Rainfall intensity varies throughout a storm in accordance with the temporal pattern of the storm.

Recovery - The development, coordination, and execution of service and site-restoration plans, the reconstitution of government operations and services, individual, private sector, nongovernmental, and public-assistance programs to provide housing and to promote restoration. Also includes long-term care and treatment of affected persons, additional measures for social, political, environmental, and economic restoration, evaluation of the incident to identify lessons learned, post-incident reporting, and development of initiatives to mitigate the effects of future incidents (ICDRM, 2009).

Reliability – Reproducibility, i.e. the achievability of similar conclusions by different evaluators following the same methods of evaluation.

Reservoir - A body of water impounded by a dam and in which water may be stored.

Residual flood risk - The risk a community is exposed to that is not being remedied through established risk treatment processes. In simple terms, for a community, it is the total risk to that community, less any measure in place to reduce that risk. The risk a community is exposed to after treatment measures have been implemented. For a town protected by a levee, the residual flood risk is the consequences of the levee being overtopped by floods larger than the design flood. For an area where flood risk is managed by land-use planning controls, the residual flood risk is the risk associated with the consequences of floods larger than the defined flood event in the community.

Resilience - The capacity for successful recovery from loss and damage. The central features of resilience are access to resources like finance, access to information and services, the capacity to manage personal affairs and the capacity to deal with the stress and emotions generated by the disaster.

Resource management - A system for identifying available resources at all levels of jurisdiction to enable timely and unrestricted access to resources needed to prepare for, respond to, or recover from an incident.

Resources - Personnel and items of equipment, supplies, and facilities available or potentially available for assignment to incident operations. Described by kind and type and may be used in operational support or supervisory capacities.

Response - Activities to address the short-term, direct effects of an incident. Includes immediate actions to save lives, protect property, and meet basic human needs. Also includes the execution of emergency operations plans/mitigation activities designed to limit the loss of life, personal injury, property damage, and other unfavourable outcomes.

Response plans - The guidance describing the intended response to any emergency. It provides guidance to actions required by management and emergency response personnel.

Responsibility - Duty to perform in a specific manner for achieving a defined result. While responsibility may be delegated to another person along with authority, the ultimate responsibility lies with the highest authority.

Return period - The average time interval between occurrences of a hydrological event of a given magnitude or greater, usually expressed in years.

Risk - Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence'. The risk is based on the consideration of the consequences of the full range of flood behaviour on communities and their social settings, and the natural and built environment.

Risk analysis - The systematic use of available information to determine how often specified (flood) events occur and the magnitude of their likely consequences. Flood risk analysis is normally undertaken as part of a floodplain management study and involves an assessment of flood levels and hazard associated with a range of flood events.

Risk assessment - The process of establishing an acceptable level of that risk for an individual, group, society, or the environment.

Risk communication - The process of providing concise, comprehensible, credible information for making effective decisions about risks. Risk communication is considered as a service to those outside the command system, with the objective of influencing behaviour.

Risk evaluation - Risk evaluation is the process of evaluating the importance of the risk associated with the failure of a dam.

The phase of risk evaluation is the point where judgments and values are (implicitly or explicitly) introduced in decision-making by including the notion of risk importance.

Risk management - The systematic application of management policies, procedures, and practices to the tasks of identifying, analysing, assessing, treating and monitoring flood risk. Flood risk management is undertaken as part of a floodplain management plan. The floodplain management plan reflects the adopted means of managing flood risk. Risk management, a subsection of overall emergency management, focuses upon mitigation preparedness activities that prevent and or reduce hazard impacts.

Risk of failure - It is the part of total risk due to the dam break.

Risk of non-failure - It concerns the situations of downstream flooding when the dam has not failed.

Risk reduction - Long-term measures to reduce the magnitude/scale/duration of adverse effects due to disaster hazards on a society at risk. Maybe through bringing about the reduction of the vulnerability of its people, structures, services, and economic activities to the impact of disaster hazards. Typical measures may include improved building standards, floodplain zoning and land-use planning, crop diversification etc. May be classified into structural and non-structural measures. Disaster mitigation and disaster prevention have also been used as alternatives.

Riverine flooding - Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam. Riverine flooding generally excludes watercourses constructed with pipes or artificial channels considered as storm water channels.

Routing - A mathematical procedure for predicting characteristics of a flood wave (such as velocity, Froude number, height, discharge, etc.) as a function of time at one or more points along a waterway or channel from that at some upstream location.

Runoff - The amount of rainfall that drains into the surface drainage network to become stream flow; also known as rainfall excess.

Safety - Refers to monitoring and reducing the risk of personnel casualties (i.e., injuries and deaths) to some acceptable level.

Scenario-based planning - Approach to assess the impact of various threats using a hazard vulnerability assessment. The threats turned out to be the basis of the scenario.

Screening analysis - Screening analysis is a semi-quantitative analysis based on risk principles. Screening analysis is usually applied to a portfolio of dams. This analysis, instead of estimating each of the probabilities considered in the risk equation, assigns risk indices based on the available information and provides, in the end, a risk index for each of the studied dams. This methodology is useful to do a preliminary ordering of the dams according to their importance in terms of safety, thus helping to determine how to focus ulterior efforts.

Security - Security in the traditional sense refers to monitoring and reducing the risk of human-induced events that adversely affect people or property (intrusion of unauthorized personnel, theft, sabotage, assault, etc.), to some acceptable level.

Seismic failure - Dam failure caused by earth movements such as earthquakes.

Sensitivity analysis - An analysis in which the relative importance of one or more of the variables thought to have an influence on the phenomenon under consideration is determined.

Severe weather - Any atmospheric condition that may be destructive or hazardous to human beings. Often associated with cyclones, severe thunderstorms, squalls, blizzard etc. and with storms of freezing precipitation or conditions.

Simulation - The process of analysing and evaluating the severity and consequences of any event or process. In recent times, mostly used to refer to modelling exercises on the computer.

Skewness coefficient - A statistical term used as a measure of the symmetry of the statistical distribution of the data. It is the third moment of a distribution. It is estimated as the number of values times the sum of the cubes of the deviations from the mean divided by the number of values minus 1, times the number of values times 2, times the standard deviation cubed.

Spillway - A dam structure that allows water to discharge from a reservoir when the water level exceeds the top of the spillway (for un-gated spillways) and when it approaches or reaches the full reservoir level (for gated spillway).

Stage - Equivalent to water level. Both stage and water level are measured with reference to a specified datum.

Stage associated with the 1-percent chance flood discharge - The stage obtained from the stage-discharge curve that corresponds to a discharge taken from the discharge–probability curve of 1 percent.

Stage-damage function - Relationship of the depth of water to damage at a structure. Damage is normally specified as a percentage of the structure or content value. The functions are generic for similar structures and are not tied to the structure location.

Stage-damage functions with uncertainty - Stage–damage functions with uncertainty are computed at each structure and aggregated by damage category to damage reach index locations. The stage is elevation or locally referenced stage associated with the structure and index location. Damage is the median estimate of structure, content, and other inundation reduction damage associated with the stage of floodwaters at the location. Uncertainty in the stage–damage function arises from errors in estimating the depth–damage function, first-floor stage, structure value, and content-to-structure-value ratio.

Stage-discharge function - A graphical relationship that yields the stage for a given discharge at a specific location on a stream or river. Referred to as a rating function or curve. These relationships are usually developed by computing water surface profiles for several discharges and plotting the stages vs. discharge relationship at a specific stream location.

Stage-discharge functions with uncertainty - Relationship of the water surface stage and discharge. Uncertainty is the distribution of the errors of stage estimates about a specific discharge.

Standard deviation - A statistical measure of the spread of a distribution around the mean.

Steady flow - All fluid flow properties such as velocity, temperature, pressure, and density are independent of time.

Storm surge - The increases in coastal water levels above predicted astronomical tide level (i.e. tidal anomaly) resulting from a range of location dependent factors including the inverted barometer effect, wind and wave set-up and astronomical tidal waves, together with any other factors that increase the tidal water level.

Stormwater flooding - Is inundation by local runoff caused by heavier than usual rainfall. It may be caused by local runoff exceeding the capacity of an urban stormwater drainage systems, flow overland on the way to waterways or by the backwater effects of mainstream flooding causing urban stormwater drainage systems to overflow.

Structural failure - Dam failure caused by the failure of the main embankment or appurtenant structure.

Structural measures – The measures designed to modify the flow of floodwaters. Measures such as raising, relocating, flood proofing and other actions associated with dam appurtenances and other structures and damageable property that modify the existing and/or future damage susceptibility.

Subjective probability - It is the degree of confidence in a result based on the available information. This probability is related to epistemological uncertainty.

Sunny day breach - A dam breach that is not associated with a hydrologic event.

Sustainable communities - Used to encompass a strategy that considers resource limitations and minimises hazard risk while developing human habitations.

Sustainable development - Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Refers to creating places that are less vulnerable to hazards and are resilient to the events. Sustainable hazard management comprises environmental quality; quality of life; disaster resilience; economic vitality; and inter- and intragenerational equity. Reducing the risk due to hazards and losses due to disasters, and working toward sustainable communities go together.

System - A functional structure to establish coordination amongst different components for achieving a common objective. Involves processes that are clearly described.

Systems approach - A strategy, which recognises that different elements must be inter-related components of a single system. Employs specific methods to achieve and maintain the overarching system. Includes the use of standardized structure, processes, knowledge, and concepts.

Task - A clearly defined and measurable activity. The smallest component of a job.

The task force - Combination of resources brought together to support a specific mission or operation. All the elements within a task force must have communications amongst themselves and a designated leader.

Team - A group of personnel who work as a unit for accomplishing assigned tasks.

Technical assistance - Support provided to States, and local governments/ organisations who have the resources but lack the complete knowledge and skills needed to perform a difficult activity.

Temporal pattern - The variation of rainfall intensity with time during a rainfall event.

Threat - An indication of likely harm/ danger, like the possibility of a hazard occurrence. Anything with the potential to cause harm.

Tolerable risk - A tolerable risk is one, which the society is ready to live with, in exchange for certain benefits as compensation. This risk is not considered negligible and therefore cannot be ignored. It has to be managed, periodically reviewed and reduced if possible.

Tools - Instruments and capabilities that allow tasks to be carried out in a professional way. Includes information systems, agreements, policies, legislative authorities etc.

Topographic map - A detailed graphic representation of natural and man-made features of a region with particular emphasis on relative position and elevation.

Total risk - It is the total risk of flooding downstream of the dam. It is produced by both the cases in which the dam fails and the ones it does not.

Training - Training is an instruction that imparts skills necessary for individuals and teams to perform their assigned responsibilities in a better way. The objectives of training should be based on competency levels. Training should attempt to address the development of skills that would be able to function under the conditions that are likely when it would be called for.

Treatment options - The measures that might be feasible for the treatment of existing, future and residual flood risk at particular locations within the floodplain. Preparation of a treatment plan requires a detailed evaluation of floodplain management options.

Tributary - A stream that flows into a larger stream or body of water.

Two-dimensional hydraulic model - Two-dimensional hydraulic modeling considers flow variations in two directions (i.e., the x- and y-direction) at each river cross-section.

Unacceptable risk - An unacceptable risk is one that cannot be accepted by society, whatever the benefits it might bring.

Uncertainty - The process of Risk Analysis incorporates a series of uncertainties that have a relevant impact in the understanding and interpretation of the probability results of the model. The term uncertainty encompasses mainly two concepts of the different essence: natural variability and epistemological uncertainty.

Unit - The group with functional responsibility for planning, logistics, or finance/ administration of a specific incident.

Unit hydrograph - A hydrograph with a volume of one centimetre of direct runoff resulting from a storm of a specified duration and areal distribution. Hydrographs from other storms of the same duration and distribution are assumed to have the same time base but with ordinates of flow in proportion to the runoff volumes.

Unsteady flow - All fluid flow properties such as velocity, temperature, pressure, and density are a function of time.

Update - A notification category for providing information about non-urgent emergency management.

The velocity of floodwater - The speed of floodwaters, measured in metres per second (m/s).

Vulnerability - The degree of susceptibility and resilience of a community, it's social setting, and the natural and built environments to flood hazards. The vulnerability is assessed in terms of the ability of the community and environment to anticipate, cope and recover from flood events. Flood awareness is an important indicator of vulnerability.

Vulnerability Analysis - The process of estimating the vulnerability of specified elements at risk to probable disaster hazards. Involves the analysis of theoretical and empirical data about the effects of particular phenomena on particular types of structures. Also involves consideration of all significant components of a society, with their physical, social and economic considerations, and the extent to which essential services are able to continue functioning.

Vulnerability Assessment - Presents the possible extent of injury and damage resulting from a hazard event of a given intensity in a given area. Should also address the impacts of hazard events on the existing and future built environment.

Warning - Dissemination of notification message signalling imminent hazard that may include advice on protective measures (e.g., warning issued by the IMD for fishermen cautioning them not to venture out into the sea when a cyclone is expected).

Warning time - With enough time, the inhabitants of the flooded area may organize their belongings and move them to higher places or away from the affected areas. In general, warning time is defined as the time elapsed between the moment the population finds out about the arriving flood (on many occasions this moment is made equal to the instant the dam fails) and the moment the flood wave reaches the first person of the population at risk.

Water speed - The dynamics of water movement may cause failures to the structures if the combination of speed and depth exceed the design maximum load.

Appendix B. SAMPLE CALCULATIONS FOR DAM BREACH PARAMETERS

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DAM BEACH CALCULATION EXAMPLES

Example Application No.1 - Embankment Dam Breach

A dam break analysis needs to be prepared for a 40 meters high and 1,800-metre long earth-fill embankment dam. The embankment longitudinal and cross sections, along with a schematic plan view are shown in Figures B-1, B-2 and B-3. Inundation areas need to be mapped for dam-breach floods caused by both a "fair-weather failure" (that is when the breach caused by internal erosion when full reservoir level (FRL) conditions exist), and for a failure produced by overtopping during a probable maximum flood (PMF). The critical water depth on the embankment dam crest at which a breach caused by overtopping begins is $H_c = 0.6$ m. Reservoir elevation/storage volume data is given in Table B-1. Determine the following parameters of a trapezoidal breach for each failure condition using the Froehlich (2017a) regression equation:

$\hat{B}_{avg}$ = Expected average width of the final breach in meters (m)

$\widehat{m}$ = Expected trapezoidal breach side-slope ratio (horizontal to vertical)

$\hat{t}_f$ = Expected breach formation time in seconds (seg.)

Also, determine the expected peak outflow from the breach using the Froehlich (2016) equation for gradually breached embankment dams.

Table B-1: Reservoir Elevation-Capacity

Elevation (m)	Storage Volume (Mm^3)
0	0
5	9
10	60
15	177
20	374
25	659
30	1044
35	1551
36	1670
37	1796
38	1930
39	2071
40	2222
41	2381
42	2550

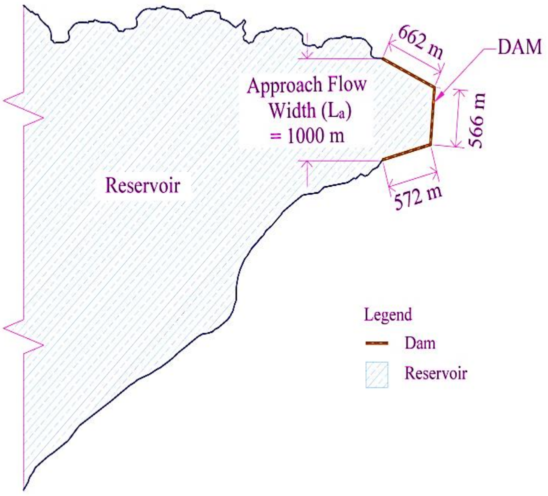

Figure B-1 Scheme Plan View for the Example Dam

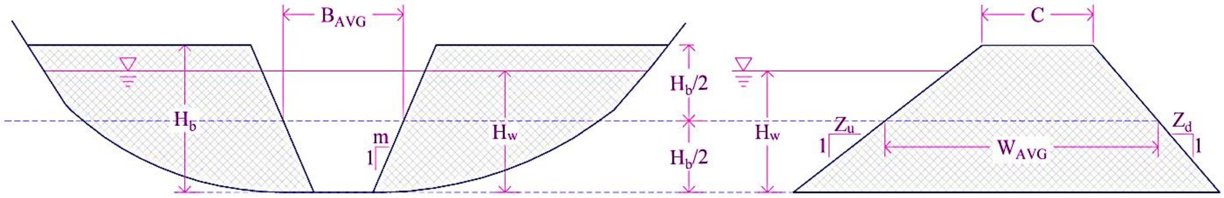

Figure B-2 Breach Variable Definition Sketch

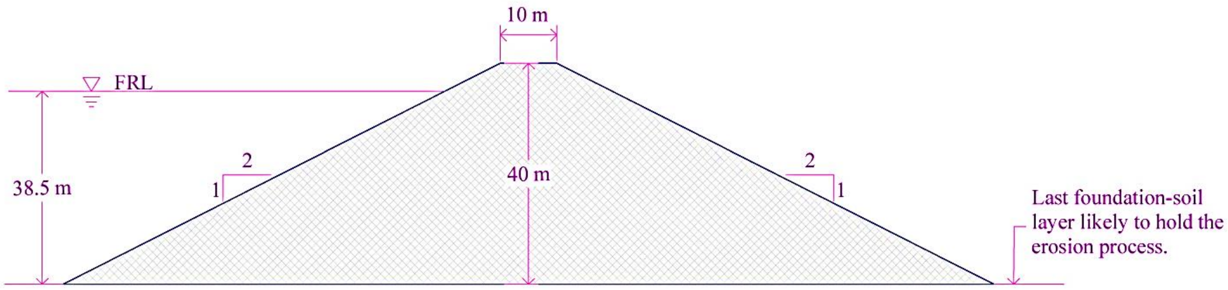

Figure B-3 Cross Section for Example Application No.1. Embankment Dam Breach

Calculating $\widehat{\mathrm{B}}_{\mathrm{avg}}$

$$\widehat{\mathrm{B}}_{\mathrm{avg}}=0.23\times \mathrm{k}_{\mathrm{M}}\times \mathrm{V}_{\mathrm{W}}^{1/3}$$

Where,

$$\mathrm{k}_{\mathrm{M}}=\begin{cases}1.0, \text{ for internal erosion failures}\\ 1.5, \text{ for overtopping failures}\end{cases}$$

V_{W} = Volume of water above breach bottom in cubic meters (m^3)

-For internal erosion failure (Fair-weather failure):

$$\widehat{\mathrm{B}}_{\mathrm{avg}}=0.23\times(1.0)\times(2{,}000{,}500{,}000.00)^{\frac{1}{3}}$$

$$\therefore \widehat{\mathrm{B}}_{\mathrm{avg}}=290\ \mathrm{m}$$

-For overtopping failure (critical depth = 0.6 m. above dam crest):

$$\widehat{\mathrm{B}}_{\mathrm{avg}}=0.23\times(1.5)\times(2{,}482{,}400{,}000.00)^{\frac{1}{3}}$$

$$\therefore \widehat{\mathrm{B}}_{\mathrm{avg}}=405\ \mathrm{m}$$

Calculating $\widehat{m}$

-For internal erosion failure (Fair-weather failure):

$$\therefore \widehat{\mathrm{m}} = 0.6$$

-For overtopping failure (critical depth = 0.6 m. above dam crest):

$$\therefore \widehat{\mathrm{m}} = 1.0$$

Calculating $\hat{t}_f$

$$\hat{\mathrm{t}}_{\mathrm{f}}=60\times\sqrt{\frac{\mathrm{V_W}}{\mathrm{gH_b^2}}}$$

Where,

V_W = Volume of water above the breach bottom in cubic meters (m^3)

H_b = Height of breach in meters (m)

-For internal erosion failure (Fair-weather failure):

$$\hat{\mathrm{t}}_{\mathrm{f}}=60\times\sqrt{\frac{2{,}000{,}500{,}000.00}{(9.807)(40)^2}}$$

$$\hat{\mathrm{t}}_{\mathrm{f}}=21{,}420.32 \text{ seg.}$$

$$\therefore \hat{\mathrm{t}}_{\mathrm{f}}= 5.95 \text{ hr.}$$

-For overtopping failure (critical depth = 0.6 m. above dam crest):

$$\hat{\mathrm{t}}_{\mathrm{f}}=60\times\sqrt{\frac{2{,}482{,}400{,}000.00}{(9.807)(40)^2}}$$

$$\hat{\mathrm{t}}_{\mathrm{f}}=23{,}861.22 \text{ seg.}$$

$$\therefore \hat{\mathrm{t}}_{\mathrm{f}}= 6.63 \text{ hr.}$$

Calculating expected peak discharge ($\widehat{Q}_P$)

$$\widehat{\mathrm{Q}}_{\mathrm{P}}=0.0175\times\mathrm{k_M}\times\mathrm{k_H}\times\sqrt{\frac{\mathrm{gV_WH_WH_b^2}}{\mathrm{W_{avg}}}} \quad (\mathit{empirical\ equation})$$

$$\widehat{Q}_P = Q_{P_{max}} \times \left(\frac{1}{1+\alpha \times t_f \sqrt{\frac{g}{H_b}}} \right)^{\beta} \quad (semi - theoretical\ equation)$$

$$Q_{P_{max}} = \begin{cases} \frac{8}{27}\left(\frac{L_a}{B_{avg}}\right)^{0.28} \left[B_{avg} - m\left(H_b - \frac{4}{5}H_W\right)\right] \sqrt{gH_W^3}, & \text{for } H_W \le H_b \\ \frac{8}{27}\left(\frac{L_a}{B_{avg}}\right)^{0.28} \left\{\left(B_{avg} - mH_b\right) - \frac{4}{5} mH_W \left[\left(1 - \frac{H_b}{H_W}\right)^{5/2} - 1\right]\right\} \sqrt{gH_W^3}, & \text{for } H_W > H_b \end{cases}$$

Where,

$\widehat{Q}_P$ = expected peak discharge in m³/s

$Q_{P_{max}}$ = maximum possible peak discharge from a breach of specified dimensions that forms instantly

$\alpha = 0.000045$

$\beta = 500 \times \left[\left(W_{avg} \times H_b^2\right) / V_W\right]^{2/3}$

W_{avg} =average width of embankment above breach bottom

L_a= approach flow width

$$k_M = \begin{cases} 1, \text{ for non-overtopping failure modes} \\ 1.85, \text{ for overtopping failure modes} \end{cases}$$

$$k_H = \begin{cases} 1, \text{ for } H_b \le H_S \\ \left(\frac{H_b}{H_S}\right)^{1/8} \text{ for } H_b > H_S \end{cases}$$

$$H_s = \begin{cases} 6.1 \text{ m. (for SI units)} \\ 20 \text{ ft. (for U.S. customary units)} \end{cases}$$

-For internal erosion failure (Fair-weather failure):

$$Q_{P_{max}} = \frac{8}{27}\left(\frac{L_a}{B_{avg}}\right)^{0.28} \left[B_{avg} - m\left(H_b - \frac{4}{5}H_W\right)\right] \sqrt{gH_W^3}$$

$$Q_{P_{max}} = \frac{8}{27}\left(\frac{1{,}000}{290}\right)^{0.28} \left[290 - 0.6\left(40 - \frac{4}{5}(38.5)\right)\right] \sqrt{(9.807)(38.5)^3}$$

$$\therefore\ Q_{P_{max}} = 89{,}149\ {}^{m^3}/_{s}$$

a. Using Empirical Equation:

$$\widehat{Q}_P = 0.0175 \times k_M \times k_H \times \sqrt{\frac{g V_W H_W H_b^2}{W_{avg}}} \quad (\mathit{empirical\ equation})$$

$$\widehat{Q}_P = 0.0175 \times (1.0) \times \left(\frac{40}{6.1}\right)^{1/8} \times \sqrt{\frac{(9.807) \times (2{,}000{,}500{,}000.00) \times (38.5) \times (40)^2}{90}}$$

$$\therefore \widehat{Q}_P = 81{,}134 \quad {m^3}/{s}$$

b. Using Semi-theoretical Equation:

$$\widehat{Q}_P = Q_{P_{max}} \times \left(\frac{1}{1 + \alpha \times t_f \sqrt{\frac{g}{H_b}}}\right)^{\beta} \quad (\mathit{semi-theoretical\ equation})$$

$$\widehat{Q}_P = (89{,}149) \times \left(\frac{1}{1 + 0.000045 \times (21{,}420.32)\sqrt{\frac{9.807}{40}}}\right)^{500 \times \left[\frac{(90) \times (40)^2}{(2{,}000{,}500{,}000.00)}\right]^{2/3}}$$

$$\therefore \widehat{Q}_P = 63{,}603 \quad {\mathrm{m}^3}/{s}$$

c. Final considerations in regard peak discharge expected values:

Special care should always be taken when applying a mathematical model to dams whose characteristics are outside the range of those used to develop the empirical equation. Analyzing the data set of historical failures used by Froehlich (2016) to develop his empirical equation (Table B-2), it can be seen that the expected value of $\widehat{Q}_p$ obtained from the empirical approach (i.e. 81,134 m3/s) is outside the range of applicability. Therefore, in this example, the value obtained from the semi-theoretical equation (i.e. 63,603 m3/s), which results are bounded by the potential maximum flow that would be produced by the instant formation of a breach, is more reliable and applicable to the data set used in this example.

Table B-2: The range of Variables in Dam Break Peak Discharge Data Set. (Froehlich, 2016)

Variable	Notation	Min.	Max.
Average Embankment Width (m)	Wavg	9.63	250
Volume above breach Bottom (Mm3)	Vw	0.0133	701
Height Water (m)	Hw	1.68	77.4
Height Breach (m)	Hb	3.66	86.9
Approach flow Width (m)	La	40	4100
Measured Peak Discharge (m^3/s)	$\widehat{Q}_p$	30	65,120

-For overtopping failure (critical depth = 0.6 m. above dam crest):

$$Q_{P_{max}}=\frac{8}{27}\left(\frac{L_a}{B_{avg}}\right)^{0.28}\left\{\left(B_{avg}\text{-}mH_b\right)\text{-}\frac{4}{5}mH_W\left[\left(1\text{-}\frac{H_b}{H_W}\right)^{5/2}\text{-}1\right]\right\}\sqrt{gH_W^3}$$

$$Q_{P_{max}}=\frac{8}{27}\left(\frac{1{,}000}{405}\right)^{0.28}\left\{(405-1.0\times 40)-\left(\frac{4}{5}\times 1.0\times 40.6\right)\times\cdots\right.$$

$$\left.\times\left[\left(1-\frac{40}{40.6}\right)^{5/2}-1\right]\right\}\sqrt{(9.807)(40.6)^3}$$

$$\therefore\ Q_{P_{max}}=122{,}874\ {}^{m^3}\!/_{s}$$

Using Semi-theoretical Equation:

Only the semi-theoretical approach will be used for the reasons explained in fair-weather failure calculation in regard to data range applicability.

$$\widehat{Q}_P=Q_{P_{max}}\times\left(\frac{1}{1+\alpha\times t_f\sqrt{\frac{g}{H_b}}}\right)^{\beta}\quad(semi-theoretical\ equation)$$

$$\widehat{Q}_P=(122{,}874)\times\left(\frac{1}{1+0.000045\times(23{,}861.22)\sqrt{\frac{9.807}{40}}}\right)^{500\times\left[\frac{(90)\times(40)^2}{(2{,}482{,}400{,}000.00)}\right]^{2/3}}$$

$$\therefore\ \widehat{Q}_P=89{,}270\ {}^{m^3}\!/_{s}$$

Example Application No.2 - Concrete/Masonry Dam Breach

A fair-weather (failure at FRL) dam breach flood inundation map needs to be prepared for the 1700 meter long masonry gravity dam shown in Figure B-3 as part of the Emergency Action Plan (EAP). Attributes of the dam are given in Table B-3. Determine the following parameters of a trapezoidal breach for each failure condition using the Froehlich (2017b) regression equation:

$\hat{B}_{avg}$ = Expected average width of the final breach in meters (m)

$\widehat{m}$ = Expected trapezoidal breach side-slope ratio (horizontal to vertical)

$\hat{t}_f$ = Expected breach formation time in seconds (seg.)

Also, determine the expected peak outflow from the breach using the Froehlich (2016) semi-theoretical equation ($Q_{P_{max}}$) to obtain the peak envelope discharge (i.e maximum bound) that can be expected from the breach.

Table B-3: Attributes of the Example Dam

Dam Attribute	Value
Dam Type	Masonry Gravity
Year Completed	1934
Purpose	Hydropower & Irrigation
Height (H_d)	40 m.
Height of Breach ($H_{b)}$	40 m. (entire dam height)
Approach Flow Width (L_a)	1200 m (~70% dam length)
Height of Water at FRL (H_w)	38.5 m
Volume of Water at FRL (V_w)	2,640 Mm^3

Figure B-3: 1700 m long Masonry Gravity Dam

Calculating $\widehat{\mathrm{B}}_{\mathrm{avg}}$

$$\widehat{\mathrm{B}}_{\mathrm{avg}}=0.12\times 1.5^{\mathrm{Type}}\times\left(\frac{\mathrm{V_W}}{\mathrm{H_b^3}}\right)^{1/4}\times\left(\frac{L_a}{\mathrm{H_b}}\right)^{2/3}\times\mathrm{H_b}$$

Where,

$\widehat{B}_{avg}$ = Expected average width of the final breach in meters (m)

$$\mathrm{Type}=\begin{cases}1, \text{ for concrete dams}\\0, \text{ for masonry dams}\end{cases}$$

$\mathrm{V_W}$ = Volume of water above the breach bottom in cubic meters (m^3)

$\mathrm{H_b}$ = Height of breach in meters (m)

$\mathrm{L_a}$= approach flow width

$$\widehat{\mathrm{B}}_{\mathrm{avg}}=0.12\times 1.5^{(0.0)}\times\left(\frac{\mathrm{V_W}}{\mathrm{H_b^3}}\right)^{1/4}\times\left(\frac{L_a}{\mathrm{H_b}}\right)^{2/3}\times\mathrm{H_b}$$

$$\widehat{\mathrm{B}}_{\mathrm{avg}}=0.12\times 1.5^{0.0}\times\left(\frac{2{,}640{,}000{,}000.00}{40^3}\right)^{1/4}\times\left(\frac{1{,}200}{40}\right)^{2/3}\times 40$$

$$\therefore\ \widehat{\mathrm{B}}_{\mathrm{avg}}=660\ \mathrm{m}$$

Calculating $\widehat{\mathrm{m}}$

For concrete/masonry gravity dams the breach side slope ratio is assumed to equal to 0: 1 (vertical), considering the structural characteristics of this type of dams.

$$\therefore\ \widehat{\mathrm{m}}=0$$

Calculating $\hat{\mathrm{t}}_{\mathrm{f}}$

For concrete/masonry gravity dams the breach formation time is assumed between the range 0.1-0.5 hours

$$\therefore\ \hat{\mathrm{t}}_{\mathrm{f}}=0.30\ \mathrm{hr.}$$

Calculating peak envelope discharge ($\mathbf{Q}_{\mathbf{P}_{\mathbf{max}}}$)

$$\mathrm{Q}_{\mathrm{P_{max}}}=\frac{8}{27}\left(\frac{\mathrm{L_a}}{\mathrm{B_{avg}}}\right)^{0.28}\left[\mathrm{B_{avg}}-\mathrm{m}\left(\mathrm{H_b}-\frac{4}{5}\mathrm{H_W}\right)\right]\sqrt{\mathrm{gH_W^3}}$$

$$\mathrm{Q}_{\mathrm{P_{max}}}=\frac{8}{27}\left(\frac{1200}{660}\right)^{0.28}\left[660-0.0\left(40-\frac{4}{5}38.5\right)\right]\sqrt{(9.807)(38.5)^3}$$

$$\therefore Q_{P_{max}} = 172{,}979 \ ^{m^3}/_{s}$$

Final consideration in regard peak envelope discharge value:
$Q_{P_{max}}$ represents the peak discharge produced by an instantaneous breach ($\hat{t}_f \sim 0$), therefore a slightly lower value should be expected for a concrete/masonry gravity dam-breach, considering the attenuation effect of the breach formation process itself in this type of dams ($0.10 \leq \hat{t}_f \leq 0.50$ hr)

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Appendix C. A FEW OTHER EQUATIONS COMMONLY USED FOR ESTIMATION OF BREACH PARAMETERS FOR EMBANKMENT DAMS

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A FEW EQUATIONS FOR ESTIMATING DAM BREACH

Following USACE (2014), the following regression equations that have been used for several dam safety studies in the literature are presented here:

1. Froehlich (2008)
2. MacDonald and Langridge-Monopolis (1984)
3. Von Thun and Gillette (1990)
4. Xu and Zhang (2009)

Froehlich (2008)

These equations, based on regression analysis of data sets from 74 earthen, zoned earthen, earthen with a core wall (i.e., clay), and rock fill dams predict average breach width, side slopes, and failure time. The equations for average breach width and failure time are:

$$B_{ave}=0.27K_oV_w^{0.32}h_b^{0.04}$$

$$t_f=63.2\sqrt{\frac{V_w}{gh_b^2}}$$

Where,

B_{ave} = average breach width (meters)

K_o = constant (1.3 for overtopping failures, 1.0 for piping)

V_w = reservoir volume at time of failure (cubic meters)

h_b = height of the final breach (meters)

g = gravitational acceleration (9.80665 meters per second squared)

t_f = breach formation time (seconds)

The average side slopes should be:

1.0 H: IV for overtopping failures

0.7 H: 1V otherwise (i.e., piping/seepage)

The height of the breach is considered as the height between the top of the dam and the natural ground elevation at the breach location.

MacDonald and Langridge-Monopolis (1984)

Their equations, based on regression analysis of 42 data sets (predominantly earth fill dams, earth fill dams with a clay core, rock fill dams) relate the volume of material eroded and breach formation time to the volume of water that passes through the breach. The equations are:

For earth fill dams:

$$V_{eroded}=0.0261(V_{out}\times h_w)^{0.769}$$

$$t_f=0.0179(V_{eroded})^{0.364}$$

For earth fill dams with clay core or rock fill dams:

$$V_{eroded}=0.00348(V_{out}\times h_w)^{0.852}$$

Where,

V_{eroded} =volume of material eroded from the dam embankment (cubic meters)

V_{out} = volume of water that passes through the breach (cubic meters) [storage volume at time of breach plus volume of inflow after breach begins, minus any spillway and gate flow after breach begins]

h_w =depth of water above the bottom of the breach (meters),

t_f =breach formation time (hours).

The breach is considered to be trapezoidal with side slopes of 0.5H: IV.

The base width of the breach may be computed from the dam geometry as:

$$W_b = \frac{V_{eroded} - h_b^2 (CZ_b + h_b Z_b Z_3/3)}{(C + h_b Z_3/2)}$$

Where,

W_b = bottom width of the breach (meters)

h_b = height from the top of the dam to bottom of breach (meters)

C = crest width of the top of dam (meters)

Z_3 = $Z_1 + Z_2$

Z_1 = average slope (Z_1: 1) of the upstream face of dam

Z_2 = average slope (Z_2:1) of the downstream face of dam

Z_b = side slopes of the breach (Z_b: 1), 0.5 for the MacDonald method

Von Thun and Gillette (1990)

These equations, based on regression analysis of 57 data sets, propose to use breach side slopes of 1.0H: 1.0V, except for dams with cohesive soils, where side slopes should be of the order of 0.5H: 1V to 0.33H: 1V. The equation for average breach width is:

$$B_{ave} = 2.5 h_w + C_b$$

Where,

B_{ave} = average breach width (meters)

h_w = depth of water above the bottom of the breach (meters)

C_b = coefficient, a function of reservoir size [see table C-1 below]

Table C-1: Suggested Values of C_b

Reservoir Size (cubic meters)	C_b (meters)
$< 1.23 \times 10^6$	6.1
1.23×10^6 - 6.17×10^6	18.3
6.17×10^6 -1.23×10^7	42.7
$> 1.23 \times 10^7$	54.9

Equations showing breach development time as a function of water depth above the breach bottom:

For erosion resistant materials

$$t_f=0.02h_w+0.25$$

For easily erodible materials

$$t_f=0.015h_w$$

Where,

t_f = breach formation time (hours)

h_w = depth of water above the bottom of the breach (meters)

Equations showing breach development time as a function of water depth above the bottom of the breach and average breach width:

For erosion resistant materials

$$t_f=\frac{B_{ave}}{4h_w}$$

For easily erodible materials

$$t_f=\frac{B_{ave}}{4h_w+61.0}$$

Where,

B_{ave} = average breach width (meters)

The limits of erosion resistant and easily erodible materials are suggested to be the upper and lower bounds corresponding respectively to well-constructed dams of erosion resistant materials and poorly constructed dams of easily eroded materials.

Xu and Zhang (2009)

Their equations are based on regression analysis of 45 data sets from homogeneous earth fill, zoned-filled, dams with core walls, and concrete faced dams for the average breach width and 28 data sets for time of failure. The equation for average breach width is:

$$\frac{B_{ave}}{h_b}=0.787\left(\frac{h_d}{h_r}\right)^{0.133}\left(\frac{V_w^{1/3}}{h_w}\right)^{0.652}e^{B_3}$$

Where,

B_{ave} = average breach width (meters)

V_w = reservoir volume at time of failure (cubic meters)

h_b = height of the final breach (meters)

h_d = height of the Dam (meters)

h_r = fifteen meters, considered as reference height for distinguishing large dams from small dams

h_w = height of the water above the breach bottom elevation at time of breach (metres)

B_3 = $b_3+b_4+b_5$ coefficient that is a function of dam properties

b_3 = -0.041, 0.026, and -0.226 for dams with corewalls, concrete faced dams, and homogeneous/zoned-fill dams, respectively

b_4 = 0.149 and -0.389 for overtopping and seepage/piping, respectively,

b_5 = 0.291, -0.14, and -0.391 for high, medium, and low dam credibility, respectively

It is suggested to assume the breach height goes from the top of the dam all the way down to the natural ground elevation at the breach location (i.e., h_b = h_d).

The equation to estimate the top width of the breach, which can then be used with the average breach width, to compute the corresponding side slopes is:

$$\frac{B_t}{h_b}=1.062\left(\frac{h_d}{h_r}\right)^{0.092}\left(\frac{V_w^{1/3}}{h_w}\right)^{0.508}e^{B_2}$$

Where,

B_t = breach top width (meters)

B_2 = $b_3+b_4+b_5$, a coefficient that is a function of dam properties

b_3 = 0.061, 0.088, and -0.089 for dams with core walls, concrete faced dams, and homogeneous/zoned-fill dams, respectively.

b_4 = 0.299 and -0.239 for overtopping and seepage/piping, respectively.

b_5 = 0.411, -0.062, and -0.289 for high, medium, and low dam erodibility, respectively.

Breach side slopes may be computed using the following equation:

$$Z=\frac{B_t\text{-}B_{ave}}{h_b}$$

The equation for breach development time is:

$$\frac{T_f}{T_r}=0.304\left(\frac{h_d}{h_r}\right)^{0.707}\left(\frac{V_w^{1/3}}{h_w}\right)^{1.228}e^{B_5}$$

Where,

T_f = breach formation time (hours)

T_r = 1 hour (unit duration)

V_w = reservoir volume at time of failure (cubic meters)

h_d = height of the dam (meters)

h_r = fifteen meters, which is considered to be a reference height for distinguishing large dams from small dams

h_w = height of the water above the breach bottom elevation at time of breach (meters)

B_5 = $b_3+b_4+b_5$, a coefficient that is a function of dam properties

b_3 = -0.327, -0.674, and -0.189 for dams with core walls, concrete faced dams, and homogeneous/zoned-fill dams, respectively

b_4 = -0.579 and-0.611 for overtopping and seepage/piping, respectively

b_5 = -1.205, -0.564, and 0.579 for high, medium, and low dam erodibility, respectively

The Xu and Zhang equation for breach development time should not be used in HEC-RAS as it estimates breach development times that are greater than what is generally used in HEC-RAS for the critical breach development time due to the fact that their breach time includes more of the initial erosion period and post erosion period.

Appendix D. FRAMEWORK OF A SAMPLE REPORT ON MAPPING FLOOD RISKS ASSOCIATED WITH DAMS

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RECOMMENDED TABLE OF CONTENTS FOR A DAM BREAK ANALYSIS REPORT

- Abstract
- Introduction
- Purpose and Scope
- Description of the Dam/Reservoir System
- Dam-Breach Analysis
  - Model Selection
  - Dam Breach Scenarios
  - Study Area Boundaries
  - Data Inputs for the Hydraulic Model
    - Elevation Data (DEM, DSM, DTM)
    - Land Cover/Use Data
    - Topographic and Bathymetric Data
    - Additional Surveys
    - Population Density
    - Hydraulic Data
    - Hydrologic Data
  - Model Development
    - Grid/Mesh Resolution
    - Roughness Coefficients
    - Flow and Boundary Conditions
    - Dam-Breach Parameters
    - Calibration and Sensitivity Analysis
    - Computational Aspects
    - Peak Discharge Validation
  - Results
    - Output Hydrographs
    - Flood Hazard/Vulnerability Reference Values
    - Population at Risk (PAR)
    - Potential Loss of Life (PLL)
- Flood-Inundation Mapping
- Sources of Uncertainty in Flood-Inundation Maps
  - Topographic Uncertainties
  - Manning's n-Value Uncertainties
  - Dam breach Parameters Uncertainty
  - Model Limitations
- Summary and Conclusions
- References
- Appendices
- Appendix A. - Inundation Maps

Abstract

The abstract may convey the main results and conclusions of the dam break analysis but the entire report must be consulted for details of the methodology, the full results, and a critical discussion of the interpretations and conclusions.

Introduction

This section should describe in general terms the study framework, explaining the basic facts and background of the entire study. Also, it should give an idea of the current state-of-the-art in the field of inundation mapping and dam break analysis. In general, the following three aspects should be included in this section: background, description of the problem, and the proposed approach to the solution.

Purpose and Scope

This chapter should indicate the detailed accomplishments and outputs to be expected after the finalisation of the dam break analysis. It should mention all the deliverables along with all the exclusions or aspects which the study will not accomplish or deliver.

Description of the Dam/Reservoir System

Aspects such as the main salient features, purpose and other particularities related to the dam, reservoir and downstream vicinity areas should be described herein. Some items that are to be included, but not be limited to, are:

a. Type of dam
b. Characteristic Levels/Elevations (MDDL, FRL, MWL, TBL, level of top of impermeable core, level of top of upstream solid parapet wall etc.)
c. Material composition of the dam
d. Height of the dam and its hydraulic head
e. Drawings (plan view, longitudinal and cross section)
f. Foundation-Soil/ Rock Characteristics
g. Description of Hydraulic Structures/outlets
h. Purpose of the reservoir
i. Brief description of the area in vicinity downstream (main villages, population, industries, economic activities, cultural importance, etc.)

Dam-Breach Analysis

Herein the most important aspects of the entire study should be developed in detail: including, but not limited to, model selection, dam breach scenarios, boundaries of the study area, input data, model development and validation process, results, and discussion about uncertainty.

Model Selection

A detailed description of the capabilities of the software and the solution scheme used to derive the results should be included in this part of the document. In general, the use of software that solves the two-dimensional shallow water equations (2DH, full Saint-Venant equations) and its integration with GIS tools is desirable.

In flood inundation mapping, the one-dimensional cross-section averaged flow modelling (1D) is valid only for those cases where the study area has very steep slopes and narrow valleys are predominant. However, for better estimations in both the floodplains and within the banks of the main channel, a coupled 1D-2DH model may be used.

Dam Breach Scenarios

It should indicate and describe all the scenarios considered in the study. As a minimum, the analysis should include the following scenarios:

a. Dam Failure at the reservoir level at normal storage elevation (FRL) and fair weather condition.

b. Dam Failure with bad weather, i.e. considering the inflow entering in the reservoir due to Probable Maximum Flood (PMF) and MWL, or Standard Project Flood (SPF)/Inflow Design Flood and MWL.

c. Downstream flood routing of the overflow through the spillways and gates, generated by PMF or Design Flood (without dam break scenario).

d. Other relevant conditions particular to the dam (like the maximum spillway discharge that is safe for the dam but may cause emergency conditions in the areas downstream).

e. Assessment of safe carrying capacity of the channel downstream and evaluation of the safe water levels there.

Limits of Study Area

Justification on how the limits of the model were established should be described here, including the following aspects:

a. Attenuation of the breach outflow hydrograph along the main river

b. Channel-conveyance capacity of the mainstream (within the river banks) receiving the total outflow in the downstream end of the model

c. The existence of a downstream dam having a reservoir that lies within the downstream limits of the hydraulic model of the upstream dam being considered for breaching analysis, which is either able or unable to absorb the total outflow hydrograph due to the dam breach upstream. In case the reservoir located downstream is not able to absorb the entire volume received from the upstream dam breach flood, a cascade failure effect should be analysed.

In case a cascade failure effect is to be considered, Figure D-1, Table D-1 and Table D-2 provided here may help as a guide to the procedure for defining the boundaries of the hydraulic model. Table D-1 and D-2 indicate the critical overtopping depth (for embankment and concrete gravity dams, respectively). These depths may be considered as the levels of water above the crest of the dam due to which a failure of the dam may be triggered with a high probability of occurrence.

Data Inputs for the Hydraulic Model

This section of the document should provide detailed information about all the data used to carry out the dam break analysis.

Table D-1: Critical Overtopping Depth for Embankment Dams (Adopted from FEMA, 1987)

Condition of Dam	Description of Dam*	Critical Overtopping Depth ** (m)
Good	Practically no seepage, no noticeable settlement, and embankment slopes in good condition	0.61
Fair	Moderate seepage, some settlement of crest, some erosion on embankment slopes	0.3
Poor	Excessive seepage, significant slump of crest, cracks in embankment, and erosion of slopes	0.0

* No special overtopping protection to resist erosion of embankment slopes is assumed

** These values should be taken as a guide and engineering judgment should be applied to every particular case.

Table D-2: Critical Overtopping Depth for Gravity Dams (Adopted from FEMA, 2008)

Height of the Dam (Ht)	Foundation Drains Condition	Critical Overtopping Depth* (m)
Ht < 25 m	Drains exist and are totally operative	> 0.10 Ht
	Drains do not exist or are not operative	> 0.05 Ht
Ht > 25 m	Drains exist and are totally operative	> 0.05 Ht
	Drains do not exist or are not operative	> 0.01 Ht

* These values should be taken as a guide and engineering judgment should be applied to every particular case.

Elevation Data

It should include a description of the main characteristics of the digital elevation model (DEM), indicating whether a digital surface model or a digital terrain model (DSM, DTM) was used for the analysis. Characteristics of the DSM/DTM like source, resolution, and height accuracy should be described here.

Land Cover/Land Use Data

Description of the main characteristics of the land cover data used to develop the roughness coefficients in the hydraulic model should be discussed under this section. Aspects like source and resolution should also be explained.

Topographic and Bathymetric Data

In case the digital elevation model (DEM) is obtained through remote sensing, a topographic and bathymetric survey should be carried out in order to validate and rectify the elevations of the model. All the information related to the ground surveys (i.e. locations, procedures, equipment, benchmarks, and control points used) along with the planimetric and vertical accuracy attained should be discussed in this section.

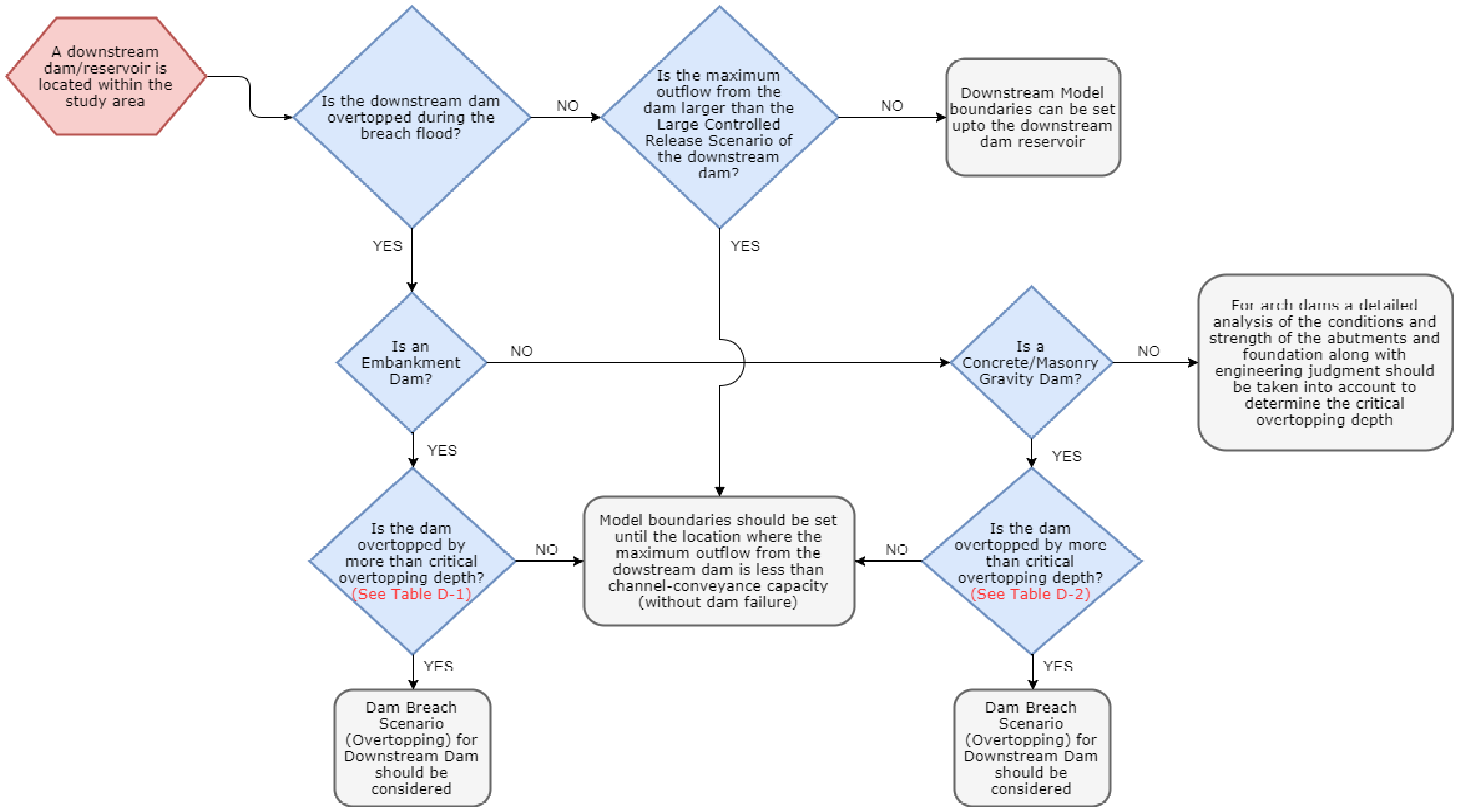

Figure D-1: General procedure to define the downstream model boundaries in case of Cascade Effect

Additional Surveys

This section may be reserved for the description of additional surveys such as satellite imageries, the geometry of the hydraulic structures (i.e. bridges, culverts), surveyed details of buildings, roads, railways and any other locations of interest. These may be required for assessment of roughness coefficients in the floodplain or constrictions in the channel for modelling the flood flow as also an assessment of the loss of properties and potential life loss.

Population Density

In order to estimate the hazard potential of the dam failure, an estimation of the population at risk should be provided in the document. Therefore, data regarding either the population density in the downstream areas or census data of the affected villages should be obtained. The sources and main characteristics of this information should be described.

Hydraulic Data

This section should present the information related to the hydraulic structures of the dam such as the geometry, elevations, operation rules and rating curves of the spillways and other gated/un-gated outlets.

Hydrologic Data

This should include a description of the inflow design flood showing the data in tabular and graphical format. The elevation-capacity curve of the reservoir or bathymetric profile of the same is to be included if a full dynamic flood routing method is being used. Additionally, if a level pool reservoir flood routing was carried out in order to validate the maximum water surface elevation of the reservoir (MWL), the results of that study should be presented in this section.

Model Development

This section of the document should describe in detail every stage of the development of the hydraulic model and, therefore, its content may be customized based on the methodologies chosen and type of model adopted to carry out the dam break analysis.

Grid/Mesh Resolution

If a two-dimensional depth-averaged (2DH) modelling is being carried out, a detailed description of the grid should be given in this section. Aspects such as grid resolution and its justification, the total number of cells, and locations of break lines should be described in this section. On the other hand, if a one-dimensional cross section-averaged model is adopted, aspects such as the total number of transects, the distance between two consecutive cross sections, river profiles, expansion and contraction coefficients etc. may be included in this section. The heading of the section may be rephrased accordingly.

Roughness Coefficients

This section should indicate how the roughness coefficients in the study area were assessed. Detailed maps, site pictures (floodplains, main river) and drawings should be included in this section indicating the spatial variation of the adopted coefficients in the study area, as well as presenting a proper justification of the values selected.

Flow and Boundary Conditions

This section should specify the hydraulic boundary conditions of the model, in both, the upstream and the downstream end. The adopted initial conditions for every particular location should be described in this section as well (initial reservoir levels, initial flows, initial gate openings, etc.).

Normally, the most common boundary conditions are the inflow hydrograph at the upstream side, and the normal depth (or rating curve) in the downstream end of the model. Any other boundary condition particular to the case under consideration should be described in this section.

Dam-Breach Parameters

A detailed explanation of the methodology/approach used to estimate the size of the breach should be included in this section. In general, two methods may be used: the regression-based methods and the physically-based methods. Whichever of them is chosen, a detailed description of equations, assumptions and limitations should be provided.

Values of the average breach width, breach bottom elevation, side slopes and formation time should be estimated for every failure scenario and described in the section.

Calibration and Sensitivity Analysis

If a calibration of the roughness coefficients is carried out, a discussion on the methodology and input data used may be discussed in this section.

Additionally, in order to deal with the uncertainty of the dam breach parameters, sensitivity analysis may be carried out to establish the best estimates of these parameters. Sensitivity analysis may be carried out taking into account all the possible range of values available for every case/equation and the results of the analysis (i.e., confidence interval, standard deviation) should be discussed in the section.

A more detailed uncertainty analysis (e.g., a probabilistic analysis, i.e., Monte Carlo simulation or similar analysis) may also be carried out. In that case, the title of the section may be rephrased accordingly.

Computational Aspects

A detailed description of the hydraulic modelling, indicating aspects like assumptions (a type of equations: diffusion wave/ full dynamic), computation interval (time step), final volume accounting error, convergence and stability concerns related with the simulations are to be included in this section. The final results should be a proven stable, convergent and minimal error solution from the mathematical model, which should be described.

Reasonableness of the Peak Discharge

Using regression equations based on actual historical failures, it is possible to validate or check for the reasonableness of the resulting peak discharges obtained through the modelling exercise. There are regression-based equations that represent the average value of the observed data, but there are other equations that represent the envelope of maximum observed values. A detailed discussion of this subject should be provided in this section.

Another check for reasonableness should be done by evaluating the breach flow, and velocities through the breach during the breach formation process. This can be accomplished by reviewing the detailed output hydrograph at the dam location and reviewing the flow rate and velocities passing through the breach. In general two aspects may be considered:

a. If the model reaches the full breach development time and size, and there are still very high flow rates and velocities going through the breach, this is a sign that either the breach is too small or the breach development time is too short (unless there are some physical constraints limiting the size of the breach).

b. If the flow rate and velocities through the breach become very small before the breach has reached its full size and before the breach development time is over, then this is an indicator that the breach size is too large, or the breach time is too long.

Results

This section should include all the pertinent results necessary to prepare a suitable emergency action plan. Flow hydrographs, hazard reference values (i.e., depth, velocities, and water surface elevations), the arrival time of the flood wave and population at risk are some of the outputs to be discussed in this section. Time of inundation and vulnerability (based on the combination of depth and velocity of water) may also be discussed.

Output Hydrographs

Flow Hydrographs (flow vs. time) at the most important locations downstream the dam (villages, bridges, roads, protected areas) should be provided as outputs in this section. This section in the report should highlight the degree of attenuation of the peak breach outflow along the downstream river channel, as well as provide important information to the local authorities about the flood severity in key locations such as bridges, culverts, and water supply installations/ locations of national or strategic importance.

Flood Hazard/Vulnerability Reference Values

Flood hazard reference values consisting of maximum water depth, maximum depth-averaged velocity, and flood wave arrival time at various locations downstream of the dam should be presented in this part of the document in a tabular format. Reference values should be estimated close to the identified important locations/villages, in order to represent the degree of danger that would be caused by the dam breach flood.

The dam breach flood severities discussed in Chapter 5 of this guideline (hazard to people, vehicles, and buildings) may also be included in this section to provide a better understanding about the levels of vulnerability to the disaster management authorities for the purpose of planning prioritisation of the evacuation process.

Population at Risk (PAR)

This section should indicate all the assumptions, procedures and methodologies used to estimate the population at risk (See *Section 6.4.7 The population at Risk* of this Guideline). A table indicating the location of the hamlet/village/town/city, its distance from the dam, and the estimated population at risk should be included either within this section or as an appendix at the end of the document, along with the reference values for flood hazard.

Potential Loss of Life (PLL)

This section should indicate all the assumptions, procedures and methodologies used to estimate the potential loss of life (See *Section 6.4.8 Potential Loss of Life* of this Guideline). A table indicating the location of the hamlet/village/town/city, its distance from the dam, and estimated potential loss of life should be included either within this section or as an appendix at the end of the document, along with the flood hazard reference values and the population at risk.

Flood-Inundation Mapping

In this section, all the main features of the process of preparation of the inundation maps should be described in detail. The scale of the maps, GIS software used, the total number of map tiles per scenario analysed, type of projection/coordinates used, legends/symbols used, description of roads, railways and villages files (source, type, levels of reliability), are some of the topics to be included.

Sources of Uncertainty in Flood-Inundation Maps

This part of the document should be reserved to discuss all the sources of uncertainty of the entire study, along with the methodology on how this uncertainty was handled. Uncertainty may be introduced into the flood-inundation maps in respect of the accuracy of the topographic, hydraulic, and hydrologic data and the modelling system used. All these aspects should be taken into account.

Topographic Uncertainties

This part should indicate the main source of uncertainty and most important limitations of the methodology, procedures, and data used for the derivation of the terrain model. (i.e., LIDAR, remote sensing, ground surveys, differential global positioning system (DGPS), etc.).

Uncertainties about Manning's n-Value

In very large flood events like that generated due to a dam break, even though the Manning's roughness coefficients may have limited effect on the overall extent of the flood-inundation area, a little variation of this roughness coefficients may affect the timing of the flood (arrival time of the first flood wave and arrival time of the flood peak) considerably. Therefore, this section of the document should explain in detail the level of uncertainty of the data used to obtain the roughness coefficients and how it was dealt with (e.g., calibration, sensitivity analysis).

Uncertainty of Dam breach parameters

If an uncertainty analysis such as sensitivity analysis or probabilistic analysis is described in the document under the section Model Development, then this item may be skipped. Otherwise, the section on Calibration and Sensitivity Analysis may be referred to.

Model Limitations

Based on the different assumptions made for the study and the previous discussion on uncertainty, a compressive discussion about the main sources of uncertainty and errors should be included in the report. It should discuss how these uncertainties/errors may be interpreted on the part of the authorities, and how these uncertainties/errors can be reduced further later on.

Summary and Conclusions

The contents of this part of the document should be related directly to the aims of the study as stated in the section purpose and scope, and sum up the essential features of the work done. In general, this section

a. Should state whether the objective of the study as mentioned in the section detailing the scope has been fulfilled

b. Should provide a brief summary of the key findings or information in the report

c. Should highlight the major outcomes of the investigation and their significance.

References

If any citations have been used in the report, this section should provide the list of such references with the details of these sources along with the date of publication.

Appendices

This section should contain material that is too detailed to include in the main report, such as raw data, detailed drawings, and final inundation maps.

Inundation Maps

These represent the most important outcome of the entire study and should be incorporated in an adequate scale and page size without any type of distortion. The second set of inundation maps (soft copy) in larger scale and page size may be included in order to be incorporated/used for the preparation of the Emergency Action Plan.

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Central Dam Safety Organisation
Central Water Commission

Vision

To remain as a premier organisation with best technical and managerial expertise for providing advisory services on matters relating to dam safety.

Mission

To provide expert services to State Dam Safety Organisations, dam owners, dam operating agencies and others concerned for ensuring safe functioning of dams with a view to protect human life, property and the environment.

Values

Integrity: Act with integrity and honesty in all our actions and practices.

Commitment: Ensure good working conditions for employees and encourage professional excellence.

Transparency: Ensure clear, accurate and complete information in communications with stakeholders and take all decisions openly based on reliable information.

Quality of service: Provide state-of-the-art technical and managerial services within agreed time frame.

Striving towards excellence: Promote continual improvement as an integral part of our working and strive towards excellence in all our endeavours.

Quality Policy

We provide technical and managerial assistance to dam owners and State Dam Safety Organisations for proper surveillance, inspection, operation and maintenance of all dams and appurtenant works in India to ensure safe functioning of dams and protecting human life, property and the environment.

We develop and nurture competent manpower and equip ourselves with state of the art technical infrastructure to provide expert services to all stakeholders.

We continually improve our systems, processes and services to ensure satisfaction of our customers.

DRIP
Dam Rehabilitation & Improvement Project