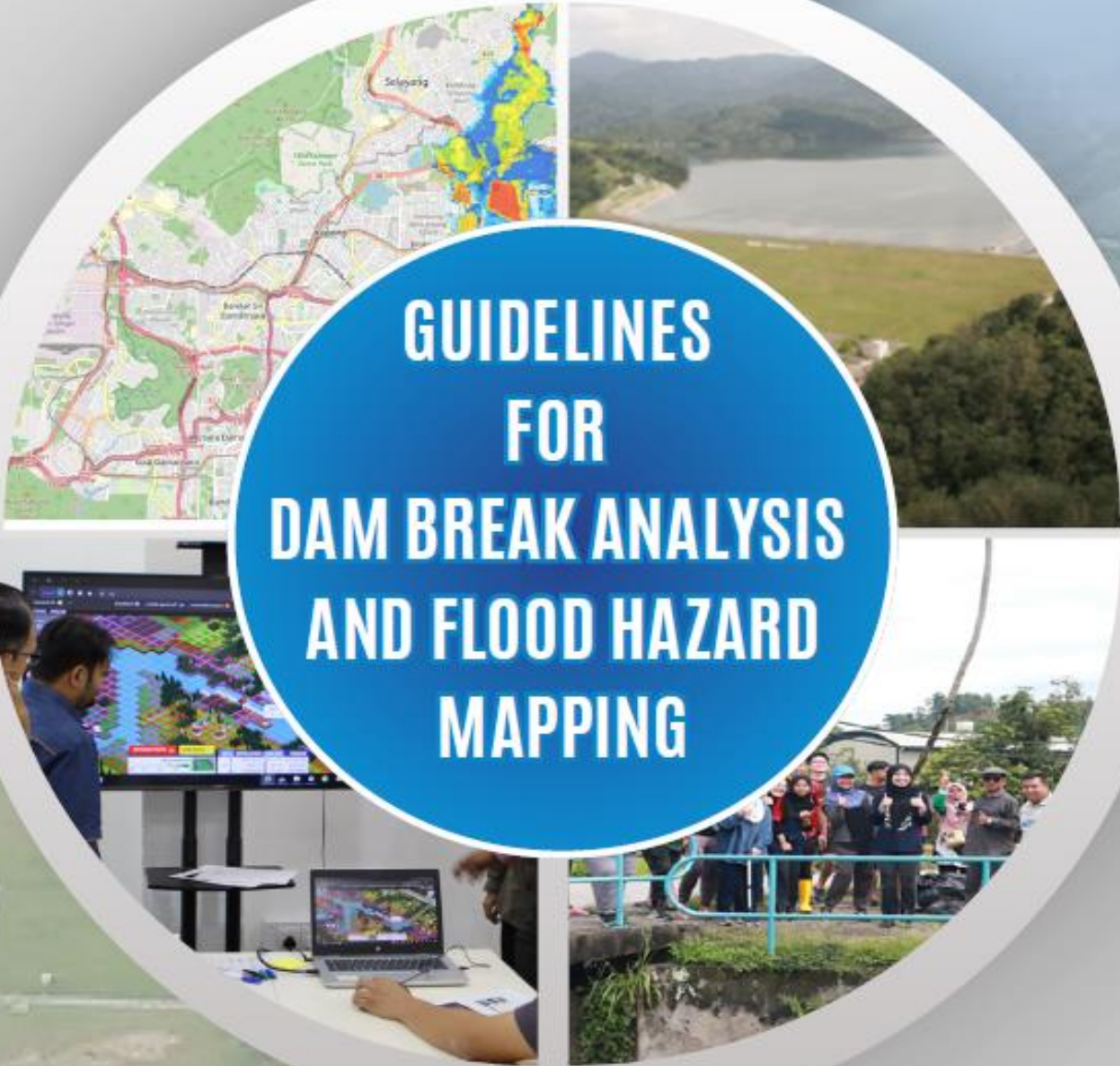
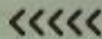


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ASIA-PACIFIC NETWORK FOR
GLOBAL CHANGE RESEARCH



GUIDELINES FOR DAM BREAK ANALYSIS AND FLOOD HAZARD MAPPING



FOREWORD

The Department of Irrigation and Drainage (DID), also known as Jabatan Pengairan dan Saliran Malaysia (JPS), plays a vital role in ensuring the safety and sustainability of Malaysia's water resources infrastructure. Among our critical responsibilities are the planning, management, and regulation of dams and associated hydraulic structure in alignment with national objectives for disaster risk reduction, public safety, and climate resilience.

The publication of the Guidelines for Dam Break Analysis and Flood Hazard Mapping represents a major step forward in strengthening our national capacity to assess and mitigate the risks associated with dam failures. It is intended to support technical practitioners, engineers, consultants, and relevant authorities in conducting systematic and scientifically grounded dam break studies across the country.



Dam break events, though rare, can result in catastrophic consequences for downstream communities, infrastructure, and the environment. Recognising this, DID has continuously prioritised the need for robust analysis and preparedness mechanisms. This includes improving early warning systems, enhancing flood risk mapping, and promoting integrated emergency response planning. These guidelines serve as a practical tool to streamline and standardise methodologies, ensuring consistency, reliability, and regulatory compliance.

The release of this guideline is especially timely with the establishment of the **National Dam Centre (NDC)** which serves as the central platform for advancing dam safety practices in Malaysia. The NDC strengthens national coordination, data integration, and technical capacity related to dam management. As the hub for dam safety excellence, the NDC plays a pivotal role in institutionalising best practices, providing technical oversight, and promoting knowledge sharing across agencies and sectors. This guideline complements the objectives of the NDC by providing a structured framework for dam break analysis and flood hazard mapping, two critical components of risk-informed dam safety management. It lays the groundwork for consistent implementation of national standards, enabling better decision-making and enhancing public safety.

As an agency under the Ministry of Energy Transition and Water Transformation (PETRA), DID remains fully committed to enhancing technical excellence, capacity building, and cross-agency collaboration in disaster risk management. This document not only reflects best practices drawn from international references, but also addresses local hydrological conditions, legal frameworks and policy directions specific to Malaysia.

I would like to express my sincere appreciation to all team members who have contributed to the development of this guideline. Your expertise and dedication are instrumental in safeguarding lives and livelihoods. It is my hope that this publication will serve as a cornerstone reference for all dam-related studies in Malaysia and will continue to evolve with emerging technologies and challenges, particularly in the face of climate change and rapid urban development.

Thank you.

YBhg. Datuk Ir. Mohamad Radzi Bin Abdul Talib
Director General
Department of Irrigation and Drainage

FOREWORD

As our nation continues to face increasing hydrological challenges, including extreme weather events and rapid urbanisation, the importance of ensuring dam safety and preparedness for potential dam-related disasters cannot be overstated. Dams are vital infrastructure for national development, serving multiple functions—from water supply and flood mitigation to hydropower generation and irrigation. However, these structures also carry inherent risks, and the failure of a dam, while rare, could result in severe downstream impacts.



As the Co-President of Malaysian National Committee on Large Dams (MYCOLD), I am honoured to contribute to this timely and important publication: *The Guidelines for Dam Break Analysis and Flood Hazard Mapping*. This guideline represents a key milestone in our collective efforts to strengthen technical standards and institutional readiness for dam safety assessments in Malaysia.

MYCOLD, as the professional society affiliated with International Commission on Large Dams (ICOLD), is committed to promoting best practices in the planning, design, operation, and safety of dams. This guideline aligns well with international principles while also being tailored to local hydrological conditions, dam typologies, and regulatory frameworks. It provides clear procedures for conducting dam break simulations and flood hazard mapping tools that are essential for risk assessment, emergency planning, and community preparedness.

I would like to express my sincere appreciation to Universiti Tenaga Nasional, the Department of Irrigation and Drainage (DID), the National Disaster Management Agency (NADMA), and all other collaborators for their leadership and technical contributions to this initiative. Special thanks are also extended to the Asia-Pacific Network for Global Change Research (APN) under the Collaborative Regional Research Programme (CRRP) for funding this important project, which has enabled the development of this comprehensive guideline and the capacity-building efforts that support it.

The spirit of inter-agency cooperation and knowledge sharing reflected in this document is commendable and serves as a model for other areas of disaster risk management. Moving forward, I encourage practitioners, policymakers, and researchers to make full use of this guideline in their work, and to continue advancing our shared goal of enhancing dam safety and public resilience in the face of growing climate variability.

Thank you.

Prof. Datin Ir. Dr. Lariyah Mohd Side

Co-President

Malaysia National Committee on Large Dams (MYCOLD)

Chairman of the Technical Committee Dam Safety (Malaysia)

PREFACE

The increasing frequency and severity of flood-related disasters in Malaysia underscores the urgent need for comprehensive and systematic approaches to dam safety and flood hazard assessment. As a critical infrastructure, dams play a central role in water resource management, flood control, and energy generation. However, in the rare event of a dam failure, the consequences can be catastrophic—posing significant threats to lives, property, and the environment.

In recognition of this, the Guidelines for Dam Break Analysis and Flood Hazard Mapping has been developed as a practical reference to support engineers, technical practitioners, authorities, and decision-makers involved in the planning, assessment, and management of dam-related risks.

This guideline outlines standardized procedures for conducting dam break simulations, hydrological and hydraulic analysis, and flood hazard mapping. It incorporates both local and international best practices, and is tailored to Malaysia’s regulatory framework, climate conditions, and technical capabilities. The methodology presented in this document aims to enhance the consistency, transparency, and quality of dam break studies across the country.

The preparation of these guidelines is the result of collaborative efforts involving technical experts, government agencies, consultants, and academia. Special acknowledgment is given to the Department of Irrigation and Drainage (DID/JPS) for its leadership in technical development, and to the National Disaster Management Agency (NADMA) for its strategic oversight and coordination in disaster preparedness.

It is our hope that this publication will serve not only as a technical manual, but also as a foundation for integrated risk management, informed land use planning, and effective emergency response in areas downstream of dams. By equipping stakeholders with the necessary tools and knowledge, we move one step closer to building a safer and more resilient Malaysia.

ACKNOWLEDGMENT

The successful preparation of the Guidelines for Dam Break Analysis and Flood Hazard Mapping would not have been possible without the collective effort, expertise, and dedication of numerous individuals and organizations. We extend our sincere gratitude to the representatives from the Department of Irrigation and Drainage, academic institutions, consulting engineers, and industry experts whose valuable contributions, reviews, and practical experience have greatly enriched the technical quality of this document.

We would also like to express our heartfelt thanks to the Asia-Pacific Network for Global Change Research (APN) for supporting this initiative through the Collaborative Regional Research Programme (CRRP) research grant. APN's support was instrumental in facilitating collaborative research, stakeholder engagement, and capacity-building activities that informed the content and development of this guideline. In addition, grateful appreciation is extended to the Indian Committee on Large Dams (INCOLD) for its technical publications and guidance which served as important references during the development of this guideline.

Finally, we thank all parties who have supported the drafting, editing, and validation processes, helping to ensure that this publication serves as a reliable and practical reference for practitioners, authorities, and policymakers involved in dam safety, hydrological assessments, and flood risk management. Your contributions are deeply appreciated, and your continued support is vital in translating these guidelines into meaningful, effective action on the ground.

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EXECUTIVE SUMMARY

The *Guidelines for Dam Break Analysis and Flood Hazard Mapping* provides a comprehensive framework for assessing flood risks associated with potential dam failures. This guidelines support the development of dam break flood hazard maps, which is an essential tool for predicting downstream impacts. These hazard maps play a critical role in emergency response planning, flood risk management, and enhancing public safety.

To ensure accurate and reliable hazard maps, critical input data must be gathered, including dam characteristics (e.g., height, length, and storage volume), potential failure modes (such as overtopping or internal erosion), and detailed downstream topography. High-quality, site-specific data is vital for producing credible flood simulations and for the design of effective mitigation strategies.

Flood behaviour is typically simulated using hydrodynamic models that estimate water depth, flow velocity, and the progression of floodwaters over time. To account for uncertainties in input data and model parameters, Monte Carlo simulations can be used to generate a range of possible outcomes. Additionally, sensitivity analysis is a valuable tool for identifying the factors that mainly influence flood predictions, thereby improving confidence in the results.

The dam break flood hazard maps should present key parameters including inundated areas, which show the zones that are likely to be affected by flooding; the peak flood stage indicating the highest water level reached during the event; flow velocity and discharge which reflect the speed and volume of water moving through the floodplain; and the flood arrival time estimating when floodwaters will reach downstream communities or infrastructure. Effective map design should emphasize clarity, accuracy, and ease of interpretation, using intuitive colour schemes, consistent symbology, and legible text to facilitate quick understanding by stakeholders.

These maps are invaluable to government agencies, emergency responders, engineers, and urban planners in preparing for and managing dam-related flood risks. By following these guidelines, practitioners can produce effective and actionable dam break flood hazard maps that enhance planning, support timely decision-making, and strengthen community resilience against potential dam failure events.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
DEM	Digital Elevation Model
DID	Department of Irrigation and Drainage
EAP	Emergency Action Plan
FEMA	Federal Emergency Management Agency, USA
FRL	Full Reservoir Level
GIS	Geographical Information System
INCOLD	Indian National Committee on Large Dams
JUPEM	Department of Survey and Mapping Malaysia
MMD	Malaysian Meteorological Department
MRSA	Malaysian Remote Sensing Agency
MyDAM	Malaysian Dam Safety Management System
MWL	Maximum Water Level
NADMA	National Disaster Management Agency
NAHRIM	National Hydraulic Research Institute of Malaysia
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
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
TNB	Tenaga Nasional Berhad
USACE	United States Army Corps of Engineers
WGS	World Geodetic System

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CHAPTER 1 INTRODUCTION

1.0 Background

Flooding is a frequent and severe hazard in Southeast Asia, intensified by factors such as climate change, rapid urbanization, and insufficient infrastructure. In Malaysia, both urban and rural communities are vulnerable to flooding, particularly during the monsoon season. Rivers and dams significantly influence flood dynamics and associated risks. Within this context, flood hazard maps serve as critical tools in disaster risk management by visually identifying flood-prone areas. These maps support a wide range of essential functions which includes risk assessment by highlighting vulnerable zones, emergency planning through the development of evacuation routes and response strategies, and land use planning by guiding development away from high-risk areas. Additionally, flood hazard maps inform flood mitigation efforts by supporting infrastructure design and the implementation of control measures. They also play a key role in raising public awareness, enhancing community preparedness, and supporting the development of effective policies and regulations. More importantly, they help address future flood risks associated with climate change. When used effectively, flood hazard maps can contribute to reducing flood-related damages, strengthening community resilience, and promoting sustainable, long-term flood risk management.

1.1 Objectives of the Guidelines

The objectives of this guideline are to support effective flood risk management and enhance public safety in relation to dam break events. It aims to provide a standardized, practical, and consistent approach for dam break flood hazard mapping in Malaysia. The guideline is intended to ensure accuracy, reliability, and comparability of flood assessments across different dam sites. It also supports emergency preparedness by identifying high-risk areas to aid in evacuation planning. In addition, the guideline helps inform land use and infrastructure development to reduce flood exposure, assists dam owners and operators in meeting regulatory safety requirements, and promotes public safety and awareness by making hazard information more transparent and accessible.

1.2 Key Stakeholders and Users

The guidelines are intended for a wide range of stakeholders involved in dam break analysis and flood hazard mapping. The Department of Irrigation and Drainage (DID) serves as the technical authority and regulator, while local governments (Pihak Berkuasa Tempatan) plays a key role in development control and evacuation planning. Disaster management agencies such as the National Disaster Management Agency (NADMA) and the Civil Defence Force (APM) can use the

information provided in this guideline for planning and coordinating emergency response strategies. Private consultants, including engineers and hydrologists, can apply the guidelines for technical modelling, analysis, and reporting. GIS and planning officers will be able to use the outputs for spatial analysis and flood risk mapping. Further, dam owners and operators, both public and private responsible for ensuring safety compliance and emergency preparedness shall ensure that common practices follow these guidelines.

1.3 National Guidelines & Practices

This guideline is developed in accordance with Malaysia's existing national guidelines, and technical standards related to dam break analysis and flood hazard map. The DID is the main agency responsible, with reference documents such as Malaysian Dam Safety Management System (MyDAMS). The National Hydraulic Research Institute of Malaysia (NAHRIM) provides technical support through studies and modelling related to hydrology and hydraulics.

1.4 Benchmarking with International Guidelines & Practices

This guideline has been benchmarked against established international practices from key agencies including the Indian Committee on Large Dams (INCOLD), the Federal Emergency Management Agency (FEMA, USA), U.S. Army Corps of Engineers (USACE), ICOLD, FEMA, USACE, USBR, INCOLD, SPANCOLD, CDA, ANCOLD. These agencies provide comprehensive frameworks for dam break analysis and flood hazard mapping that are widely recognized and adopted. This benchmarking exercise ensures that the proposed national guidelines are aligned with international standards while being adapted to local conditions, data availability, and institutional frameworks.

1.5 Guideline Structure and Overview Concept

This guideline is divided into seven main chapters. Chapter 1 gives an introduction, including the purpose of the guidelines, key users, and reference to national and international practices. Chapter 2 explains the types of dams, how they are classified, possible failure types, and flood risks related to dam breaks. Chapter 3 covers the types of data such as topography, river, and dam information that are required in order to carry out the analysis. Chapter 4 focuses on how to do hydrological analysis, including rainfall and flood estimation. Chapter 5 explains how to model a dam break, including breach parameters, prediction methods, and flood simulation. Chapter 6 describes how to prepare flood hazard maps using GIS, including map elements and design. Chapter 7 looks at how to assess flood hazards, plan evacuation routes and shelters, and support emergency

response.

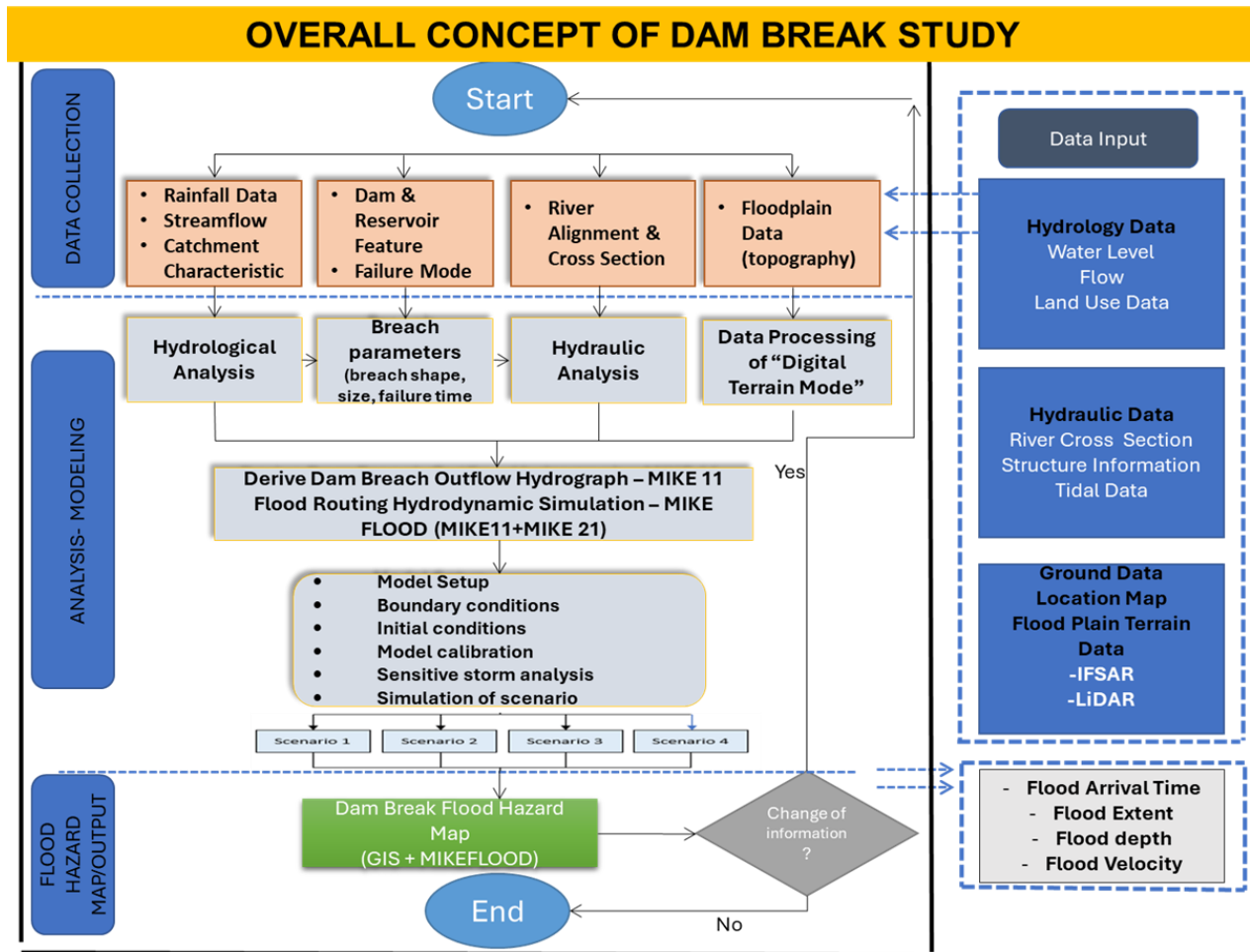


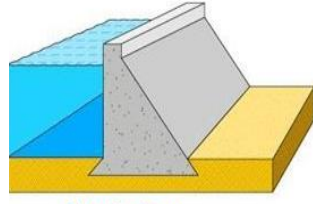
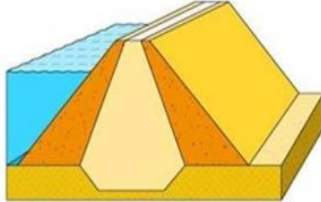

Figure 1.1 Overview methodology of dam break analysis

CHAPTER 2 FLOOD RISK ASSOCIATED WITH DAMS

2.1 Types of dams

Dams are classified based on their construction materials. The main types are concrete or masonry dams, embankment dams, and composite dams. Concrete and masonry dams include structures like arch and gravity dams. Embankment dams are built using natural materials like clay and rock. Composite dams combine different materials such as earth embankment with a concrete spillway. The choice of dam type depends on several factors including foundation conditions, topography, material availability, spillway design, seismic risk, construction methods, and cost.

Table 2.1 Dam types

Concrete and Masonry Dams	Includes arch, buttress, gravity, multi-arch, and roller-compacted concrete (RCC) dams. Older dams (50+ years) are commonly masonry-built due to labor-intensive techniques.	 <p style="text-align: center; color: blue; font-weight: bold;">Gravity Dam</p>
Figure 2.1 Gravity dams*		
Embankment Dams	Constructed using natural materials such as clay, rock, or erosion-resistant soil. These dams usually include an impermeable core to reduce seepage, a permeable filter layer to manage internal water flow, upstream protection (e.g., stone cladding) to prevent erosion.	 <p style="text-align: center; color: blue; font-weight: bold;">Earth Dam</p>
Figure 2.2 Earth dam*		
Composite Dams	Combination of one or more dam types. Most often a large section of a dam will be either an embankment or gravity dam.	
Figure 2.3 Folsom Dam, California (central concrete spillway flanked on either side by earthen wing dams) **		

* <https://engineeringdiscoveries.com/the-ultimate-guide-to-types-of-dams-embankment-gravity-arch-and-buttress-dams/>
 ** https://damtoolbox.org/wiki/Composite_Dams

2.2 Dam classification systems

Dams can also be classified based on hydraulic head and gross storage capacity. Hydraulic head refers to the vertical height difference between the maximum water level in the reservoir and

the downstream ground level, which affects the energy potential and risk level of the dam. Gross storage capacity is the total volume of water that the dam can store when the reservoir is full, which helps determine the potential impact during a dam failure.

Table 2.2 The dam classifications based on the hydraulic head and the total storage capacity (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 (1% AEP)
Intermediate	10 to 60	12 to 30	Standard project Flood (SPF)
Large	> 60	> 30	PMF

* AEP = Annual Exceedance Probability

2.3 Dam hazard classification

The dam hazard rating for dams by MyDAMS (2017) is based on the environmental and cultural values, infrastructure, and economics as summarized in Table 2.3.

Table 2.3 Dam Hazard Rating (MyDAMS,2017)

Hazard Classification	PAR	Environmental and cultural values	Infrastructure, and economics
Low	0	Minimal short-term loss. No long-term loss	Low economic losses. Area contains limited infrastructure or services
Significant	1-10	No significant loss. Marginal deterioration of important flora and fauna habitat. Restoration is highly possible	Significant economic losses involving recreational facilities, infrequently used workplaces and transportation routes
High	11-100	Significant loss or deterioration of critical flora and fauna habitat Restoration is possible but impractical	High economic losses affecting infrastructure, public transportation and commercial facilities
Very High	>100	Major loss or deterioration of critical flora and fauna habitat Restoration is impossible.	Very high economic losses affecting important infrastructure or services (e.g. hospital, highway, industrial area, storage facilities for dangerous substances)

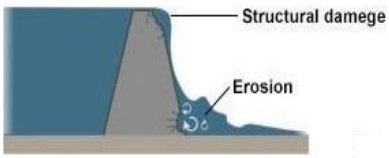
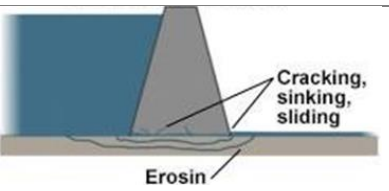
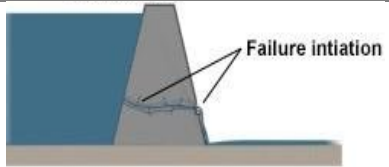
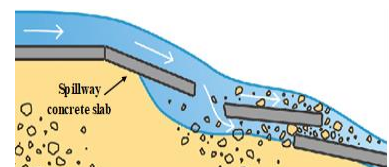

*PAR= Population at Risk

2.4 Dam failure modes

Dam failures may be gradual or sudden, depending on the dam type and cause. Concrete Gravity/Arch dams typically fail suddenly. Embankment dams usually fail progressively due to

erosion or seepage. In general, common causes of dam failure include flooding/overtopping (leading cause), seepage/piping, structural, spillway gate, earthquakes, poor design/construction. Dam failures fall into six categories: *Hydrologic, Geologic, Piping/Internal Erosion, Structural, Seismic, Human-Influenced, and Floods from Large Controlled Releases*

Table 2.4 Categories of dam failures modes

Dam Failure Mode	Cause	Consequence	
Hydrologic	<ul style="list-style-type: none"> • Poor design or malfunctioning spillways • Water exceeding dam height 	<ul style="list-style-type: none"> • Downstream erosion • Structural damage 	 <p>Figure 2.4 Overtopping (Bharti et al., 2020)</p>
Geologic/Foundation	<ul style="list-style-type: none"> • Continuous seepage through dam or foundation • Poor foundation design 	<ul style="list-style-type: none"> • Internal erosion • Piping formation weakening the dam structure • Rapid water level changes 	 <p>Figure 2.5 Foundation (Bharti et al., 2020)</p>
Piping/Internal Erosion	<ul style="list-style-type: none"> • Seepage erodes materials forming paths • Fine soil particles moving through larger ones • Poor seepage control 	<ul style="list-style-type: none"> • Erosion expands upstream 	 <p>Figure 2.6 Piping (seepage) (Bharti et al., 2020)</p>
Structural	<ul style="list-style-type: none"> • Poor design • Inadequate maintenance • Wear over time • Overloading during flooding 	<ul style="list-style-type: none"> • Failure of embankments or auxiliary components (spillways) • Structural stress during high water levels can cause collapse 	 <p>Figure 2.7 Spillway failure (Heidarzadeh et al., 2022)</p>
Seismic	<ul style="list-style-type: none"> • Earthquakes causing ground movement and cracking 	<ul style="list-style-type: none"> • Sudden structural failure • Possible overtopping or cracking 	 <p>Figure 2.8 Dam damage (Jing, et.al, 2021)</p>


Floods from Large Controlled Releases	<ul style="list-style-type: none"> • Overflow from dam • Controlled releases without consideration for downstream capacity • Development reducing river's flood flow capacity 	<ul style="list-style-type: none"> • Downstream flooding • Increased risk of dam breach 	
Human-Influenced Failure (under MKN and police justification)	<ul style="list-style-type: none"> • Misoperation (e.g. gate left open) • Sabotage or intentional damage • Poor design or maintenance 	<ul style="list-style-type: none"> • Overtopping or collapse • Breach due to lowered dam crest or gate failure 	

Figure 2.9 Overflow spillway of Oroville Dam, CA*

*<https://damfailures.org/lessons-learned/downstream-flooding-can-be-caused-by-spillway-flows-that-exceed-channel-capacity-or-as-a-result-of-reservoir-misoperation/>

**MKN = “Majlis Keselamatan Negara” or National Security Council

2.5 Overview of Dam Break Scenarios

Dam break scenarios are used to model the possible impacts of dam-related flooding under different conditions. The potential failure scenarios can be categorized as Non-hydrologic and Hydrologic.

- **Non – Hydrologic:**

CDF (Clear Day Failure): A dam failure that occurs on a normal day without heavy rain. Typical failures include *design/construction flaws, piping failures, seepage failure, weak foundation, overtopping due to operational failure, aging infrastructure components (e.g., gates, valve).*

- **Hydrologic:**

PMF Break (Probable Maximum Flood with Dam Break): A dam failure that occurs during the most extreme possible flood. Typical failures include *spillway overtopping, spillway gates failures, scour/erosive failure, seepage and internal erosion, seismic activity.*



Figure 2.10 Dam break scenarios overview

CHAPTER 3 DATA PREPARATION

Accurate and comprehensive data collection is essential for reliable dam break flood hazard mapping. The following categories outline the key data types required for modeling and analysis.

3.1 Topographical data

This data shows elevation (height), slope (steepness), and natural or man-made features like rivers, roads, and buildings. It helps create Digital Elevation Models (DEMs) which is 3D maps of the land surface used in flood modeling. Topographical data can come from different sources such as LiDAR (light detection and ranging) and satellites. In Malaysia, the main agencies that provide this data include:

Table 3.1 LiDAR data available in Malaysia

Sources	Description
Department of Survey and Mapping Malaysia (JUPEM)	Data type: LIDAR DEM Resolution: High (1-5m) Coverage: Selected area Very accurate, useful for detailed analysis https://archive.data.gov.my/
Malaysian Remote Sensing Agency (MRSA)	Data type: Satellite DEM Resolution: Moderate (10–30 m) Coverage: Nationwide Good for general modeling https://rsopendata.mysa.gov.my/opendata.html

In addition to the sources mentioned earlier, several global Digital Elevation Model (DEM) datasets are freely available and can serve as useful alternatives when local elevation data is not accessible.

Table 3.2 Global sources for high-resolution DEMs

Sources	Description
SRTM (Shuttle Radar Topography Mission)	Resolution: 30 m (SRTM-1), 90 m (SRTM-3) Coverage: 60°N to 56°S Free and widely used https://earthexplorer.usgs.gov/
NASA DEM	Resolution: Varies (10 m – 90 m) Coverage: Global https://earthdata.nasa.gov/
Copernicus GLO-30 / GLO-90	Resolution: 30m/90m Coverage: Global (except poles) https://portal.opentopography.org/datasets
Advanced Land Observing Satellite (ALOS) (JAXA)	Resolution: 30m Coverage: Global Freely available for commercial and non-commercial use Better accuracy than SRTM

	https://opentopography.org/news/updated-alos-world-3d-dem-now-available-through-opentopography
ASTER GDEM	Resolution: 30 m Coverage: 83°N and 83°S Freely available https://asterweb.jpl.nasa.gov/gdem.asp

3.2 Hydrological data

Hydrological data is essential to define the inflow, rainfall, and river conditions used in dam break simulations. It helps estimate flood magnitude, validate models, and understand the likely impacts downstream. The hydrological data includes **rainfall, climate data, historical flood records evaporation rates, river discharge, water level, inflow and outflow.**

Table 3.3 Hydrological data available in Malaysia

Sources	Description
Malaysia Meteorological Department (MET Malaysia)	Data provided: Rainfall, climate data Available: 1970 – present (hourly, daily) https://mymetdata.met.gov.my/
DID/JPS (Department of Irrigation and Drainage)	Data provided: Flood records, streamflow, river discharge, water level Available: 1970 – present (hourly, daily, real-time) https://archive.data.gov.my/data/ms_MY/organization/jabatan-pengairan-dan-saliran-jps?tags=hidrologi
Dam Owners (e.g. Tenaga Nasional Berhad – TNB, DID and others)	Data provided: Inflow and outflow Available: Ongoing (real-time or hourly) Data-sharing agreements required for access to detailed records.

In cases where local hydrological data is limited or unavailable, users are encouraged to refer to global data sources as summarized in Table 3.4.

Table 3.4 Global hydrological data sources

Sources	Description
NOAA National Centers for Environmental Information (NCEI)	Data provided: Rainfall, climate data Available: 1963 – present (daily, monthly, seasonal, and yearly) https://www.ncei.noaa.gov/
NASA Earthdata (EOSDIS)	Data provided: Precipitation, surface temperature, streamflow, evaporation, soil moisture Available: 1994 – present (hourly, daily, monthly, and yearly, near real-time) https://www.earthdata.nasa.gov/about/esdis/eosdis
European Centre for Medium-Range Weather Forecasts (ECMWF)	Data provided: Precipitation, streamflow, evaporation, soil moisture, climate data Available: 1979 - present (hourly, daily, monthly, yearly, near real time) https://www.ecmwf.int/
Global Runoff Data Centre (GRDC)	Data provided: River discharge Available: 1987 - 2019 (daily, monthly, yearly) https://grdc.bafg.de/

Copernicus Climate Data Store (CDS)	Data provided: Rainfall, temperature, streamflow, soil moisture, evapotranspiration Available: 1940- present (hourly,daily, monthly, yearly) https://cds.climate.copernicus.eu/
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3.3 Dam and river structure data

The components of dam and river structure data include:

- **Dam Characteristics:** Type, location, height, storage capacity, spillway design, foundation details, and condition assessments.
- **River Geometry:** Cross-section, riverbed profile (cross-sectional and longitudinal profile), flow path, bank structure (details see Table 3.5)

Technical data on dams and river structures can be obtained from various sources including the DID, NAHRIM, the Ministry of Energy Transition and Water Transformation (PETRA), the Ministry of Natural Resources and Environment (NRES), Engineering consulting firms, State Water Authorities, the Malaysian National Committees on Large Dams (MYCOLD), Tenaga Nasional Berhad (TNB), and others dam-owning agencies.

Table 3.5 Characteristics of river geometry

Characteristic	Description
Cross-Sectional Profiles (depth and width)	V-Shaped, U-Shaped, Trapezoidal, Rectangular, W-Shaped, Complex Shape

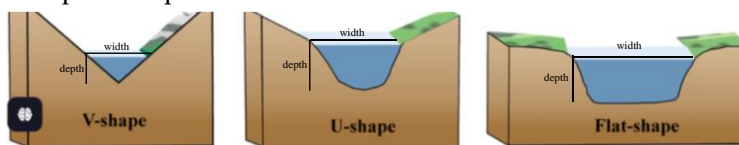


Figure 3.1 Three river cross-sectional types (Liu et al., 2020)

Longitudinal profile

- Classes slope gradient*
- Little or no slope: 0 - 3 % gradient
 - Gentle: 4 - 9 % gradient
 - Moderate: 10 - 15 % gradient
 - Steep: 16 - 30 % gradient
 - Extremely steep: 31 - 60% gradient
 - Excessively steep: > 60% gradient

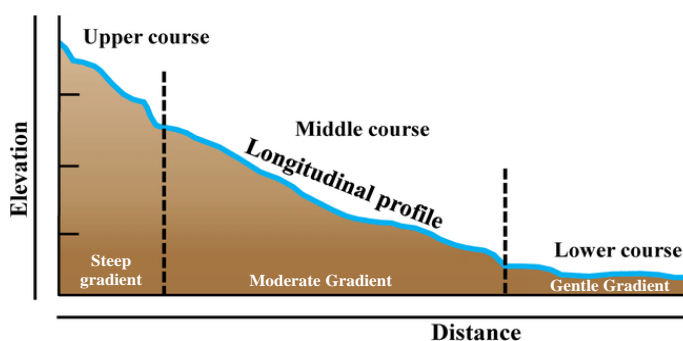


Figure 3.2 Long profile (Liu et al., 2020)

Bank Structure	Material (soil, rock, concrete/artificial structure), riverbank slope, human-made structures, type of vegetation along riverbanks.
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* <https://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/cmp/slope.html>

Sample layout and cross-section profile of Batu Dam and Sg. Batu is provided in **APPENDIX A**.

3.4 Catchment Characteristics

The components of catchment characteristics include data of catchment area size, topography (slope and elevation of the land), soil properties (e.g., type, texture, permeability), land use/land cover classification (forest, urban, agriculture, etc.).

Table 3.6 Catchment characteristic, soil properties and use/land cover source in Malaysia

Characteristic	Description/Source
Catchment area size	DID (https://www.water.gov.my)
Soil properties	Department of Agriculture Malaysia https://geotanih.doa.gov.my/ National Geospatial Centre (Ministry of Natural Resources and Environmental) https://www.mygeoportal.gov.my/en
Land use/land cover	Department of Statistics Malaysia https://open.dosm.gov.my/ Department of Agriculture Malaysia https://geotanih.doa.gov.my/ PLANMalaysia (Federal Department of Town and Country Planning) https://www.planmalaysia.gov.my National Geospatial Centre (Ministry of Natural Resources and Environmental) https://www.mygeoportal.gov.my/en

Global sources that are available are summarized in Table 3.7.

Table 3.7 Global soil properties and use/land cover data source

Characteristic	Description/Source
Soil properties	Global Soil Data (FAO/ISRIC) https://soilgrids.org European Soil Data Centre (ESDAC) https://esdac.jrc.ec.europa.eu/content/generalized-soil-map-peninsular-malaysia USGS (U.S. Geological Survey) https://www.usgs.gov FAO (Food and Agriculture Organization) https://www.fao.org/soils-portal
Land use/land cover	Copernicus (EU) https://land.copernicus.eu ESA (European Space Agency) https://www.esa-landcover-cci.org

USGS (U.S. Geological Survey)
<https://www.usgs.gov>

NOAA (National Oceanic and Atmospheric Administration)
<https://www.noaa.gov>

European Environment Agency (EEA)
<https://www.eea.europa.eu>

3.5 Building footprints

Building footprint data refers to the spatial outlines or shapes of buildings as represented on a map or satellite image. It helps to identify structures at risk and estimate population exposure. It also allows modelers to assess how floodwater interacts with structures and estimate the depth of flooding within buildings.

Table 3.8 Source for building footprints data

Sources	Description
Google Open Buildings	Available: 2016 – 2023 https://sites.research.google/gr/open-buildings/
OpenStreetMap (OSM)	Available: 2013 – Present https://www.openstreetmap.org
Google Earth	Available: 2000 – Present https://earth.google.com

Summary table of data collection and analysis for dam analysis shown in Table 3.8

Table 3.9 Data type and purpose for dam analysis

Type of Data	Purpose (Type of Analysis)
a) Hydrological Data	
- Rainfall	- Hydrology analysis, IDF curve, hydrological modelling and hydraulic modelling.
- Streamflow / Discharge	- Hydrology analysis (hydrograph), rating curve, hydrological modelling and hydraulic modelling.
- River stage	- Hydraulic analysis, rating curve, flood map and hydraulic modelling.
b) Hydraulic Data	
- Sediment data	- Hydraulic analysis and hydraulic modelling.
- Tidal data	- Hydraulic analysis and hydraulic modelling.
c) River Characteristics	
- Cross-section and Longitudinal Section	- Hydraulic analysis, hydraulic modelling and detailed design.
- River Geometry	- Hydraulic modelling.
- River Structure	- Hydraulic analysis, flood map, detailed design and hydraulic model.
d) Maps & Plans	
- Topographic maps	- Hydrology analysis, hydraulic analysis and flood map.
- Structural plan & drainage layout	- Hydraulic analysis and flood map.
- Local development plan	- Hydraulic analysis, flood map and detailed design.
- Master development plan	- Flood map, detailed design and hydraulic analysis.
- Landuse map (existing & future)	- Hydraulic analysis, hydraulic analysis, flood map and hydrological modelling.
- Soil map	- Hydraulic analysis, sedimentation and erosion analysis.
- Geology map	- Detailed design.
- Contour map	- Flood map and hydraulic modelling, hydrology analysis.
- Site survey plan	- Hydraulic analysis, flood map, hydraulic modelling and detailed design.
- Cadastral plan/ Sheet	- Hydraulic analysis and flood map, detail design.
e) River Section & Corridor Survey	
- River section	- Hydraulic analysis and hydraulic modelling.
- Corridor survey	- Hydraulic analysis and flood map.
f) Satellites & Images	
- Images (Aerial photograph)	- Flood map.
- Digital Earth Model (DEM) & Digital Terrain Model (DTM)	- Hydraulic analysis and flood map.
- Satellite imagery (Earth Mapping)	- Flood map.

g) Vulnerability Data	
- Socio-economy data	- Flood damage assessment and ERP.
- Physical Data	- Flood damage assessment.
h) Data for Previous Flood Events & Related Studies	
- Flood prone area	- Built-up platform level and flood map.
- Flood level	- Hydraulic analysis, flood map and hydraulic modelling.
- Extent of flooding	- Hydraulic analysis and flood map.
- Flood depth	- Hydraulic analysis and flood map.
- Flood damage	- Hydraulic analysis and flood map.
- Flood history	- Hydraulic analysis and flood map.
- Documented report	- Hydrology analysis, hydraulic analysis, flood map, flood damage assessment and detailed design.
- Oral/communication/interview	- Hydrology analysis, hydraulic analysis, flood map, ERP and flood damage assessment.
i) Flood Properties	- Flood risk and detailed design.
j) Soil Investigation	- Detailed design.
k) Catchments Characteristics	- Hydrology analysis, hydraulic analysis, hydrological modelling and hydraulic modelling.
l) Data for Operation and Maintenance	
- As Built Plan	- Standard Operation and Maintenance Procedure.

CHAPTER 4 HYDROLOGICAL ANALYSIS AND MODELLING

4.1 Hydrological Analysis

Hydrological analysis provides the basis for estimating inflow hydrographs that simulate potential flood scenarios. It involves the assessment of rainfall, runoff, and river flow characteristics within the dam's catchment area. This analysis supports the design of inflow flood scenarios such as the Probable Maximum Flood (PMF) and CDF.

4.1.1 Rainfall time series

A long-term rainfall time series is needed to identify patterns, detect extreme events, and derive design storms. This data can be obtained from rain gauge stations or remote sensing sources. Important considerations include data completeness and quality control (removing errors, filling gaps), temporal resolution (e.g., daily, hourly) suitable for modeling needs, and consistent surrounding stations (cross-validation where necessary). For details can refer Department of Irrigation and Drainage Malaysia. (2000). Urban stormwater management manual for Malaysia (Vol. 13, Section 13.4: Rainfall time series).

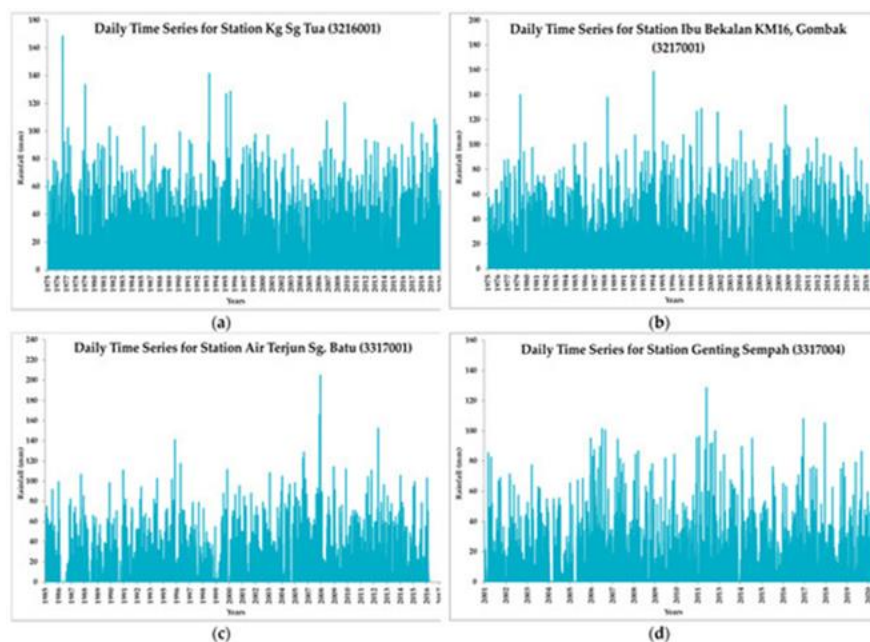


Figure 4.1 Example plotted daily rainfall time series (Allias Omar et al., 2022)

4.1.2 Double Mass Curve (DMC)

A double mass curve (DMC) is a graphical method used in hydrology and meteorology to assess the consistency of data, detect shifts in data trends, and analyze the relationships between variables like precipitation and runoff. It involves cumulative values of one hydrologic variable

(e.g., precipitation at a station) plotted against the cumulative values of a related variable (e.g., the average cumulative precipitation of several surrounding stations) (Figure 4.2). The resulting curve is called a double mass curve. If the data is consistent (i.e., the relationship between the two variables remains constant), the double mass curve will be a straight line. A change in the slope of the curve indicates a change in the relationship between the variables, suggesting a potential inconsistency in the data.

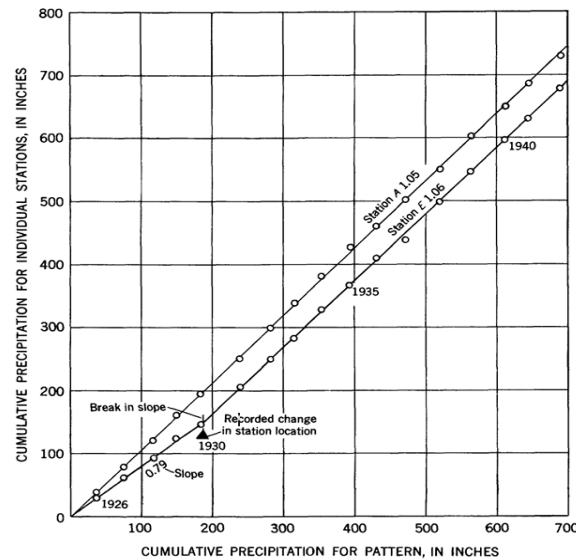


Figure 4.2 Double-mass curve of precipitation data (Searcy & Hardison, 1960)

4.2 Inflow Design Flood (IDF)

The selection of the Inflow Design Flood (IDF) for a dam should be based on its hazard classification as outlined in the MyDAMS guidelines. The recommended minimum inflow design flood (IDF) for each hazard category is summarized in Table 4.1.

Table 4.1 Recommended Minimum Inflow Design Floods (MyDAMS, 2017)

Dam Hazard Rating	PAR	AEP of IDF
Low	0	1 in 100 to 1 in 1,000
Significant	1-10	1 in 1,000 to 1 in 1,000
High	11-100	1 in 10,000
Very High	>100	PMF

*PAR= Population at Risk

Low hazard rating dams is only required to perform hydrograph analysis (refer HP1, DID). This level of design is generally sufficient due to the lower potential consequences of failure. For very high hazard rating dams, the PMF must be used. To estimate the PMF, the Probable Maximum Precipitation (PMP) must be calculated first.

Figure 4.3 illustrated summary of hydrological analysis need for input in modelling.

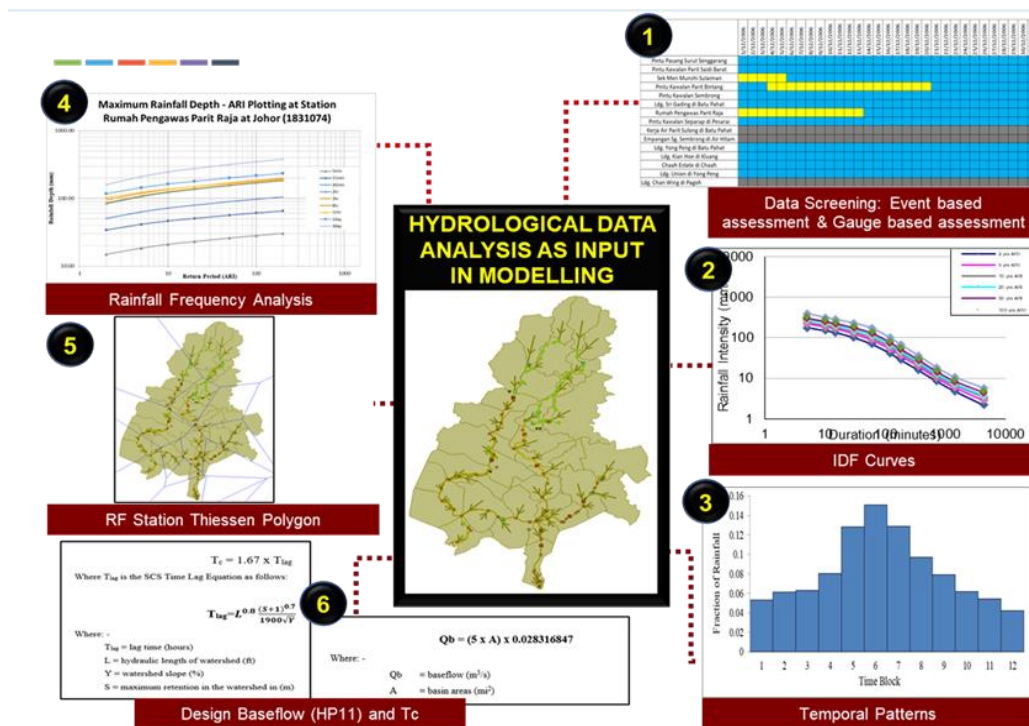


Figure 4.3 Summary data input for hydrological analysis

4.3 Probable Maximum Precipitation (PMP)

Probable Maximum Precipitation (PMP) is defined as the highest amount of rainfall that can occur in a specific area over a set period, without considering long-term climate trends (WHO, 2009). PMP is used to estimate the Probable Maximum Flood (PMF) for dam catchments and to develop the PMF hydrograph. According to NAHRIM Technical Research Publication No. 1, PMP can be estimated using either physical or statistical methods. More information is available in NAHRIM Technical Research Publication No. 1 – Derivation of Probable Maximum Precipitation for Design Floods in Malaysia.

4.3.1 Statistical Method (Hershfield)

Hershfield’s method (1961, 1965) is one of the primary approaches recommended by the WMO (1986) for estimating Probable Maximum Precipitation (PMP). This statistical method is widely used especially at stations with long-term rainfall records. However, if the data record is too short to capture extreme events, the PMP estimates may be underestimated. In Malaysia, the Hershfield method has been applied to estimate PMP for various durations, including 30 minutes, 1 hour, 3 hours, 6 hours, 12 hours, 1 day, 2 days, 3 days, 5 days, and 7 days.

$$X_{pmp} = \bar{x}_n + K_m \cdot \sigma_n$$

where:

K_m = Frequency factor (typically derived from envelope curves)

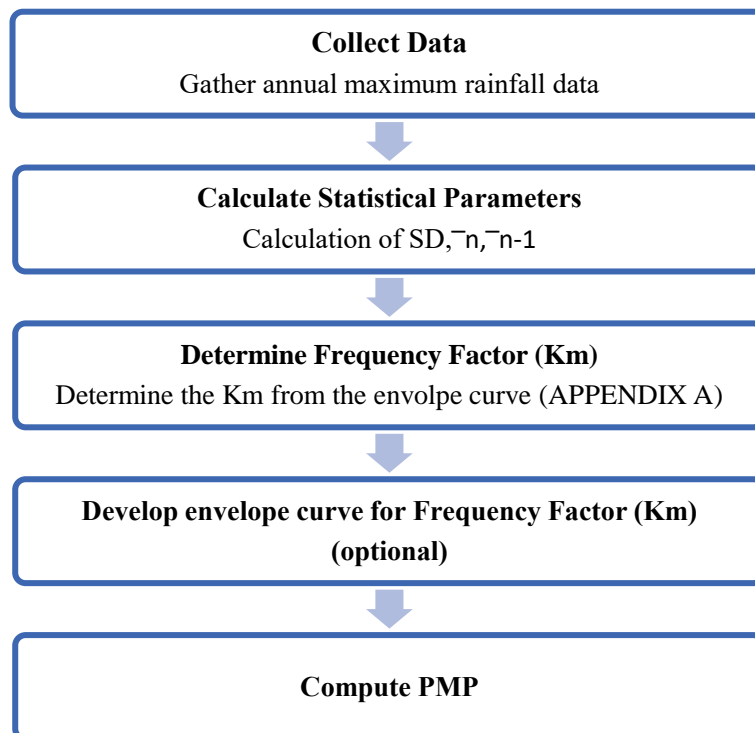
σ_n = Standard deviation of the annual maximum precipitation (SD)

\bar{x}_n = mean of the annual maximum precipitation.

To obtain accurate results, the 20 highest rainfall values should be removed before calculating the mean and standard deviation for each station

$$K_m = (X_1 - \bar{x}_{n-1}) / \sigma_{n-1}$$

In Malaysia, NAHRIM has developed K_m curves separately for West Malaysia and East Malaysia. These curves provide K_m values for various rainfall durations. Users should refer to the appropriate K_m values in **Appendix B** and apply them directly in the PMP calculation. The following are the steps to calculate PMP based on the NAHRIM approach:



An example of **PMP calculation** using Hershfield's statistical method is provided in **APPENDIX B** to guide through the process step by step.

4.3.2 Physical method (Hydro-meteorological)

This method assumes that PMP occurs during a storm with **maximum atmospheric moisture** and **peak storm efficiency**. Because certain factors—such as air convergence and condensation—cannot be measured directly, the highest recorded rainfall from past extreme storm events is used as the baseline. PMP is then estimated by adjusting this observed maximum rainfall using a **Moisture Maximization Factor (MMF)**:

$$R_m = R_0 \times \frac{W_m}{W_s}$$

where

R_m = Maximized rainfall (PMP)

R_0 = Highest observed rainfall

W_s = Precipitable water corresponding to storm dew point

W_m = Precipitable water corresponding to maximum dew point at the location of storm

The amount of precipitable water (W) in a column of air of height z is calculated as

$$W = \int_0^z \rho_w dz = - \int_0^{p_z} \frac{\rho_w}{\rho_a g} dp = \int_0^{p_z} \frac{q}{g} dp$$

where

ρ_a and ρ_w = densities of air and water vapour

q = specific humidity (~mixing ratio)

p_z = atmospheric pressure at altitude z ,

g = acceleration due to gravity

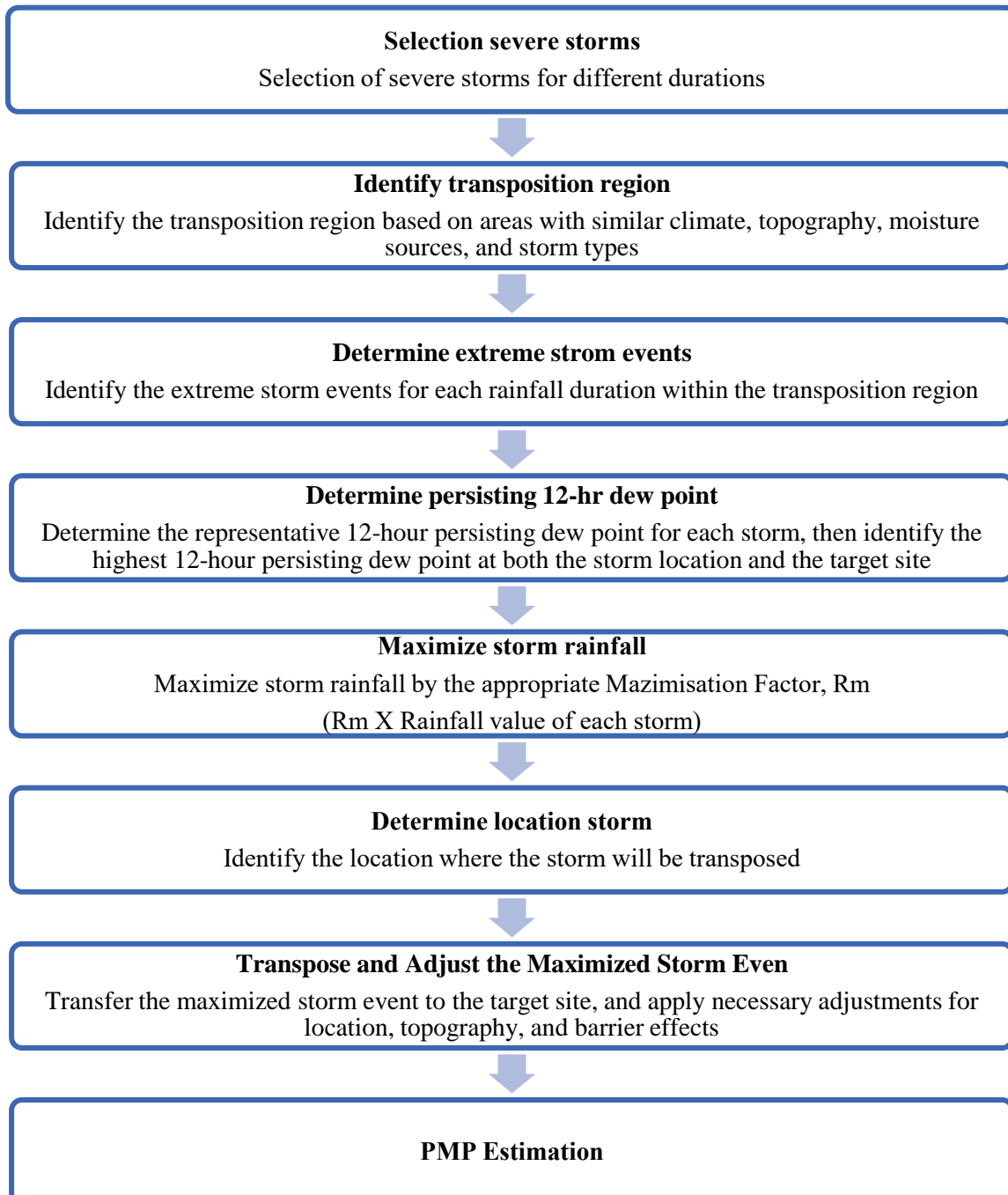
If vertical sounding data (like weather balloon data) isn't available, precipitable water in the atmosphere can be estimated using sea-level dew point temperatures and standard atmospheric calculations. The rainfall data can be adjusted using the following techniques:

- | | |
|-----------------------------------|---|
| (i) Moisture Maximization: | - Multiply the observed rainfall by a Moisture Maximization Factor (MMF).
MMF = Maximum moisture / Moisture during the actual storm. |
| (ii) Transposition: | - Move storm data from a nearby area with similar climate and terrain to your study area.
- Useful when your catchment doesn't have enough storm data |
| (iii) Envelopment: | - Pick the highest rainfall values from different data sources. |

-
- Helps estimate extreme rainfall when data is not consistent across all areas or durations.
-

Note: This method is data-intensive and requires detailed storm data (dewpoint, elevation, moisture, etc.). It is more complex than the statistical method.

Below are the steps to calculate PMP using physical method:



For detailed explanation and example calculations, refer to *NAHRIM Technical Research Publication No. 1*.

4.4 Rainfall-runoff (RR) models

These models are used to simulate how rainfall is transformed into surface runoff within a catchment or watershed. They help to predict water flow resulting from rainfall events. One of the key outputs of these models is the runoff hydrograph which illustrates how the flow of water from the catchment changes over time in response to rainfall.

4.4.1 Model Types

Several types of rainfall-runoff models can be used depending on data availability, catchment characteristics, and study requirements. Common categories include:

Table 4.2 Common model categories (Sitterson et al., 2018)

Model Type	Description	Examples
Conceptual Models	Use simplified water balance components to simulate runoff generation.	HEC-HMS, TOPMODEL
Physically-Based Models	Simulate detailed processes using spatial data on soil, land cover, and terrain.	MIKE SHE, SWMM
Empirical Models	Use statistical or simplified equations based on observed data.	Rational Method, SCS-CN

For the full list of computer modeling software and more details, refer to Computer Models and Software, Urban Stormwater Management Manual, DID in Appendix 17.A.

4.4.2 Input data requirements

To run a rainfall-runoff model, required data is typically summarized as follows:

Table 4.3 Data input requirements

Rainfall	Design storms (e.g., 50-year, 100-year, PMP) or historical events with suitable time resolution
Catchment	Area, slope, land use/cover, soil type, drainage network
Hydrological Parameters	Curve Number (CN), infiltration rate, time of concentration, initial abstraction
Topographic	Digital Elevation Model (DEM) for delineating flow paths

* All input data must be processed and quality-checked before using the model.

4.4.3 Calibration and validation

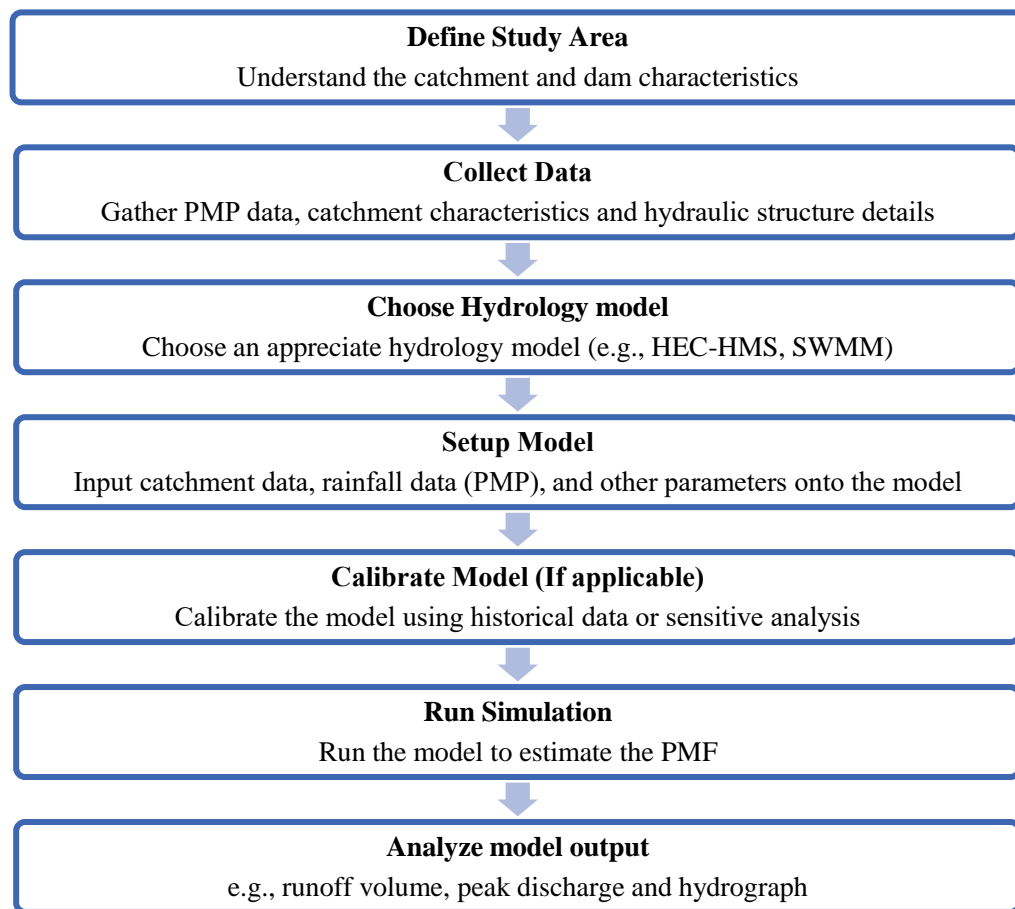
Model accuracy should be tested through calibration (adjusting parameters to match observed data) and validation (testing with other events, if available) using performance indicators like Nash-Sutcliffe Efficiency (NSE), RMSE, or correlation coefficient. If the observed flow data is not available, use regional estimates and run sensitivity analysis to check the model's reliability.

4.5 Probable Maximum Flood (PMF)

The PMF is the largest theoretical flood that could result from the most extreme combination of meteorological and hydrological conditions. It is calculated using PMP data specific to the region. There are **two main methods** for estimating PMF:

- **Hydrological Process Models**
- **The Unit Hydrograph Method** (Not recommended for mountainous regions)

This guideline focuses on PMF estimation using **hydrological models**. The steps for applying this method are outlined below:



For the full list of hydrology models, refer to Computer Models and Software, Urban Stormwater Management Manual, DID (Appendix 17.A).

The Unit Hydrograph Method is not recommended for mountainous regions because it assumes a linear and uniform response from the catchment. This simplification does not adequately represent the complex hydrological and physical processes—such as variable infiltration, steep gradients, and rapid runoff—that typically occur in mountainous terrains.

CHAPTER 5 DAM BREAK MODELLING

5.1 Introduction to Breach Parameters

Breach parameters are essential components in dam break modelling, as they define the physical characteristics of the breach that forms in a dam during failure. These parameters directly influence the outflow hydrograph, flood peak, timing, and extent of downstream inundation. Accurate selection and estimation of breach parameters are crucial for simulating realistic dam failure scenarios and assessing potential flood risks. Key breach parameters typically include breach formation time, breach width, breach depth, breach side slopes (horizontal-to-vertical (H:V) ratio), and breach shape (geometric profile e.g., trapezoidal, triangular, or rectangular).

5.2 Estimation of Dam Breach Parameters

5.2.1 Breach Parameters for Embankment Dams

The dimensions of a trapezoidal dam break are shown in Figure 3.4 below. Breaching begins when the reservoir water surface elevation reaches the failure elevation Y_f (above the datum). The formulae are (Froehlich, 2017a):

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

where, \hat{B}_{avg} = expected value of B_{avg} in metres (shown as in the figure as \bar{B})

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

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

where, \hat{m} = (shown as ‘z’ in the figure) expected average break side-slope ratio (horizontal: vertical) and,

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

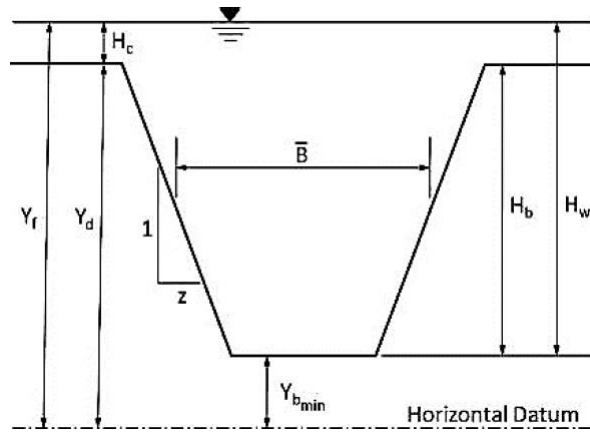


Figure 5.1 Final dimensions of a trapezoidal embankment dam break approximation in meters (adopted from Froehlich, 2008)

where,

\hat{t}_f = break formation time in seconds

V_w = Volume of water above break bottom in m^3

H_b = Height of break in meters

5.2.2 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 break in case of concrete and masonry dams:

$$B_{avg} = 0.12 \times 1.5^{Type} \times \left(\frac{V_w}{H_b^3} \right)^{1/4} \times \left(\frac{L_a}{H_b} \right)^{2/3} \times H_b$$

where,

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

L_a = approach flow width

5.2.3 Dam Breach Hydrograph and Peak Outflow

5.2.3.1 Empirical Equation for Estimating Peak Discharge

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

$$\hat{Q}_p = 0.0175 \times k_M \times k_H \times \sqrt{\frac{g V_w H_w H_b^2}{W_{avg}}}$$

where,

\hat{Q}_P = Peak discharge in m³/s

$$k_m = \begin{cases} 1, & \text{for non – overtopping failure modes} \\ 1.85, & \text{for overtopping failure modes} \end{cases}$$

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

H_b = height of break in metres

H_S =6.1 m

H_W = height of water above the break bottom

g = acceleration due to gravity

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

The effect of embankment height on peak discharge as described by the factor k_H changes significantly when $H_b > 6.1$ m. For smaller dams, peak discharge tends to be higher than expected. Soil properties such as compaction, cohesion, and particle size also play a key role in embankment erosion, speeding up break growth and increasing peak discharge.

5.2.3.2 Semi-theoretical Equations for Estimating Peak Discharge

The semi-theoretical formula is presented below:

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

where,

$Q_{P_{max}}$ = maximum possible peak discharge from a break of specified dimensions that forms instantly, equation as below

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

α =0.000045

β =500 × [(W_{avg} × H_b^2)/ V_W]^{2/3}

\hat{Q}_p applies to embankment dams, while Q_{pmax} is the maximum peak discharge from the instant removal of a water barrier. Q_{pmax} , based on theory, can be used to check the estimated peak discharge for concrete dams.

5.3 Estimation of Uncertainty Parameters

Differences of dam characteristics and condition (e.g. size, materials, reservoir volume, and erosion conditions) can lead to uncertainty in predicting breach width, formation time, and peak flood flow. This affects the accuracy of dam break flood models. Main sources of uncertainty include limited data, different site conditions and model assumptions.

To reduce these uncertainties and improve the reliability of dam break modeling, several approaches can be applied which include sensitivity analysis, Monte Carlo simulations (e.g., peak discharge at 10%, 50%, and 90% confidence levels - see details on Froehlich and Goodell, 2012), envelope curves (use curves based on past dam failures, e.g., from USACE), and comparing different models (empirical vs physical).

5.4 Breach Prediction Methods

There are several methods to estimate breach parameters such as breach width, height, formation time, and peak outflow. These include:

- **Empirical methods** – based on historical dam failures.
- **Semi-physical models** – combine simplified physical processes with input data.
- **Physically based models** – simulate the full breaching process using hydraulic and soil mechanics principles.

A **tiered approach** is often used to match the method with the level of study required, thereby supporting more effective and informed decision-making. The table below summarizes how different breach prediction methods can be applied.

Table 5.1 Tiered approach to dam breach flood mapping (Central Water Commission,2018)

Tier	Applications	Breach Parameter Prediction	Peak Discharge Prediction	Flow Routing	Risk Evaluation
Tier 1 (Basic)	<ul style="list-style-type: none"> • Initial screening • Low hazard dams • Low-resolution terrain (e.g., SRTM, ASTER, ALOS) 	Empirical formulas	Empirical methods (or unsteady routing if inflow hydrograph is available)	Simplified tools (e.g., HEC-HMS, Geo-Dam-BREACH, SMPDBK)	Peak flow, water level, wave travel time

Tier 2 (Intermediate)	<ul style="list-style-type: none"> • Significant or high hazard dams • Medium-resolution terrain (e.g., 10 m LiDAR, INTERMAP) 	Empirical formulas	Unsteady flow routing through breach	1D models (e.g., HEC-RAS, MIKE-11)	Peak flow, water level, wave travel time, 31 approx.. PAR
Tier 3 (Advanced)	<ul style="list-style-type: none"> • High hazard dams with complex downstream • High-resolution LiDAR terrain 	Empirical, WinDAM-B, or 1D/2D erosion models	Unsteady flow routing through breach	1D/2D models	Detailed PAR, flood extent, wave travel time

5.4.1 Empirical models

Empirical methods use equations developed from historical dam failure data. These methods are easy to apply and are widely used when detailed data is not available.

Examples: Froehlich (2008, 2017), Von Thun & Gillette (1990), MacDonald & Langridge-Monopolis (1984), Xu & Zhang (2009). These methods also have reasonably good correlation when comparing predicted values with actual observed values.

Advantages: Easy to apply, suitable for early-stage studies and sensitivity analysis

Limitations: Based on past cases, may not fit unique or large dams, large uncertainties in some cases

Formulas for Von Thun & Gillette (1990), MacDonald & Langridge-Monopolis (1984), and Xu & Zhang (2009) are provided in Appendix C.

Table 5.2 Common empirical models (West et al., 2018)

Froehlich (2008, 2017)	Estimates breach width and formation time based on dam height and reservoir volume, Most accurate and widely used, Suitable for embankment dams, Recommended as the standard model
Von Thun & Gillette (1990)	Provides typical breach dimensions for earthfill dams based on observed data, Accurate and simple to use, Good for quick estimates, also a reliable choice
MacDonald & Langridge-Monopolis (1984)	Uses eroded volume to calculate breach dimensions, accurate in only 1 out of 3 tested cases, less reliable for failure time
Xu & Zhang (2009)	Useful for complex cases, heavily depends on soil erodibility (hard to quantify), Better for advanced studies, not ideal for routine use

* Froehlich (2008/2017) and Von Thun & Gillette (1990) are recommended for most applications

An example calculation using the **Froehlich (2017)** formula to estimate breach parameters is included in **Appendix D**.

Table 5.3 shows the possible range of breach parameters for different types of dams which helps users to choose reasonable values when detailed site data is not available.

Table 5.3 Possible range of break parameters (USACE, 2014)

Dam Type	Average Breach Width (Bavg)	Horizontal Component of Breach Side Slope (H) (H:V)	Failure Time,tf (hrs)
Earthen / Rockfill	(0.5 to 3.0) x HD	0 to 1.0	0.5 to 4.0
	(1.0 to 5.0) x HD	0 to 1.0	0.1 to 1.0
	(2.0 to 5.0) x HD	0 to 1.0 (slightly larger)	0.1 to 1.0
	(0.5 to 5.0) x HD*	0 to 1.0	0.1 to 4.0*
Concrete Gravity	Multiple Monoliths	Vertical	0.1 to 0.5
	Usually $\leq 0.5 L$		0.1 to 0.3
	Usually $\leq 0.5 L$		0.1 to 0.2
	Multiple Monoliths		0.1 to 0.5
Concrete Arch	Entire Dam	Valley wall slope	
	Entire Dam	0 to valley walls	≤ 0.1
	(0.8 x L) to L	0 to valley walls	
	(0.8 x L) to L	0 to valley walls	
Slag / Refuse	(0.8 x L) to L	1.0 to 2.0	0.1 to 0.3
	(0.8 x L) to L		≤ 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 break), and may therefore have longer breach widths and times than what is shown here. HD = height of the dam; L = length of the dam crest

5.4.2 Semi-Physical Models

Semi-Physical models include some physical processes, but they are simpler and faster to run than full physical models. These models estimate the breach outflow hydrograph based on input such as erosion rates or breach geometry parameters.

Example: HEC-RAS (Allows users to input breach shape and growth rates manually or select regression-based defaults).

Advantages: More realistic than empirical-only models, good for intermediate-level analysis.

Limitations: Still involves assumptions, accuracy depends on user input.

5.4.3 Physical-based Models

Physically based models simulate the **entire dam breaching process** using detailed equations based on hydraulic, structural integrity, and soil mechanics characteristics. These include erosion, sediment transport, slope stability, piping, headcutting, dam material properties, reservoir forces, erosion rates.

Examples: EMBREA, WinDAM, AREBA, HR BREACH, NWS, SMPDBK and others.

Advantages: High accuracy if data is sufficient, useful for final design or forensic analysis.

Limitations: Complex and time-consuming, requires detailed input and calibration.

Table 5.4 Example of physical-based models (West et al., 2018)

Model	Description
EMBREA	Focus: Embankment dam breaches (overtopping/piping)
HR Wallingford (UK)	Advantages: Suitable for both simple and complex dam structures, flexible (does not assume a fixed breach shape), can

	simulate erosion and slope failure realistically, user-friendly interface, supports Monte Carlo simulations Limitations: Simple one-dimensional flow calculations
WinDAM USDA ARS, NRCS, Kansas State University (USA)	Focus: Breach modeling for earthen embankments (internal erosion and surface erosion) Advantages: Capability to model erosion in multiple earthen auxiliary spillways Limitations: Only model homogeneous earthen dams, breach development must be pre-defined.
AREBA HR Wallingford (UK)	Focus: Overtopping failures (homogeneous and composite embankments), internal erosion failures (homogeneous dams) Advantages: Extremely fast simulations (sub-second runtimes), ideal for quick assessments and model iteration, minimal data input is required- Limitations: Pre-defined breach geometry, less suitable for highly detailed breach progression analysis

EMBREA is a flexible and comprehensive model. This model is the best for complex dams requiring detailed failure mechanism simulations. WinDAM is well-suited for use in standard earthen dam assessments, particularly in agricultural or rural settings. AREBA is known for its simplicity, speed, and ease of use, making it suitable for quick assessments and preliminary analysis.

5.5 Hydrodynamic Modelling

This type of modelling simulates how the water flows and spreads downstream after a breach happens. It focuses on the movement of floodwater across channels and floodplains. Output predictions include maximum water depth, flood extent, flood arrival time, and flow velocity.

5.5.1 Modelling software

Various models have been developed to simulate dam breach processes and downstream flood routing. Early models include DAMBRK (1977), followed by FLDWAV, HEC-1, HEC-HMS, and HEC-RAS for hydrologic and hydraulic analysis. The summary table below shows the models developed for dam break analysis and flood routing:

Table 5.5 Model software for dam break analysis

Model	Purpose
CFX, Fluent ANSYS	3D fluid dynamics simulations in complex systems (e.g., industrial applications)
InfoWorks ICM Autodesk	Integrated 1D, 2D, and 1D+2D hydrodynamic and hydraulic modeling for flood modeling
TUFLOW Classic/ TUFLOW/ TUFLOW FV BMT WBM	1D, 2D, and 3D hydrodynamic modeling for floodplains, rivers, and coastal areas

Flood Modeller Pro CH2M Hill (formerly Halcrow Group)	1D and 2D hydrodynamic solvers for river, floodplain, and urban drainage modeling
SOBEK Suite / DELFT3D DELTARES	1D, 2D, and 3D hydrodynamic modeling for rivers, floodplains, and coastal areas
MIKE11/MIKE21/MIKE3 DHI Group	1D, 2D, and 3D hydrodynamic modeling for rivers, coastal areas, and urban water
MASCARET / TELEMAC Electricité de France	Hydrodynamic modeling for river and coastal areas (2D and 3D capabilities)
ISIS Halcrow Group (now CH2M Hill)	1D and 2D hydrodynamic modeling for rivers, floodplains, and hydraulic structures
HEC-RAS US Army Corps of Engineers (USACE)	1D, 2D, and 3D hydrodynamic modeling for river, floodplain, and dam break analysis
PCSWMM CHI (Computer Hydraulics Inc.)	1D, 2D, and 3D hydrodynamic modeling for stormwater and urban drainage systems

Figure 5.2 illustrates the summary input data required for dam break flood hydrodynamic modelling.

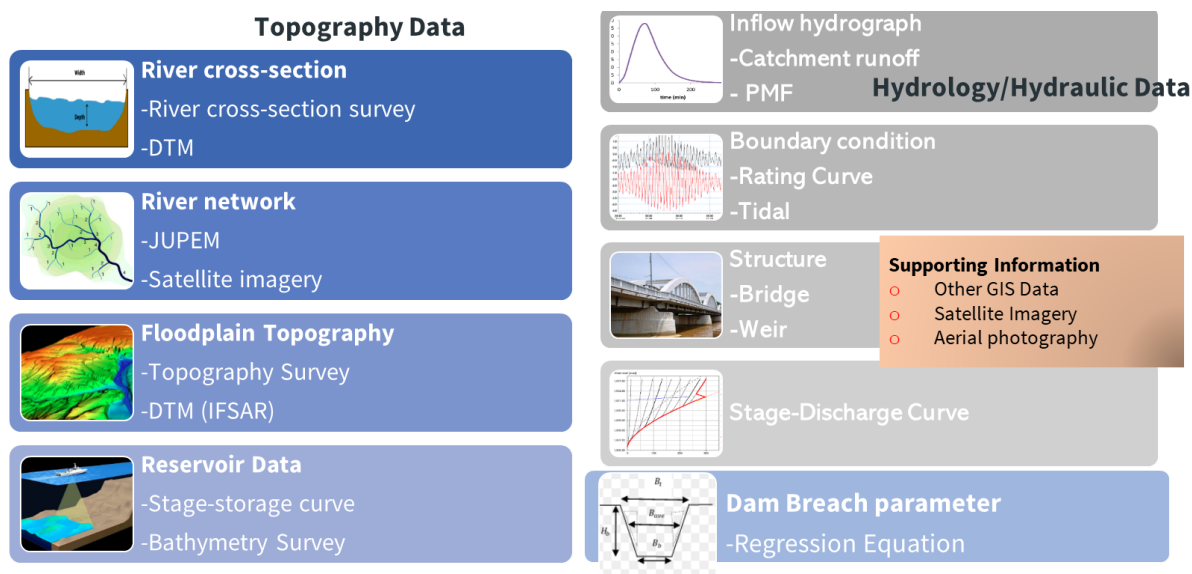


Figure 5.2 Overview of data input for hydrodynamic model

5.5.2 Model Dimensions

The choice of model dimension—1D, 2D, or 3D—depends on the complexity of the area being studied, available data, and the purpose of the simulation. Each model differs in dimensionality and produces different results.

1D (One-Dimensional) Models

1D models simulate water flow in one direction, usually downstream along a river or channel. They are best for simple river systems or long, narrow channels, and are useful for quick assessments.

Advantages: Fast computation, less data required and easy to setup, suitable for steep or well-defined channels, low cost, works on standard PCs, basic training

Limitations: Cannot show how water spreads overland, less accurate in complex terrain or urban areas

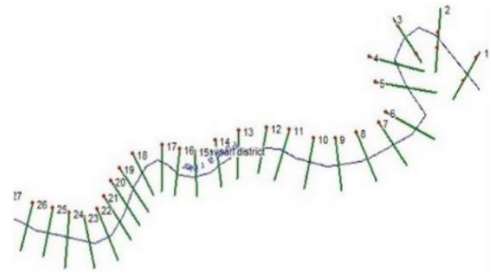


Figure 5.3 1D model output (Pathan et al., 2021)

2D (Two-Dimensional) Models

2D models simulate water flow in two directions (x and y). These models are suitable for **floodplains, urban areas, dam break scenarios with overland flow.**

Advantages: More accurate for simulating flood extent, can show how water spreads in different directions, moderate cost and moderate training

Limitations: Requires more data and computation time, needs detailed topographic input (e.g., DEM).

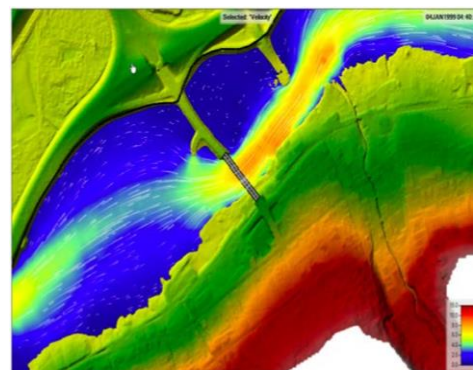


Figure 5.4 2D model output (HEC-RAS 2D User's Manual, 2022)

3D (Three-Dimensional) Models

3D models simulate flow in all three directions: length (x), width (y), and depth (z). Includes turbulence and vertical structures.

Advantages: High accuracy, captures vertical changes and turbulence, best for detailed/local flow analysis.

Limitations: Complex setup & long run times, high cost, requires high-performance computing (HPC), advanced training.

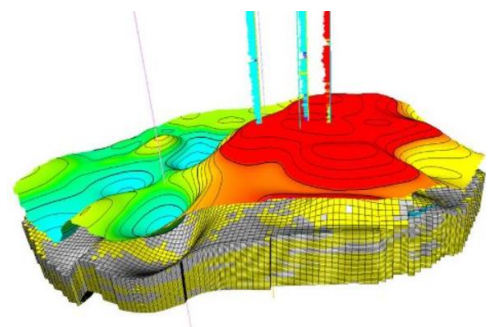


Figure 5.5 3D model output*

*<https://kpfu.ru/eng/priority-areas/oil-production-refining-and-petrochemistry/world-class-laboratories/3d-geo-modelling>

A full list of 1D, 2D, and 3D models, along with their availability is provided in **APPENDIX E**.

5.5.3 Downstream Flood Routing

Flood routing determines flooded areas, depths, flow velocities, and warning times after a dam breach. Models must balance accuracy and computational demand. Typically, the analysis extends downstream to a major river, reservoir, or the sea, or until flow velocity drops below 0.3 m/s. Figure 5.5 illustrates the general procedure for defining downstream model boundaries in the event of a cascade failure scenario. This figure serves as a useful reference to guide the delineation of hydraulic model boundaries in such cases. Tables 5.6 and 5.7 present the critical overtopping depths for embankment and concrete gravity dams, respectively. These values represent the threshold water levels above the dam crest at which the likelihood of dam failure significantly increases. They should be used as reference parameters when establishing potential failure conditions within the hydraulic modelling framework.

Table 5.6 Critical Overtopping Depth for Embankment Dams (Central Water Commission,2018)

Dam condition	Dam Description*	Critical Overtopping Depth ** (m)
Good	No seepage, no settlement, slopes intact	0.61
Fair	Moderate seepage, minor crest settlement, some slope erosion	0.3
Poor	Excessive seepage, major crest slump, cracks, and severe slope erosion	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 5.7 Critical Overtopping Depth for Gravity Dams (Central Water Commission,2018)

Dam Height (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

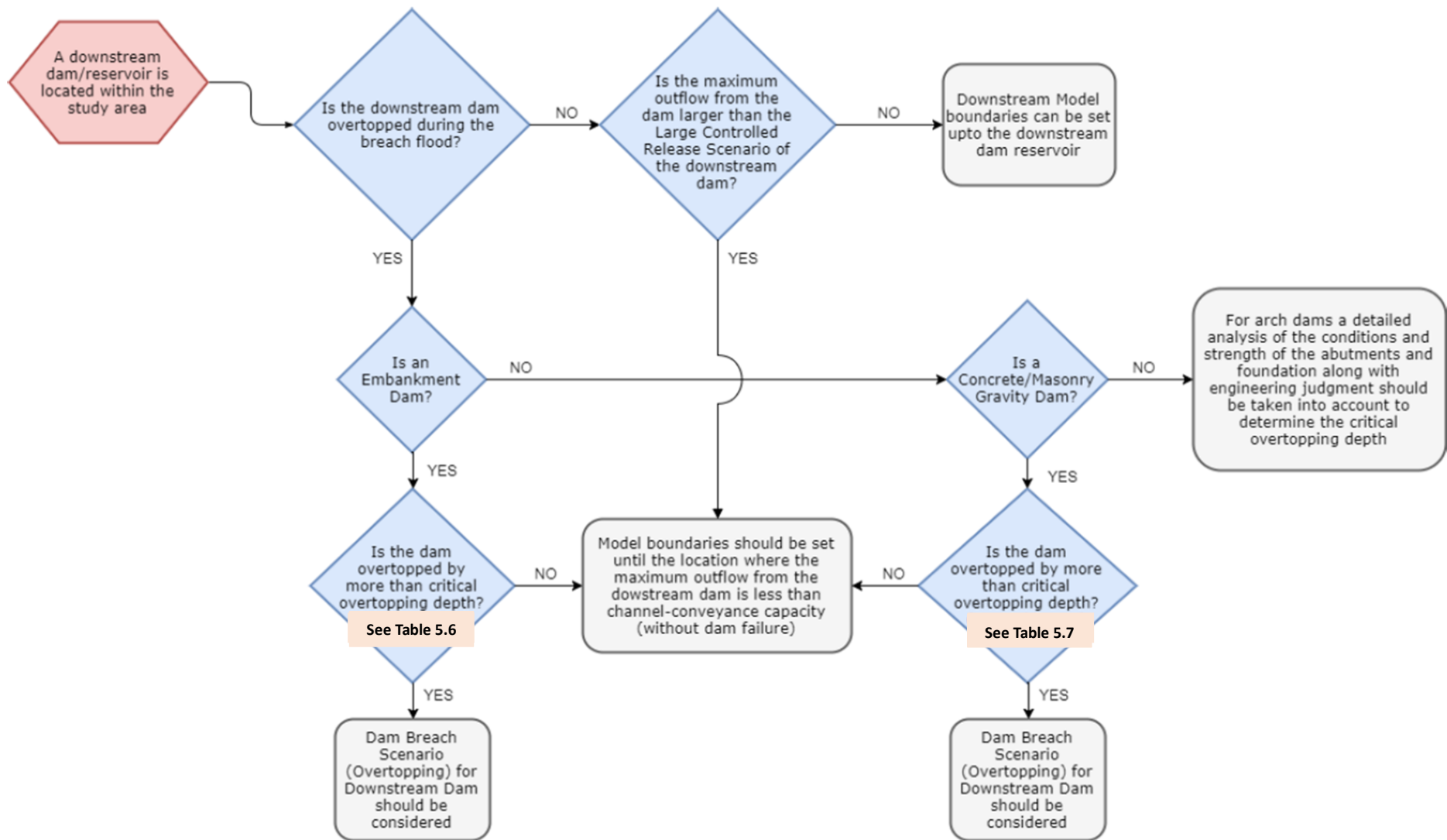


Figure 5.6 General procedure to define the downstream model boundaries in case of Cascade Effect (Central Water Commission,2018)

CHAPTER 6 FLOOD HAZARD MAP GUIDANCE

6.1 Introduction

A flood hazard map shows areas that are at risk of flooding. It helps identify zones that may be affected based on flood depth, extent, and likelihood. These maps use standardized colors and symbols to represent different hazard levels, supporting planning efforts, emergency response, and public awareness. Map-making involves planning, data analysis, design, and final delivery.

6.2 Coordinate System and Map Projection

Map projection ensures that spatial data is accurately represented on a flat map. In flood hazard mapping, a suitable projection helps maintain the correct position, shape, and scale of flood zones. All spatial data **must use the Geocentric Datum of Malaysia 2000 (GDM2000)**.

Table 6.1 GDM 2000 Coordinates System

Coordinate System		Geodetic Datum	
Malaysia Real-Time Kinematic GNSS Network (MyRTKnet)		Ellipsoid: GRS80 Reference Frame: ITRF2000 Epoch: 2000.0	
Nama GCS	EPSG (WKID)	ESRI Name	Coverage Area
GDM2000	4742	GCS_GDM_2000	Seluruh Semenanjung, Sabah dan Sarawak

Table 6.2 GDM 2000 Projection Information

Projection	EPSG (WKID)	ESRI Name	Coverage Area
GDM2000 / East Malaysia BRSO	3375	GDM_2000_BRSO_East_Malaysia	Sabah dan Sarawak
GDM2000 / Peninsula RSO	3376	GDM_2000_MRSO_Peninsular_Malaysia	Semenanjung Malaysia

6.3 Map Elements

Maps include several common elements depending on their purpose, audience, and scale. The key elements consist of:

- **Title/Subtitle** Clearly states the map’s purpose, area, and topic, usually the largest text.
- **Author/Source(s)** Authority logo, project number, Revision number and date (month Year)
- **Index** Shows how the map fits into a larger series, useful for large flood areas
- **Legend/Symbology** Explain map symbols (dots, lines, shapes) clearly, usually in a box.
POI category, District boundary, main river, railway, road, flood depth, cadastral lot and state boundary etc.

- **Date of Preparation** Indicates when the map or its data was produced, showing data relevance
- **Orientation/North Arrow** Shows the direction of true north for accurate navigation
- **Grid/Coordinates** Displays latitude and longitude lines to help locate places and measure distances.
- **Scale** Shows the relationship between map distance and real-world distance
 - 1:50,000 scale – Commonly used for larger areas.
 - 1:25,000 scale – Used for smaller areas.
 - 1:40,000 scale – Used for more detailed areas
- **Others** Includes features like map projection, neat lines (borders), inset maps (for broader context), logos, and labels with readable fonts.

Figure 6.1 illustrates key elements in flood hazard map

FLOOD HAZARD MAP

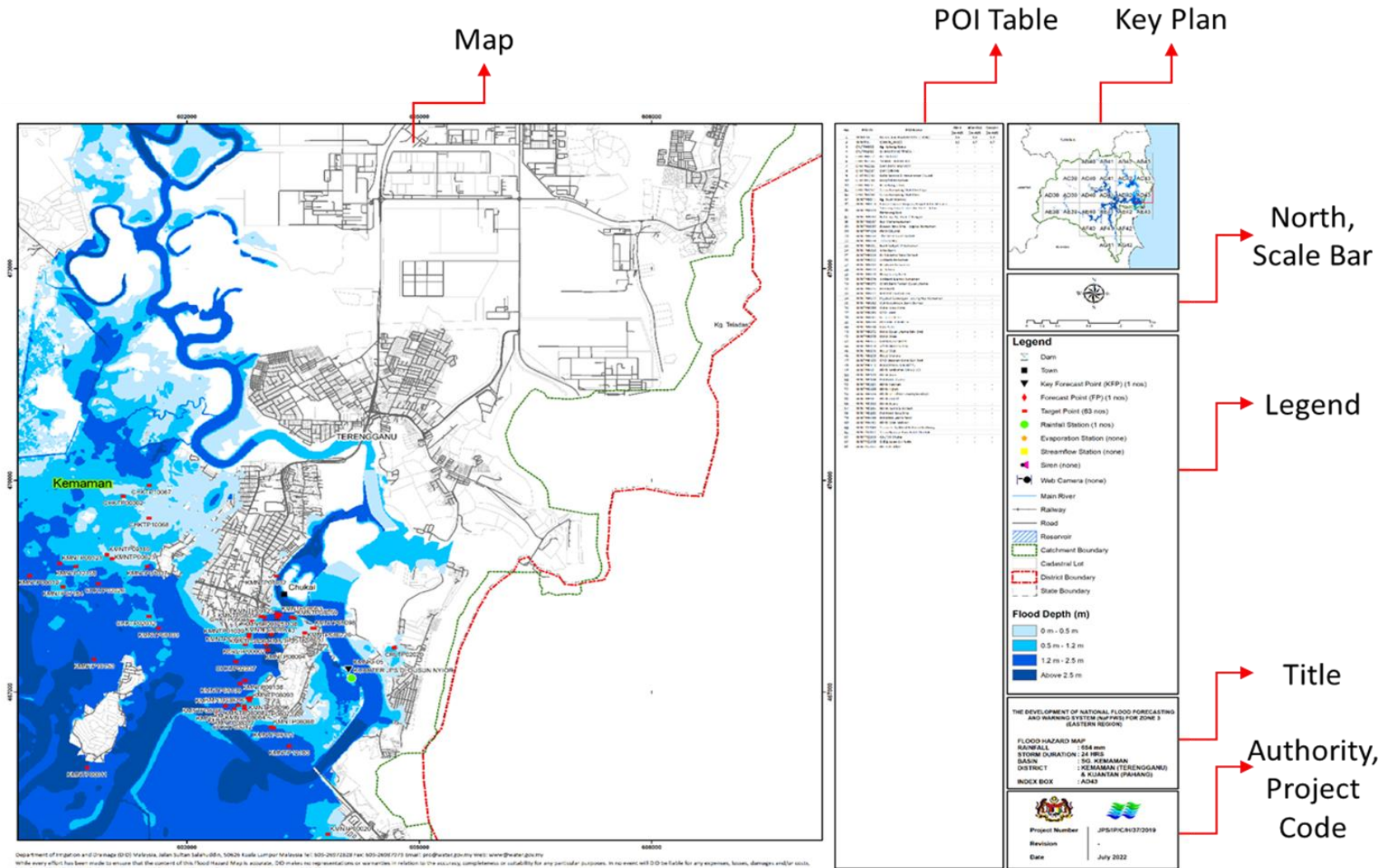


Figure 6.1 Element in flood hazard map

6.4 Map Design

Good map design ensures clarity, accuracy, and visual appeal. It considers how people read and understand information, using points, lines, or area symbols based on the feature type and map scale. The key elements include:

- **Colours** - Colours enhance map appeal. Use fewer than 12 colors to avoid confusion and consider colorblind-friendly designs. For large areas, pastel colors are better than bright ones (*see section 6.6*)
- **Legibility** - Symbols must be clear: minimum 0.5 mm for hollow symbols, 0.4 mm for solid ones. Maintain enough spacing to avoid clutter.
- **Balance** - A balanced map places key features thoughtfully, with the visual center slightly above the geometric center. Hill shading typically assumes light from the northwest for natural appearance.
- **Principles of Cartographic Design**
 - **Concept before Compilation:** Include only essential features.
 - **Hierarchy with Harmony:** Highlight key features and group related ones.
 - **Simplicity from Sacrifice:** Remove unnecessary details to suit the scale.
 - **Maximum Information with Minimum Cost:** Deliver clear, informative maps.
 - **Engage Emotion for Understanding:** Design maps to capture attention and improve comprehension.
 - **Cartographic Generalization Method:** Simplifies complex data to fit the map's scale and improve readability. Methods include:
 - **Simplification:** Remove unnecessary details
 - **Smoothing:** Even out small irregularities
 - **Aggregation:** Group similar points
 - **Amalgamation:** Merge small features
 - **Merging:** Combine parallel lines
 - **Collapsing:** Simplify multi-dimensional features
 - **Refinement:** Remove minor features
 - **Typification:** Use patterns to represent many features
 - **Exaggeration:** Enlarge features for visibility
 - **Enhancement:** Adjust size for clarity
 - **Displacement:** Shift features to prevent overlap
 - **Classification:** Group features by type

6.5 Geographical Information Systems (GIS)

Geographic Information Systems (GIS) transforms mapping by enabling digital maps that support dynamic scaling, data overlays, and easy updates. GIS handles unlimited data and performs advanced analysis, making it essential for spatial queries, change detection, and site selection.

6.5.1 GIS Software Options

GIS software platforms can be broadly categorized into the following groups:

- **Open-Source Desktop GIS:** *Free desktop-based GIS platforms that support spatial data analysis and visualization.*
Examples: *QGIS, GRASS GIS, gvSIG, SAGA GIS, uDig, GeoDa, OpenJump, Diva GIS*
- **Web-based Map Servers:** *Free and open-source tools designed for creating and serving web-based interactive maps.*
Examples: *GeoServer, MapServer, MapGuide Open Source, Mapnik*
- **Spatial Database Management Systems (SDBMS):** *Systems designed to manage, store, and query spatial data efficiently.*
Examples: *PostGIS, SpatiaLite, TerraLib*
- **Commercial GIS Software:** *Proprietary platforms offering comprehensive features for professional spatial analysis.*
Examples: *ArcGIS, MapInfo, GeoMedia, Smallworld, Maptitude, CARTO*

6.5.2 GIS Data Types

In GIS, real-world features are represented as spatial data organized into thematic layers. These data are typically classified into two main types:

- **Raster Data:** Data represented as a grid of cells (pixels), each holding a numeric value corresponding to a specific attribute.
Examples: *Digital Elevation Model (DEM), land use maps, flood depth grids, velocity surfaces, arrival time layers.*
- **Vector Data:** Data represented by geometric shapes such as points, lines, and polygons that define specific features.
Examples: *Trees (points), rivers (lines), city boundaries or soil zones (polygons).*

Note: All GIS data utilized in dam break studies must be compliant with the GDC-JPS format and adhere to MS 1759:2004 – Malaysia Standards for Geographic Information/Geomatics.

Note: For data deliverables, all GIS data utilized in dam break studies must be compliant with the GDC-DID format and adhere to

- Spesifikasi dan Rekabentuk data Geospasial Bagi Pusat Pangkalan Data Geospasial DID (GDC-DID)- Jabatan Pengairan dan Saliran (December 2014)
- Malaysia Standards for Geographic Information/Geomatics – Features and Attribute Codes (MS 1759:2004) published by MaCGDI (2004)

In the case of the spatial features that cannot be found and unrepresentative uncompleted with the standard above, the users shall propose changes/new feature in addition to the standard to the Division of Facility Management and GIS, DID using the same format as in the standard. All GIS data shall come with the metadata according to the current MyGDI metadata standard.

FILE GEODATABASE DEVELOPMENT

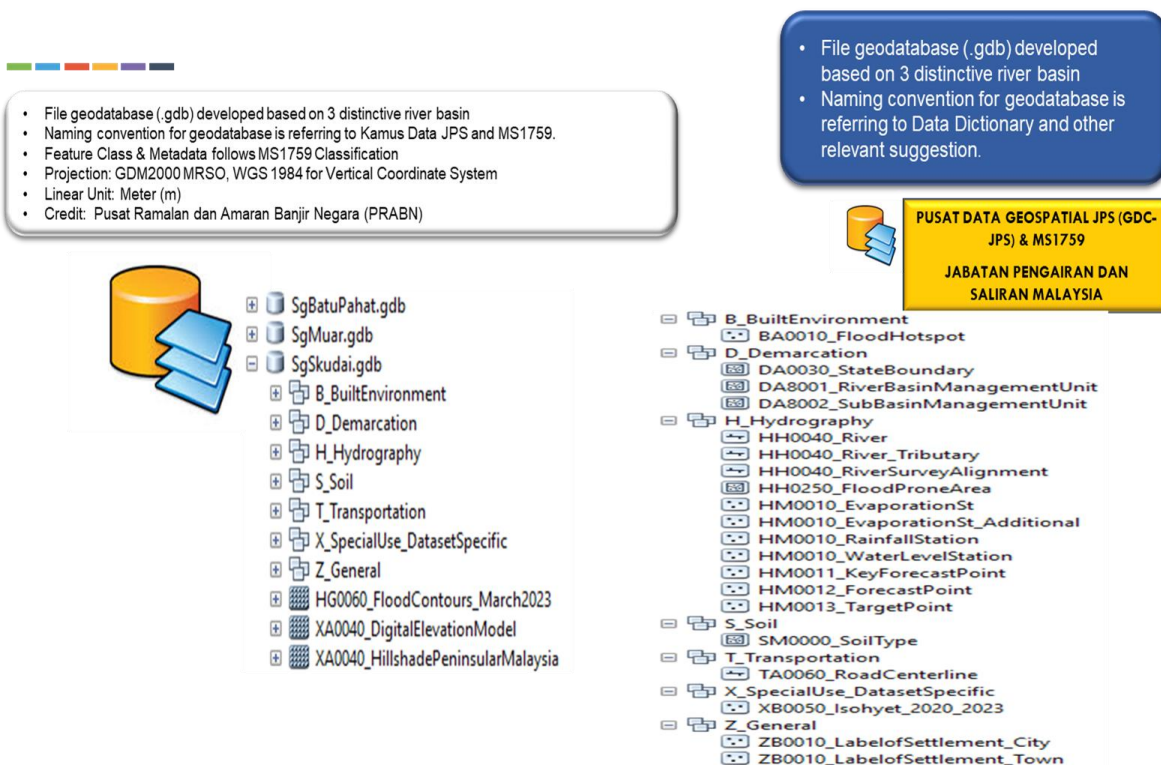


Figure 6.2 Overview of file geodatabase development

6.5.3 Limitations and Uncertainties in GIS

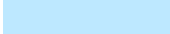
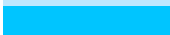










GIS has several limitations:

- **Data Accuracy:** Inaccuracies from measurement errors or outdated data.
- **Scale Issues:** Data collected at different scales may not fit well together.
- **Data Integration Challenges:** Combining data from various sources can create inconsistencies.

- **Cost and Complexity:** High-end GIS software and hardware can be expensive and require skilled personnel.
- **Generalization Errors:** Simplifying complex features for mapping can lead to loss of details.
- **Interpretation Bias:** Maps can be misinterpreted if poorly designed or if data is misunderstood.

6.6 Color Scheme

The flood depth shall be denoted by the color scheme below:

Colour	Flood Depth	Colour Name	R	G	B
	0 – 0.5m	Sodalite Blue	190	232	255
	0.5 – 1.2m	Big Sky Blue	0	197	255
	1.2 – 2.5m	Lapis Lazuli	0	92	230
	2.5 – 3.0 m	Ultra Blue	0	77	168
	3.1 – 4.0 m	-	146	208	30
	4.1 – 5.0 m	-	206	237	0
	5.1 – 6.0 m	Solar Yellow	255	255	0
	6.1 – 7.0 m	-	255	204	0
	7.1 – 8.0 m	-	255	153	0
	8.1 – 9.0 m	-	255	102	0
	9.1 – 10.0 m	-	255	51	0
	Above 10.0 m	Mars Red	255	0	0

The color coded for hazard rating category is shown in section 7.2.1.

An example of flood hazard map of Batu Dam for PMF is available in **APPENDIX F**.

CHAPTER 7 FLOOD HAZARD ASSESSMENT

7.1 Introduction

Flood hazard assessment refers to the potential threat posed by floodwater to people, property, and the environment. It involves identifying areas that could be flooded if a dam fails and estimating the severity of the flood. This includes the depth, velocity, and extent of water flow downstream of the dam. The flood hazard information is used to identify high-risk areas while supporting emergency response planning. It helps determine the severity of the threat, guide land use decisions, and support the development of evacuation plans and emergency zones. Accurate flood hazard mapping is essential to protect lives and reduce damage during dam-related emergencies.

7.2 Flood Hazard Rating

Flood hazard rating measures flood risks to people, buildings, and infrastructure, based on water depth, flow velocity, and debris load. In Malaysia, researchers and practitioners use the Debris Factor to determine Hazard Rating. In other countries such as India, hazard classification is more detailed with separate categories for people and buildings. Below are three categories used to rate flood hazard levels.

7.2.1 Debris Factor

Hazard Rating can be determined using the equation provided below or any appropriate equation, subject to approval by DID:

$$HR = D*(V+0.5) + DF$$

where,

D = depth

V = velocity

DF = debris factor

These debris factors are given in the table below.

Depths	Debris Factor (Conservative Approach)
0 to 0.25	0.5
d > 0.75m and/or v > 2	1

Hazard should be calculated at each time step in the model because the maximum hazard may not happen at the same time as the maximum depth or velocity.

The flood hazard classes are described in Table 7.1 below:

Table 7.1 Flood Hazard Classes

HR = d x (v +0.5) + DF	Hazard to people	Description
0	No Hazard	-
< 0.75m	Very Low Hazard	Caution (Level 1) “Caution: Flood zone with shallow flowing water or deep standing water” ⚠ <i>It is still possible to walk through the water.</i>
0.75 m – 1.25 m	Danger for some	Dangerous for some (Level 2) – i.e. children Danger: Flood zone with deep or fast-flowing water ⚠ <i>The ground floor of the buildings will be flooded and inhabitants have to either move to the first floor or evacuate.</i>
1.25 m – 2.0 m	Danger for most	Dangerous for most (Level 3) “Danger: Flood zone with deep fast flowing water ⚠ The ground floor and possibly the roof will be covered by water. Evacuation is a compulsory action.
> 2.0 m	Danger for all	Dangerous for all (Level 4) “Extreme Danger: Flood zone with deep fast flowing water (more than 2.0m flood depth) ⚠ The ground floor and possibly the roof will be covered by water. Evacuation is a compulsory action.

The maps of hazard rating category shall be denoted by the color scheme below:

Flood Hazard Rating	Hazard to People	R	G	B
0	No Hazard	0	77	168
< 0.5	Very Low	146	208	30
0.5 – 1.2	Danger for some	255	255	0
1.2 – 2.5	Danger for most	227	108	0
> 2.5	Danger for all	255	0	0

Example of flood hazard rating map of Batu Dam for PMF is available in **APPENDIX G**.

7.2.2 Hazard to People

Water depth and flow velocity are key factors affecting drowning and stability risks. Vulnerable groups — children, the elderly, and people with disabilities — face higher risks, requiring tailored safety measures. The table below summarizes flood hazards to people:

Table 7.2 The hazards to people during flood events (Central Water Commission,2018)

Factors Affecting Stability	Safety Criteria
<ul style="list-style-type: none"> - Depth - Velocity - Conditions (uneven surface, slippery, obstacles) 	<p><u>Infants, small children (H×M≤25)/ older person</u></p> <ul style="list-style-type: none"> -Safe: $D \times V \text{ (m}^2/\text{s)} = 0$ -Extreme hazard: $D \times V > 0$
	<p><u>Children (H×M: 25-50 kg):</u></p> <ul style="list-style-type: none"> -Safe: $D \times V \text{ (m}^2/\text{s)} = 0$ -Low hazard: $D \times V < 0.4$, max depth: 0.5 m, max velocity: 3.0 m/s -Significant hazard: $0.4 \leq D \times V < 0.6$ -Extreme hazard: $D \times V \geq 0.6$
	<p><u>Adults (H×M > 50 kg):</u></p> <ul style="list-style-type: none"> -Safe: $D \times V \text{ (m}^2/\text{s)} = 0$ -Low hazard: $D \times V < 0.6$, -Moderate hazard: $0.6 \leq D \times V < 0.8 \text{ m}^2/\text{s}$ -Significant hazard: $0.8 \leq D \times V < 1.2 \text{ m}^2/\text{s}$ -Extreme hazard: : $D \times V \geq 1.2$ <p style="text-align: center;"><i>max depth: 1.2 m, max velocity: 3.0 m/s</i></p>

The figures of flood hazard regimes (infants, children, and adults) and threshold stability are available in **APPENDIX H** (Figure H1 and Figure H2)

7.2.3 Hazard to Buildings

Buildings face risks from hydrostatic pressure, flow velocity, and debris impact during floods. Structural failure is more likely to occur without flood-resilient design. Building codes and land-use planning must address these hazards to improve safety and resilience. The table below summarizes flood hazards to people:

Table 7.3 The hazards to buildings during flood events (Central Water Commission,2018)

Factors Affecting Stability	Safety Criteria
<ul style="list-style-type: none"> - Hydrostatic actions - Hydrodynamic actions - Erosion and scour) 	<p>Low hazard: $0 < D/V \leq 2$</p> <p>Moderate hazard: $2 < D/V \leq 4$</p> <p>Extreme hazard: $D/V > 4$</p>
	<ul style="list-style-type: none"> -Stability affected at velocities $> 2 \text{ m/s}$ -Damage potential at depths $> 2 \text{ m}$ due to pressure and debris impact

The figures for threshold stability is available in **APPENDIX H** (Figure H3)

7.3 Evacuation Route

Evacuation routes are planned paths used to safely move people away from high-risk areas during a dam break event. These routes should be easily accessible, clearly marked, free from flood hazards, and able to support the expected number of evacuees. Working closely with local authorities is important to make sure the routes stay open and safe during emergencies. When planning evacuation routes, it is important to:

- identify high ground or safe zones.
- ensure the routes avoid flood-prone or blocked areas.
- consider the needs of vulnerable groups such as the elderly, children, and people with disabilities.
- coordinate with local emergency services (like NADMA, police, fire department, local councils) to make sure the routes are practical and supported.

Communities should know their evacuation routes. Regular training and drills can help people respond quickly in a real emergency.

7.4 Evacuation Shelters

An evacuation shelter is a safe place where people can stay temporarily. The shelter provides basic needs such as food, water, rest areas, medical help, and protection from weather. These facilities should be located outside the predicted flood area which is easily accessible via evacuation routes and have enough space to relocate victims. There are two main types:

Table 7.4 Types of shelters

Permanent shelters Permanent Disaster Relocation Centers (PPK)	Equipped with basic amenities and facilities to cater to the needs of the displaced population including living spaces, sanitation facilities, and potentially even recreational areas Example: Dewan Seberguna Taman Kota Jaya, Kota Tinggi, Johor
Temporary shelters Temporary Evacuation Centers	Located in existing structures like schools, community halls, or other suitable buildings Example: School, community halls, mosques, other suitable public buildings

NADMA is responsible for coordinating and managing both PPKs and PPS, ensuring that appropriate measures are in place for disaster preparedness and response.

7.5 Emergency Planning Zone (EPZ) / Priority Area

The Emergency Planning Zone or Priority Area is most at risk if a dam breaks. Areas categorized as EPZ zones must be prioritized in disaster planning and well-prepared to reduce loss of lives and property damage. EPZ is usually defined based on:

- Flood hazard levels (depth, speed, extent)
- Population exposure and presence of vulnerable groups

EPZ helps authorities to:

- focus emergency response efforts where the risk is highest
- plan for early warning, evacuation, and rescue operations
- protect critical infrastructure and vulnerable communities

Priority areas within the EPZ may include schools, hospitals, residential zones, key roads and bridges.

7.6 Hazard Level for Flood & Dam Break (Incremental Hazard)

An incremental hazard refers to the additional risk or damage caused only by a dam failure, beyond what would happen if the dam didn't fail. It helps separate the effects of the dam failure from natural flooding or other events that would occur anyway. To evaluate incremental hazards:

- a dam failure scenario is simulated during a flood or normal conditions.
- the same event is simulated again without dam failure.
- the results are compared to see the extra consequences—such as impacts on people, economy, environment, and infrastructure—caused by the dam failure.

These extra impacts are considered to contribute to incremental hazards. (See Figure 7.1)

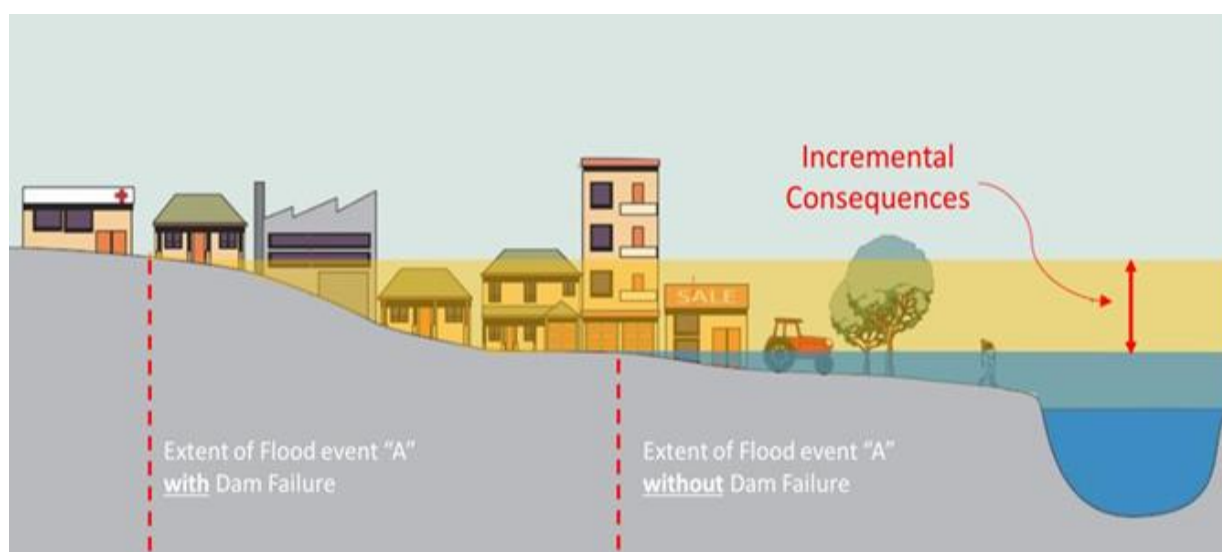


Figure 7.1 Incremental Hazard (Risk) Assessment (Central Water Commission, 2020)

7.7 Emergency Response for the Community

An effective emergency response strategy can help to reduce loss of lives and property damage during a dam break or flood. It includes all actions taken before, during, and after a dam break or flood to keep people safe. A well-prepared community can respond quickly and effectively when danger strikes. The community actions include:

- **Stay Informed:** Listen to official announcements from NADMA, police, local councils (PBT), or JPS through sirens, SMS alerts (e.g., MySMS 15888), TV, radio, or social media.
- **Follow Evacuation Orders:** Leave immediately when instructed by authorities. Use official evacuation routes and proceed to the nearest designated shelter (PPS/PPK).
- **Help Vulnerable Groups:** Support children, elderly people, OKU (persons with disabilities), and anyone needing assistance to evacuate safely.
- **Prepare a Grab Bag:** Keep a small bag with important items: IC, medications, water, dry food, clothes, phone charger, flashlight, and copies of important documents.
- **Stay Calm and Cooperate:** Remain calm, follow instructions from rescue teams (e.g., APM, BOMBA, RELA), and support your family and neighbours.
- **Join Community Drills:** Participate in evacuation drills and disaster awareness programmes organized by NADMA, JPS, local councils, or schools.

The emergency response strategy can reduce confusion and panic in the community during flood events, as well as speed up evacuation and rescue operations. More importantly, it helps to save lives and protect homes, especially in high-risk areas.

APPENDICES:

APPENDIX A SAMPLE LAYOUT AND CROSS-SECTION PROFILE OF BATU DAM AND SG. BATU

APPENDIX B EXAMPLE CALCULATION DETERMINE PMP (HERSHFIELD'S METHOD)

APPENDIX C OTHER EMPIRICAL MODELS FORMULA – DAM BREACH PARAMETER

APPENDIX D EXAMPLE CALCULATION DETERMINE FOR DAM BREACH (Froehlich (2017))

APPENDIX E LIST ID, 2D AND 3D MODELS

APPENDIX F EXAMPLE FLOOD HAZARD MAP OF BATU DAM (PMF)

APPENDIX G EXAMPLE FLOOD HAZARD RATING MAP OF BATU DAM (PMF)

APPENDIX H FIGURES FLOOD HAZARD REGIMES (PEOPLE) AND STABILITY THRESHOLD FLOOD (PEOPLE, BUILDING)

APPENDIX I RECOMMENDED TABLE OF CONTENTS FOR A DAM BREAK ANALYSIS REPORT

APPENDIX B EXAMPLE CALCULATION DETERMINE PMP (HERSHFIELD'S METHOD)

Collection of rainfall Data

The station closest to the dam site, with 45 years of rainfall data (1950-2004), was selected. The required data for PMP estimation includes the annual maximum daily rainfall for 1-, 2-, and 3-day durations.

Year	1 day	2 day	3 day
*1950	58.9	93.6	139.3
1951	144.7	178.9	241.2
1952	121.9	149.8	203
1953	208.2	231	413.8
1954	332.7	345.3	345.3
1955	287	358.1	363.1
1956	232.4	288.2	341.5
1957	167.6	327.6	379.6
1958	124.4	177.7	191.6
1959	184.1	245.8	309.2
1960	272.7	459.3	477.3
1961	214.1	413.7	493.7
1962	307.3	307.3	421.3
1963	302.2	260.2	293.28
1964	117.6	182	231.8
1965	305	509.2	526.7
1966	213.8	264.3	308.2
1967	303	589.7	777.4
1968	119.3	146.5	145.9
1969	175.2	177.7	225.9
1970	165	227	287.1
1971	258.5	272.7	323.4
1972	297.1	425.6	530.4
1973	197.8	271.4	323
1974	312.5	329.5	424.5
1975	408	525.5	668.5
1976	213.5	276.5	357
1977	126	144	170.5
1978	115	167	236.5
1979	147	205.5	298.5
1980	119	182	139.5
1981	316.5	450.5	496.5
*1982	13	13	24
*1986	67	127	164
*1987	30	30	55
1989	38	70	98
*1990	40	63	83
1992	50	90	140
1993	50	90	109
1994	50	95	135
1995	40	73	102
1996	45	85	115
1997	45	86	124
*1998	50	100	150
1999	50	77	112
*2000	70	70	110
*2001	50	80	110
*2002	100	143	187
2003	160	280	295
*2004	70	110	110

Compute statistical parameters using rainfall data

The table below shows the mean, standard deviation, and highest recorded rainfall for 1, 2, and 3-day durations.

Statistical Parameters	Duration		
	1 day	2 day	3 day
Mean	157.72	217.30	266.15
STDev	103.95	140.76	164.54
Max	408.00	589.70	777.40

Determine the Frequency Factor (Km) from the envelop curve

The equations representing the enveloping curves (**Figure A1 – West Malaysia**) are as follow:

$$K_m = 6E-05x^2 - 0.0557x + 16.141 \text{ (1 day duration)}$$

$$K_m = 4E-05x^2 - 0.0424x + 16.221 \text{ (2-day duration)}$$

$$K_m = 2E-05x^2 - 0.0324x + 15.948 \text{ (3-day duration)}$$

K_m = frequency factor (km) and

X = mean annual maximum rainfall

From Figure A1 – West Malaysia or from equations, the values of K_m can be obtained by substitute the mean annual maximum rainfall for various durations (from the table above):

$$K_m = 8.85 \text{ (1-day duration)}$$

$$K_m \text{ for } = 8.90 \text{ (2- day duration)}$$

Km for = 8.74 (3- day duration)

Computation of PMP Point

Use Hershfield equation to calculate point PMP is as follows:

$$X_{PMP} = \bar{X} + K_m \sigma_n$$

where,

\bar{X} = Mean of the annual maximum rainfall

Km = Frequency Factor

σ_n = Standard Deviation

Therefore, the estimated of PMP are:

$$PMP = 157.72 + 8.85 * 103.95 = 1,077.7 \text{ mm (1-day duration)}$$

$$PMP = 217.30 + 8.90 * 140.76 = 1,470.1 \text{ mm (2-day duration)}$$

$$PMP = 266.15 + 8.74 * 164.54 = 1,704.2 \text{ mm (3-day duration)}$$

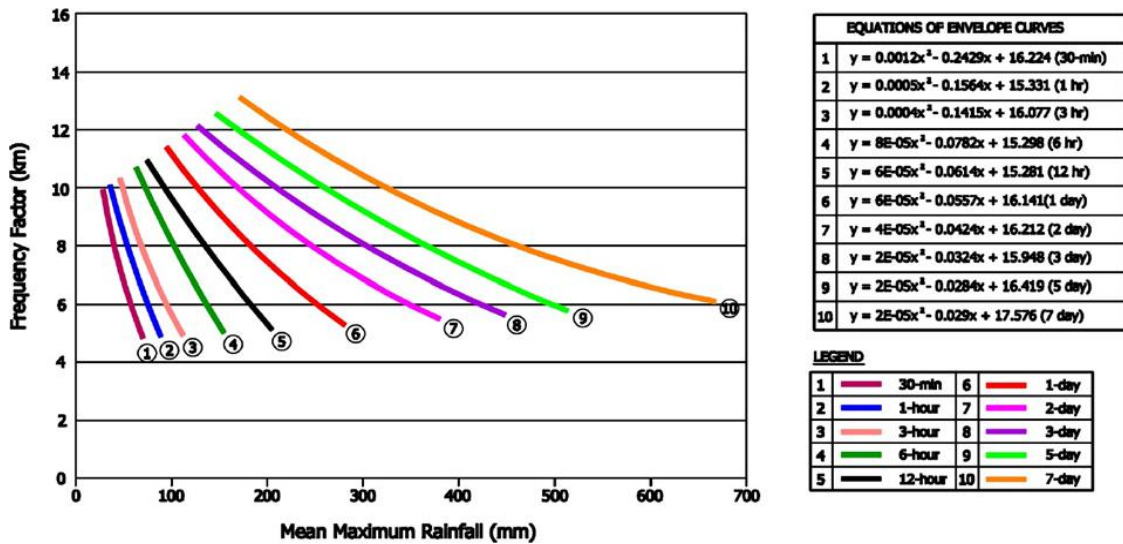


Figure B1. Km Envelope Curve (West Malaysia)

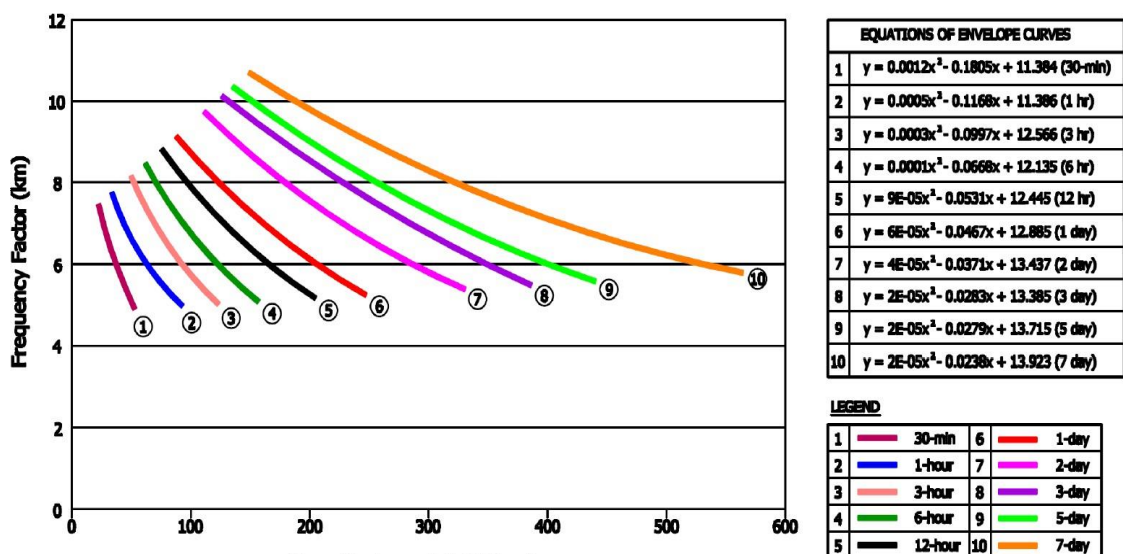


Figure B2. Km Envelope Curve (East Malaysia)

$y = K_m$, $x =$ mean maximum rainfall, \bar{X} (mm)

APPENDIX C OTHER EMPIRICAL MODELS FORMULA – DAM BREACH PARAMETER

MacDonald and Langridge-Monopolis (1984)	Von Thun and Gillette (1990)	Xu and Zhang (2009)										
<p>The equations are: <i>For earth fill dams:</i> $V_{eroded} = 0.0261(V_{out} \times h_w)^{0.769}$ $t_f = 0.0179(V_{eroded})^{0.364}$ <i>For earth fill dams with clay core or rock fill dams:</i> $V_{eroded} = 0.00348(V_{out} \times h_w)^{0.852}$ where, V_{eroded} = volume of material eroded from the dam embankment (m³) V_{out} = volume of water that passes through the breach (m³) [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 (m), t_f = breach formation time (hr). The breach is 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</p>	<p>The equation is: $B_{ave} = 2.5h_w + C_b$ where, B_{ave} = average breach width (m) h_w = depth of water above the bottom of the breach (m) C_b = coefficient, a function of reservoir size [see table C1 below] <div style="text-align: center;"> <p>Table C1. Suggested C_b values</p> <table border="1" data-bbox="943 679 1384 879"> <thead> <tr> <th>Reservoir Size (cubic meters)</th> <th>C_b (meters)</th> </tr> </thead> <tbody> <tr> <td>< 1.23×10^6</td> <td>6.1</td> </tr> <tr> <td>$1.23 \times 10^6 - 6.17 \times 10^6$</td> <td>18.3</td> </tr> <tr> <td>$6.17 \times 10^6 - 1.23 \times 10^7$</td> <td>42.7</td> </tr> <tr> <td>> 1.23×10^7</td> <td>54.9</td> </tr> </tbody> </table> </div> 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 (hr) h_w = depth of water above the bottom of the breach (m) For erosion resistant materials:</p>	Reservoir Size (cubic meters)	C_b (meters)	< 1.23×10^6	6.1	$1.23 \times 10^6 - 6.17 \times 10^6$	18.3	$6.17 \times 10^6 - 1.23 \times 10^7$	42.7	> 1.23×10^7	54.9	<p>The equation 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 (m) V_w = reservoir volume at time of failure (m³) h_b = height of the final breach (m) h_d = height of the dam (m) h_r = 15 m, reference point to differentiate between large and small dams. h_w = height of the water above the breach bottom elevation at time of breach (m) $B_3 = b_3 + b_4 + b_5$ coefficient that is a function of dam properties $b_3 = -0.041, 0.026, \text{ and } -0.226$ for dams with corewalls, concrete faced dams, and homogeneous/zoned-fill dams $b_4 = 0.149 \text{ and } -0.389$ for overtopping and seepage/piping $b_5 = 0.291, -0.14, \text{ and } -0.391$ for high, medium, and low dam credibility It is suggested to assume the breach height from the dam crest down to the natural ground level at the breach location (i.e., $h_b = h_d$). The equation to estimate the top width of the breach is:</p>
Reservoir Size (cubic meters)	C_b (meters)											
< 1.23×10^6	6.1											
$1.23 \times 10^6 - 6.17 \times 10^6$	18.3											
$6.17 \times 10^6 - 1.23 \times 10^7$	42.7											
> 1.23×10^7	54.9											

<p>Z_2 = average slope ($Z_2:1$) of the downstream face of dam</p> <p>Z_b = side slopes of the breach ($Z_b: 1$), 0.5 for the MacDonald method</p>	$t_f = \frac{B_{ave}}{4h_w}$ <p><i>For easily erodible materials:</i></p> $t_f = \frac{B_{ave}}{4h_w + 61.0}$ <p>where, B_{ave} = average breach width (m)</p> <p>The erosion limits represent two extremes:</p> <ul style="list-style-type: none"> • Upper bound – for well-built dams made of erosion-resistant materials • Lower bound – for poorly built dams made of easily erodible materials 	$\frac{B_t}{h_b} = 1.062 \left(\frac{h_d}{h_r} \right)^{0.092} \left(\frac{V_w^{1/3}}{h_w} \right)^{0.508} e^{B_2}$ <p>where, B_t = breach top width (m) 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 b_4 = 0.299 and -0.239 for overtopping and seepage/piping b_5 = 0.411, -0.062, and -0.289 for high, medium, and low dam erodibility</p> <p>The equation for breach side slopes is:</p> $Z = \frac{B_t - B_{ave}}{h_b}$ <p>The equation for breach development time is:</p> $\frac{T_f}{T_r} = 0.304 \left(\frac{h_d}{h_r} \right)^{0.707} \left(\frac{V_w^{1/3}}{h_w} \right)^{1.228} e^{B_5}$ <p>where, T_f = breach formation time (hr) T_r = 1 hour (unit duration) B_3 = $b_3 + b_4 + b_5$, (similar as above) b_3 = -0.327, -0.674, and -0.189 for dams with core walls, concrete faced dams, and homogeneous/zoned-fill dams, b_4 = -0.579 and -0.611 for overtopping and seepage/piping b_5 = -1.205, -0.564, and 0.579 for high, medium, and low dam erodibility,</p>
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APPENDIX D EXAMPLE CALCULATION FOR DAM BREAK (Froehlich (2017))

Example Application for Embankment Dam Breach

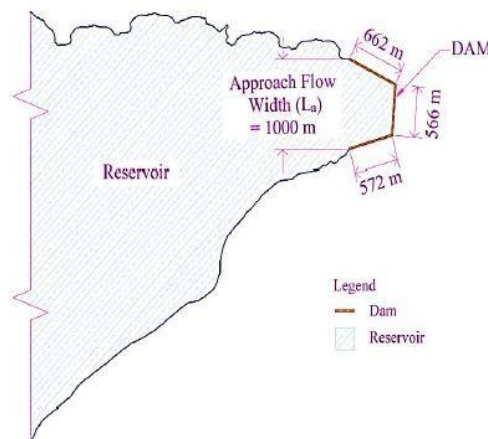
A dam break analysis is required for a 40-meter high, 1800-meter long earthfill embankment dam. The analysis will map flooding areas for breaks caused by two scenarios: a "fair-weather failure" (internal erosion at full reservoir level) and overtopping during a probable maximum flood (PMF). The breaks starts when the water depth on the dam crest reaches, $H_c = 0.6$ m. Reservoir elevation/storage data is provided in Table B.1. Using the Froehlich (2017a) regression equation, calculate the following for each failure scenario:

- \hat{B}_{avg} : Average width of the final break (meters)
- \hat{m} : Trapezoidal break side-slope ratio (horizontal to vertical)
- \hat{t}_f : Break formation time (seconds)

Also, use the Froehlich (2016) equation to determine the expected peak outflow from the break.

Table D1 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



the

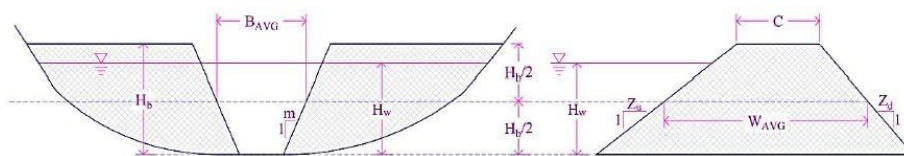


Figure B.2 Breach Variable Definition Sketch

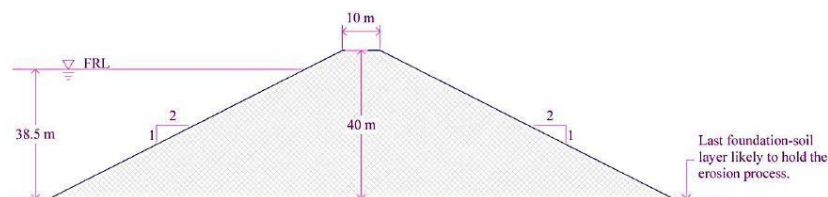


Figure D.2 Cross Section for Example Application No.1. Embankment Dam

Calculating \hat{B}_{avg}

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

where,

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

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

➤ For internal erosion failure (Fair-weather failure):

$$\hat{B}_{avg} = 0.23 \times (1.0) \times (2,000,500,000.00)^{1/3}$$

$$\hat{B}_{avg} = 290 \text{ m}$$

➤ For overtopping failure (critical depth = 0.6 m. above dam crest):

$$\hat{B}_{avg} = 0.23 \times (1.5) \times (2,482,400,000.00)$$

$$\hat{B}_{avg} = 405 \text{ m}$$

Calculating \hat{m}

➤ For internal erosion failure (Fair-weather failure):

$$\hat{m} = 0.6$$

➤ For overtopping failure (critical depth = 0.6 m. above dam crest):

$$\hat{m} = 1.0$$

Calculating \hat{t}_f

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

where,

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

H_b = Height of breach in metres

➤ For internal erosion failure (Fair-weather failure):

$$\hat{t}_f = 60 \times \sqrt{\frac{2,000,500,000}{(9.807)(40)^2}}$$

$$\hat{t}_f = 21,420.32 \text{ seg.}$$

$$\hat{t}_f = 5.95 \text{ hr.}$$

➤ For overtopping failure (critical depth = 0.6 m. above dam crest):

$$\hat{t}_f = 60 \times \sqrt{\frac{2,482,400,00}{(9.807)(40)^2}}$$

$$\hat{t}_f = 23,861.22 \text{ seg.}$$

$$\hat{t}_f = 6.63 \text{ hr.}$$

Calculating expected peak discharge (\hat{Q}_p)

$$\hat{Q}_p = 0.0175 \times k_M \times k_H \times \sqrt{\frac{g V_w H_w H_b^2}{W_{avg}}} \quad (\text{empirical equation})$$

$$\hat{Q}_p = Q_{p_{max}} \times \left(\frac{1}{1 + \alpha \times t_f \sqrt{\frac{g}{H_b}}} \right)^\beta \quad (\text{semi-theoretical equation})$$

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

where,

\hat{Q}_p = expected peak discharge in m^3/s

$Q_{p_{max}}$ = maximum possible peak discharge from a breach of specified dimensions that forms instantly

α = 0.000045

β = $500 \times [(W_{avg} \times H_b^2) / V_w]^{2/3}$

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

L_a = approach flow width

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

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

$H_s = \begin{cases} 6.1 \text{ m} & (\text{for SI units}) \\ 20 \text{ ft} & (\text{for U.S customary units}) \end{cases}$

➤ For internal erosion failure (Fair-weather failure):

$$Q_{p_{max}} = \frac{8}{27} \left(\frac{L_a}{B_{avg}} \right)^{0.28} \left[B_{avg} - m \left(H_b - \frac{4}{5} H_w \right) \right] \sqrt{g H_w^3}$$

$$Q_{p_{max}} = \frac{8}{27} \left(\frac{1,000}{290} \right)^{0.28} \left[290 - 0.6 \left(40 - \frac{4}{5} (38.5) \right) \right] \sqrt{(9.807)(38.5)^3}$$

$$Q_{p_{max}} = 89,149 \text{ m}^3/s$$

a. Using Empirical Equation:

$$\hat{Q}_p = 0.0175 \times k_M \times k_H \times \sqrt{\frac{g V_w H_w H_b^2}{W_{avg}}} \quad (\text{empirical equation})$$

$$\hat{Q}_p = 0.0175 \times (1.0) \times \left(\frac{40}{6.1} \right)^{1/8} \times \sqrt{\frac{(9.807) \times (2,000,500,000.00) \times (38.5) \times (40)^2}{90}}$$

b. Using Semi-theoretical Equation:

$$\hat{Q}_P = Q_{P_{\max}} \times \left(\frac{1}{1 + \alpha \times t_f \sqrt{\frac{g}{H_b}}} \right)^\beta \quad (\text{semi - theoretical equation})$$

$$\hat{Q}_P = (89,149) \times \left(\frac{1}{1 + 0.000045 \times (21,420.32) \sqrt{\frac{9.807}{40}}} \right)^{500 \times \left[\frac{(90) \times (40)^2}{(2,000,500,000.00)} \right]^{2/3}}$$

$$\hat{Q}_P = 63,603 \text{ m}^3/\text{s}$$

c. Final considerations in regard peak discharge expected values:

Care should be taken when applying a model to dams outside the range of the data used to develop the equation. Analysing the historical failure data from Froehlich (2016) (Table B-2), it is clear that the empirical approach's expected peak flow (81,134 m³/s) falls outside the valid range. Therefore, the value from the semi-theoretical equation (63,603 m³/s), which is limited by the maximum possible flow from an instant breach, is more reliable and applicable in this case.

Table D2 The range of Variables in Dam Break Peak Discharge Data Set

Variable	Notation	Min.	Max.
Average Embankment Width (m)	W _{avg}	9.63	250
Volume above breach Bottom (Mm ³)	V _w	0.0133	701
Height Water (m)	H _w	1.68	77.4
Height Breach (m)	H _b	3.66	86.9
Approach flow Width (m)	L _a	40	4100
Measured Peak Discharge (m ³ /s)	\hat{Q}_p	30	65,120

➤ For overtopping failure (critical depth = 0.6 m. above dam crest):

$$Q_{P_{\max}} = \frac{8}{27} \left(\frac{L_a}{B_{\text{avg}}} \right)^{0.28} \left\{ (B_{\text{avg}} - mH_b) - \frac{4}{5} mH_w \left[\left(1 - \frac{H_b}{H_w} \right)^{5/2} - 1 \right] \right\} \sqrt{gH_w^3}$$

$$Q_{P_{\max}} = \frac{8}{27} \left(\frac{1,000}{405} \right)^{0.28} \left\{ (405 - 1.0 \times 40) - \left(\frac{4}{5} \times 1.0 \times 40.6 \right) \times \dots \right.$$

$$\left. \times \left[\left(1 - \frac{40}{40.6} \right)^{5/2} - 1 \right] \right\} \sqrt{(9.807)(40.6)^3}$$

$$\therefore Q_{P_{\max}} = 122,874 \text{ m}^3/\text{s}$$

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.

$$\hat{Q}_P = Q_{P_{\max}} \times \left(\frac{1}{1 + \alpha \times t_f \sqrt{\frac{g}{H_b}}} \right)^\beta \quad (\text{semi - theoretical equation})$$

$$\hat{Q}_P = (122,874) \times \left(\frac{1}{1 + 0.000045 \times (23,861.22) \sqrt{\frac{9.807}{40}}} \right)^{500 \times \left[\frac{(90) \times (40)^2}{(2,482,400,000.00)} \right]^{2/3}}$$

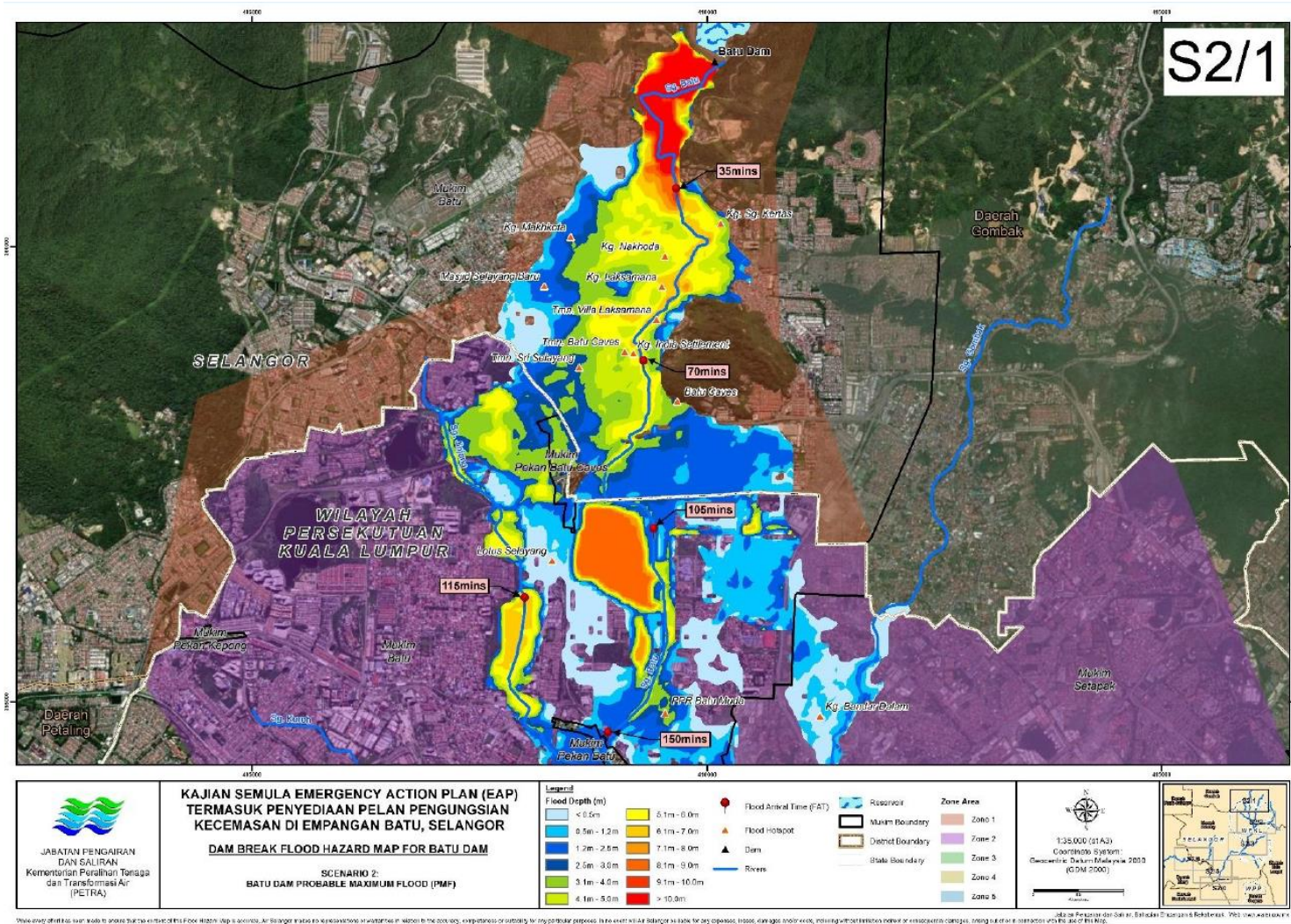
$$\therefore \hat{Q}_P = 89,270 \text{ m}^3/\text{s}$$

APPENDIX E LIST ID, 2D AND 3D MODELS

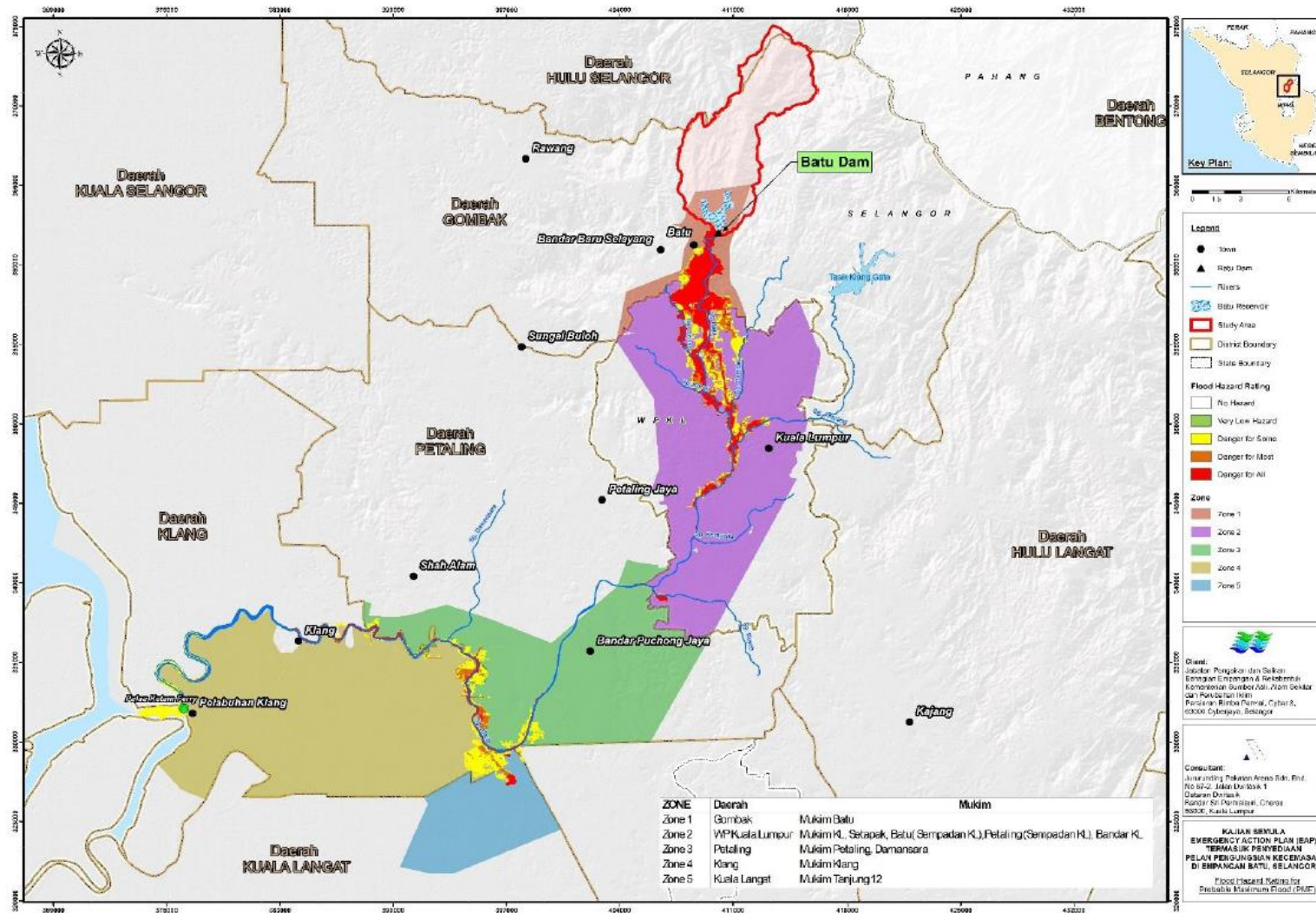
Software Developer/ Country	1D	2D	1D+2D	3D	Licence Type
ANSYS				CFX, Fluent	Commercial
CRCCH Australia					Open Source
Autodesk	InfoWorks ICM	InfoWorks ICM	InfoWorks ICM		Commercial
BMT WBM	TUFLOW Classic	TUFLOW Classic	TUFLOW	TUFLOW FV	Commercial
CH2M Hill (formerly Halcrow Group)	Flood Modeller Pro 1D solvers	Flood Modeller Pro 2D solvers	Flood Modeller Pro		Commercial
CHI	PCSWMM	PCSWMM	PCSWMM		Commercial
DELTARES	SOBEK Suite	SOBEK Suite : DELFT3D	SOBEK Suite	DELFT3D	Commercial
DHI	MIKE11/MI KE HYDRO River	MIKE21	MIKE Flood MIKE URBAN	MIKE 3	Commercial
Electricite de France	MASCARE T	TELEMAC 2D		TELEMAC 3D	Open Source
France					Open Source
Halcrow Group Limited	ISIS-1D ISIS-FAST	ISIS-2D (now CH2M HILL) ISIS-FAST	ISIS-FREE		Open Source & Commercial
International Centre for Water Hazard and Risk Management (ICHARM) Japan	Rainfall- Runoff- Inundation (RRI)	Rainfall- Runoff- Inundation (RRI)			Open Source
Swedish meteorological and Hydrological Institute					Open Source
Tokyo University		CaMa- Flood		GETFLOWS	Research
United Kingdom (UKCEH)					Open Source & Commercial
United States Environmental Protection Agency (US EPA)	SWMM5				Open Source

United States National Centers for Environmental Prediction					Open Source & Commercial
US Army Corps of Engineers (USACE)	HEC-RAS	HEC-RAS	HEC-RAS		Open Source

APPENDIX F EXAMPLE FLOOD HAZARD MAP OF BATU DAM (PMF)



APPENDIX G EXAMPLE FLOOD HAZARD RATING MAP OF BATU DAM (PMF)



APPENDIX H FIGURES FLOOD HAZARD REGIMES (PEOPLE) & STABILITY THRESHOLD FLOOD (PEOPLE, BUILDING)

D×V (m ² s ⁻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; Danger- ous 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; Danger- ous to some	
0.8 – 1.2			Significant Hazard; Danger- ous to most	
> 1.2			Extreme Hazard; Danger- ous to all	

Figure H1 Flood hazard regimes for infants, children and adults (Cox et al., 2010)

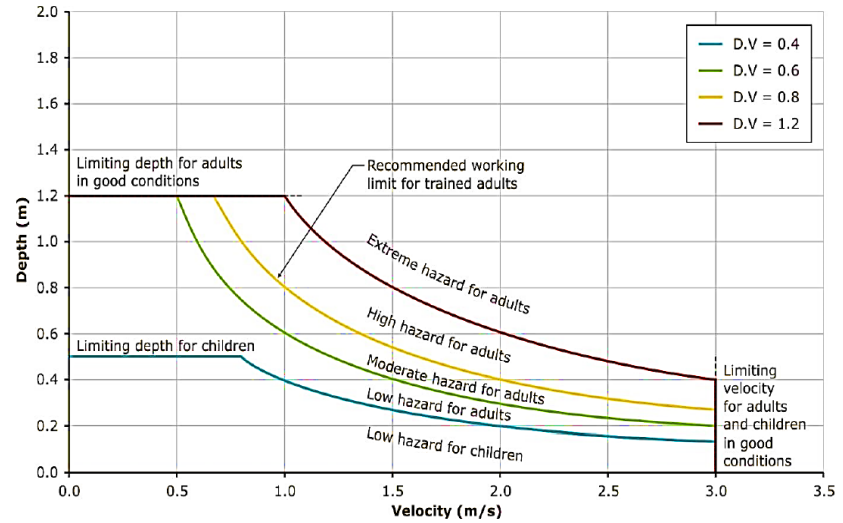


Figure H2 Threshold for stability of persons in flood (Cox et al., 2010)

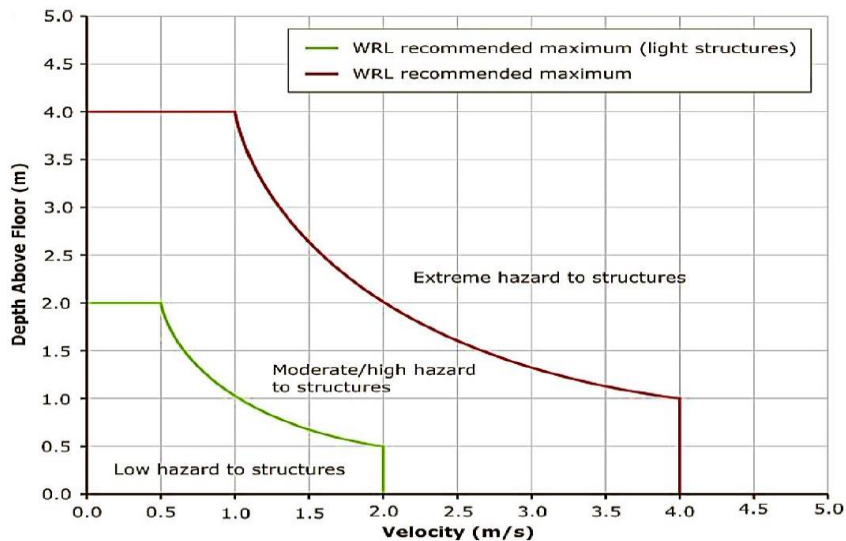


Figure H3 Thresholds for building stability in flood (Smith et al., 2014)

APPENDIX I RECOMMENDED THE TABLE OF CONTENTS FOR A DAM BREAK ANALYSIS REPORT

Recommended Table of Contents for A Dam Break Analysis Report

Abstract

Introduction

Purpose and Scope

Description of the Dam/Reservoir System

Dam Break Analysis

Model Selection

Dam Break Scenarios

Study Area Boundaries

Data Inputs for the hydrology and hydrodynamic model

Topographic Data

Hydraulic Data

Hydrologic Data

Land Cover/Use Data

Soil and geology data

Model Development

Grid/Mesh Resolution

Roughness Coefficients

Flow and Boundary Conditions

Dam Brach Parameters

Calibration and Sensitivity Analysis

Computational Aspects

Peak Discharge Validation

Results

Flood hazard map

Flood hazard rating

Output Hydrographs

Flood Hazard/Vulnerability Reference Values

Flood Hazard Mapping

Summary and Conclusions

References

Appendices

Appendix A. – Flood Hazard Maps

Abstract

Highlights the main results and conclusions of the dam break analysis. For full details, including methodology, results, and discussions, the entire report should be read.

Introduction

Overview of the study, including the background, problem been addressed and proposed solution approach

Purpose and Scope

the goals of the study and what will be delivered. It also outlines what is not covered in the analysis.

Description of the Dam/Reservoir System

Key details about the dam, reservoir, and downstream areas, including type of dam, key water levels (e.g., MDDL, FRL, MWL), materials used, dam height and hydraulic head, drawings (plans, sections), foundation characteristics, hydraulic structures and outlets, reservoir purpose, downstream area (villages, industries, etc.)

Dam Break Analysis

The main study components include model selection, dam break scenarios, study area boundaries, input data, model development and validation, results and uncertainty discussion.

Model Selection

Details description on the software and method used.

Dam Break Scenarios

Outlines all the break scenarios considered in the analysis for example normal conditions i.e CDF, severe weather i. e PMF

Limits of Study Area

Justifies the limits of the hydraulic model.

Data Inputs for the hydrology and hydrodynamic model

Provides details on all the data used for the dam break analysis.

Model Development

Details the steps involved in developing the hydrology and hydrodynamic model. It will be customized based on the methods and model type chosen for the dam break analysis.

Grid/Mesh Resolution

Describes the grid used for the model. For 2D models, it includes grid size, cell count, and break lines. For 1D models, it covers cross sections, spacing, and river profiles.

Roughness Coefficients

Explains how roughness values were determined, showing maps, photos, and justifications for the values used in the model.

Flow and Boundary Conditions

Defines the model's boundaries, including initial water levels, flow rates, and gate openings. It typically includes upstream inflows and downstream normal depth or rating curves.

Dam Break Parameters

Explains how the dam break size is estimated, including methods, assumptions, and results for break width, depth, side slopes, and formation time.

Calibration and Sensitivity Analysis

If roughness values are adjusted, the method and data are explained. Sensitivity analysis tests how changes in parameters affect the results, and uncertainty analysis (e.g., Monte Carlo simulation) may also be used.

Computational Aspects

Covers the modeling assumptions, type of equations used, time steps, and how stability and accuracy were ensured in the results.

Reasonableness of the Peak Discharge

Checks the model's peak discharge against historical data using regression equations. Flow rates and velocities during dam break formation are also checked for consistency.

Results

Presents key results including flow hydrographs, hazard values (depth, velocity, elevation), flood wave arrival times, and another interest findings.

Output Hydrographs

Flow hydrographs at critical downstream locations (villages, bridges, roads) show the flood severity and help inform local authorities on key flood points.

Flood Hazard/Vulnerability Reference Values

Flood hazard values (depth, velocity, arrival time) at key locations help authorities assess risk and prioritize evacuation.

Flood Hazard Mapping

Details on how flood hazard maps were made, including scale, GIS software, number of tiles, coordinate system, and sources for roads and villages.

Summary and Conclusions

Summarizes whether the study objectives were met and highlights key findings and their significance.

References

Lists all citations used in the report.

Appendices

Includes raw data, detailed drawings, and final flood hazard maps.

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