NEW ZEALAND
Society on Large Dams

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New Zealand Dam Safety Guidelines 2024

# MODULE 2
# CONSEQUENCE ASSESSMENT AND DAM POTENTIAL IMPACT CLASSIFICATION

# Abstract

Dam safety objectives and principles that are applicable to the investigation, design, construction, commissioning, operation, assessment, rehabilitation, and decommissioning of dams in New Zealand are included in the Parent Document. The Parent Document also includes a glossary of terms used in these Guidelines. This module principally details the system and constituent methods for assessment of dam-break flood hazard consequence assessments and classification of dams in New Zealand.

Assessments of dam-break flood hazard consequences and classification of dams are essential to ensure that appropriate performance criteria are used in the design and safety evaluation of dams, and that an appropriate level of care is reflected in their operational procedures. Furthermore, dam-break flood hazard and consequence assessments assist Owners in emergency planning and preparedness, in understanding the risks posed by the presence of dams, and in developing risk reduction measures to address unacceptable risks.

A dam's classification, termed its Potential Impact Classification (PIC), is purely a function of the consequences of a hypothetical failure breach or other uncontrolled release of the stored contents. It has no correlation with the probability of the dam failing or experiencing a dam safety incident.

In broad terms, the process for PIC requires the assessment of the damage level to community buildings, historical and cultural places, critical or major infrastructure and the environment, as well as the potential life safety impacts to people who may be present within the flood inundation zone resulting from a hypothetical dam failure or dam safety incident. The combination of the maximum overall damage level across all damage level categories and the potential life safety impact is used to determine the PIC of a dam. The potential damage levels and life safety impacts can change with time and, given the long life expectancy of most dams, their PICs need to be reviewed periodically to ensure the classification remains consistent with the potential hazard.

This module includes limited discussion on the role of regulators in respect of dam safety. Reference should be made to Module 1: Legal Requirements for a more complete description of their roles and responsibilities.

## Notice to reader

Although this module is configured to be as self-contained as practicable from a technical standpoint, readers should familiarise themselves with the principles, objectives, and limitations outlined in the Parent Document and Module 1: Legal Requirements before considering the information in this or any other module.

## Document history

| Release | Date | Released with |
|---|---|---|
| Original | May 2015 | Parent and all modules |
| 2023 | December 2023 | Updates to Parent and Modules 1, 2 and 5 |
| 2024 | December 2024 | Updates to Parent and all Modules |

# Contents

# 1. Introduction

## 1.1 Principles and objectives

Assessment of dam-break flood hazard consequences and classification of dams are essential to ensure that appropriate performance criteria are used in the design and safety evaluation of a dam, and that an appropriate level of care is reflected in operational procedures. Furthermore, dam-break flood hazard and consequence assessments assist Owners in emergency planning and preparedness, in understanding the risks posed by the presence of the dam, and in developing risk reduction measures to reduce any unacceptable risks. Principle 1 in the Parent Document states:

**The consequences of a dam failure should be understood so that appropriate design, construction, and management actions can be applied to protect people, property, and the environment.**

Dams store water or other fluid at a height elevated above downstream topography which creates the potential for uncontrolled release of their contents in the unlikely event of either a component failure or a dam failure[1]. Dams therefore pose a potential hazard to people, buildings, infrastructure, historical and cultural places, and the environment in the downstream area that could be affected by the release of stored contents. In addition, dam failure can have a range of other impacts such as reputational and financial impacts on the dam Owner, decline in economic activity and output within the flood-affected areas, impacts on the wellbeing of people, and disruption to the flow of goods and services.

Generally, where the consequences of a dam failure are greater, the design, operational, and maintenance processes associated with the dam should be more robust and resilient to reduce the likelihood of dam failure.

The objective of this module is to provide guidelines to support a consistent assessment of dam-break flood hazard, consequence, and classification of dams in New Zealand. This guidance is also intended to provide a consistent interpretation of requirements under the Building (Dam Safety) Regulations (2022).

The primary focus of this module is the assessment of dam-break flood hazard and consequences for water storage dams. Specific guidance related to breach analysis for tailings dams and dams with highly sedimented reservoirs is provided in section 5.9, although the general principles of dam-break flood hazard and consequence assessment still apply to such facilities.

## 1.2 Dam classification system

A dam classification system that reflects the consequences of a dam failure, together with engineering design and assessment criteria appropriate to the hazard posed by the dam, provides the framework for establishing an appropriate level of safety for a dam.

A dam's classification is termed its Potential Impact Classification (PIC). Other countries may use terms such as hazard category, hazard rating, or consequence category. However, the objective of classifying a dam according to its potential impact, hazard, or consequence remains consistent. A dam's classification is purely a function of the consequences of a hypothetical failure breach or other uncontrolled release of the stored contents. It has no correlation with the probability of the dam failing or experiencing a dam safety incident.

Legal requirements for the classification of dams in New Zealand are described in Module 1: Legal Requirements.

1. In these Guidelines, the terms 'dam failure', 'dam-break' and 'dam breach' are used interchangeably. They all refer to an uncontrolled release of water, or other fluid, from a reservoir due to the failure of a dam or its appurtenant structures, resulting from structural failure or other deficiency.

## 1.3 Breach scenarios and incremental consequences

The breach scenarios for a dam vary depending on the nature of its design, construction, hazards specific to the site (refer Module 3: Investigation, Design and Analysis) and the conditions under which it may fail. For example, a dam failure occurring under dry weather conditions (when the reservoir is full and under normal inflow conditions) is commonly referred to as a 'sunny day failure', while a failure occurring under flood inflow conditions is referred to as a 'rainy day failure'. Refer to section 2.3.3 for further discussion on 'sunny day' and 'rainy day' failure scenarios.

The incremental consequences of potential dam failure, which are the consequences directly attributable to dam failure, are the key consideration in determining a dam's PIC. These consequences are assessed relative to a base 'no dam failure' condition. For a 'sunny day' dam-break flood, the incremental consequences are the total damages incurred as a result of that hypothetical occurrence. For a 'rainy day' dam-break flood, the incremental consequences are based on the total damages incurred by the hypothetical dam-break flood less any damages incurred by the base flood without dam failure.

Dam classification should consider both 'sunny day' and 'rainy day' breach scenarios which are appropriate to the particular dam. The PIC should be determined separately for each scenario, and the PIC assigned to the dam should be based on the scenario that predicts the greatest magnitude of incremental adverse consequence.

## 1.4 Scope of module

This module addresses:

- The assessment of dam-break flood hazards and consequences (section 2).
- The determination of a dam's Potential Impact Classification to reflect the consequences of potential dam failure (section 3).
- The determination of Potential Impact Classification of subsidiary dams, canals, and appurtenant structures (section 4).
- Other issues and factors that should be considered for dam-break flood hazard and consequence assessments (section 5).

Figure 1.1 presents an overview of the dam classification process as outlined in this module.

A list of reference documents cited is included in section 6 at the end of the module to assist Owners and their Technical Advisors in the assessment of dam failure consequences and the classification of dams.

Where specific sources of information are cited in this module, it should be understood that these sources may be revised, updated, or superseded by advancements in knowledge and practice. Technical Advisors should use the latest and most appropriate sources of information aligned with these originally cited sources.

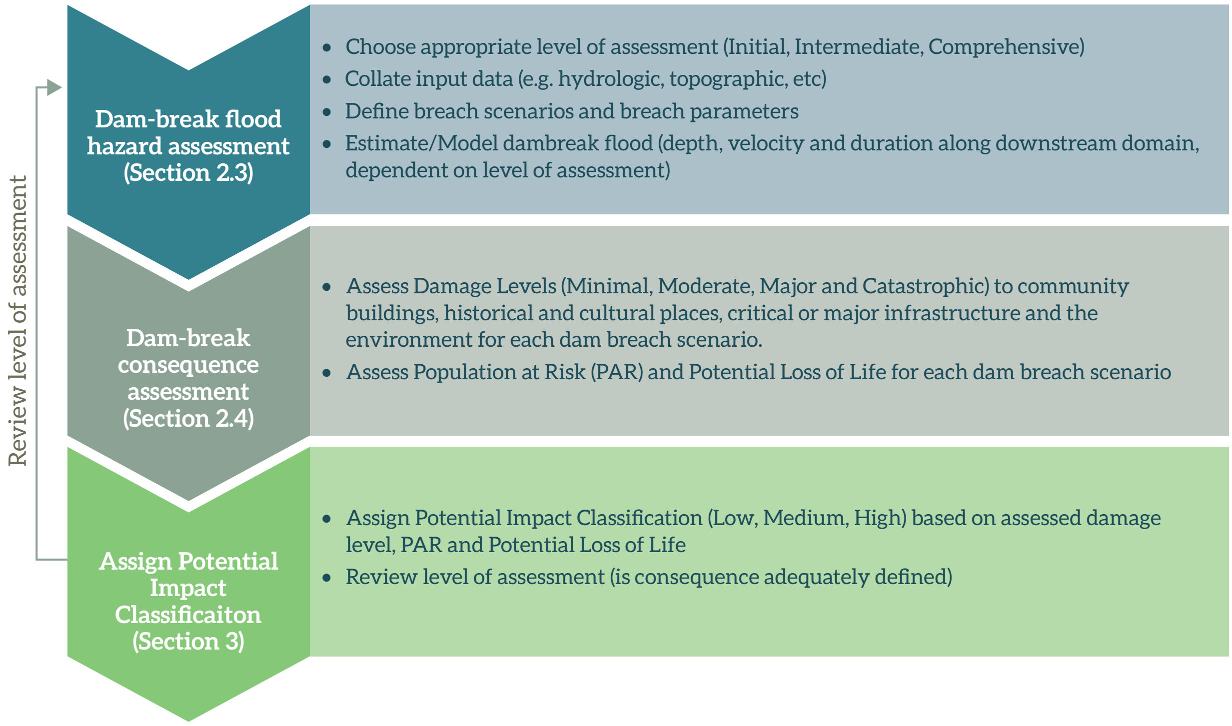


*Figure 1.1: Overview of the dam classification process*

# 2. Dam-break flood hazard and consequence assessments

## 2.1 Overview

Dam-break flood hazard and consequence assessments are key items required to determine the Potential Impact Classification of a dam. It is important that these assessments are undertaken by experienced and qualified Technical Advisors.

Dam-break flood hazard and consequence assessments are also useful in:

- Understanding the potential consequences and hazard from a hypothetical dam failure (refer Principle 1 in the Parent Document).
- Emergency planning and preparedness, by identifying the potential consequences of dam failure and response actions to avert failure or mitigate the consequences of failure (refer Module 6: Emergency Preparedness).
- Providing input on the consequences of failure for risk assessment studies or business risk determinations (refer Module 7, section 5.4).

Guidance for completing dam-break flood hazard and consequence assessments, including inputs, procedures and outputs is provided in the following sub-sections.

Dam-break flood hazard and consequence assessments should be carried out for worst case 'sunny day' and 'rainy day' failure scenarios for the main dam to determine a dam's PIC. However, in addition to this, similar assessments may need to be carried out for a hypothetical failure of a portion of the main dam other than the maximum section, a subsidiary reservoir retaining structure (e.g. saddle dam, thrust block) or an appurtenant structure (e.g. spillway). Refer to section 4 for further guidance on PIC determination for such structures.

## 2.2 General considerations

### 2.2.1 Levels of assessment

Procedures for evaluating dam-break flood inundation extents and the consequential impacts downstream for a hypothetical dam failure can vary from engineering judgement to sophisticated methods of analysis. As such, there are many potential choices when performing dam-break flood hazard and consequence assessments to determine a dam's PIC or to develop dam-break flood inundation maps for emergency preparedness plan documents. Because dam-break flood hazard and consequence assessments will not always require the most sophisticated tools available, different levels of assessment can be completed (initial, intermediate or comprehensive).

In general, the level of dam-break flood hazard and consequence assessment should correlate with the scale and complexity of the dam and the nature of the downstream area potentially impacted by a hypothetical dam breach flood. Assessment of dams that are anticipated to have a Medium or High PIC and are located upstream of populated areas or highly developed floodplains should use more sophisticated modelling and analysis tools to properly assess the consequences of a dam failure. Assessment of dams that are anticipated to have a Low PIC and are situated upstream of sparsely populated areas could rely on more approximate assessment methods.

In some circumstances it may be self-evident that a particular dam has a High PIC (for example a very large dam upstream of a densely populated area). A dam Owner may elect to take a presumptive approach and assign a High PIC to their dam without completion of a formal dam-break flood hazard and consequence assessment. However, even if this approach is followed, a dam-break flood hazard and consequence assessment will likely be required for other purposes. For instance, it may support the development of an Emergency Action Plan (refer to Module 6) or facilitate the selection of the Inflow Design Flood (refer to Module 3, section 4.2).

Figure 2.1 provides an overview of the selection process for different levels of assessment for a dam-break flood hazard and consequence assessment process. The following sub-sections provide a general discussion of the different levels of assessment (initial, intermediate, or comprehensive). Section 2.2.2 provides an overview of the general process for an initial assessment and section 2.2.3 covers both intermediate and comprehensive levels of assessment.

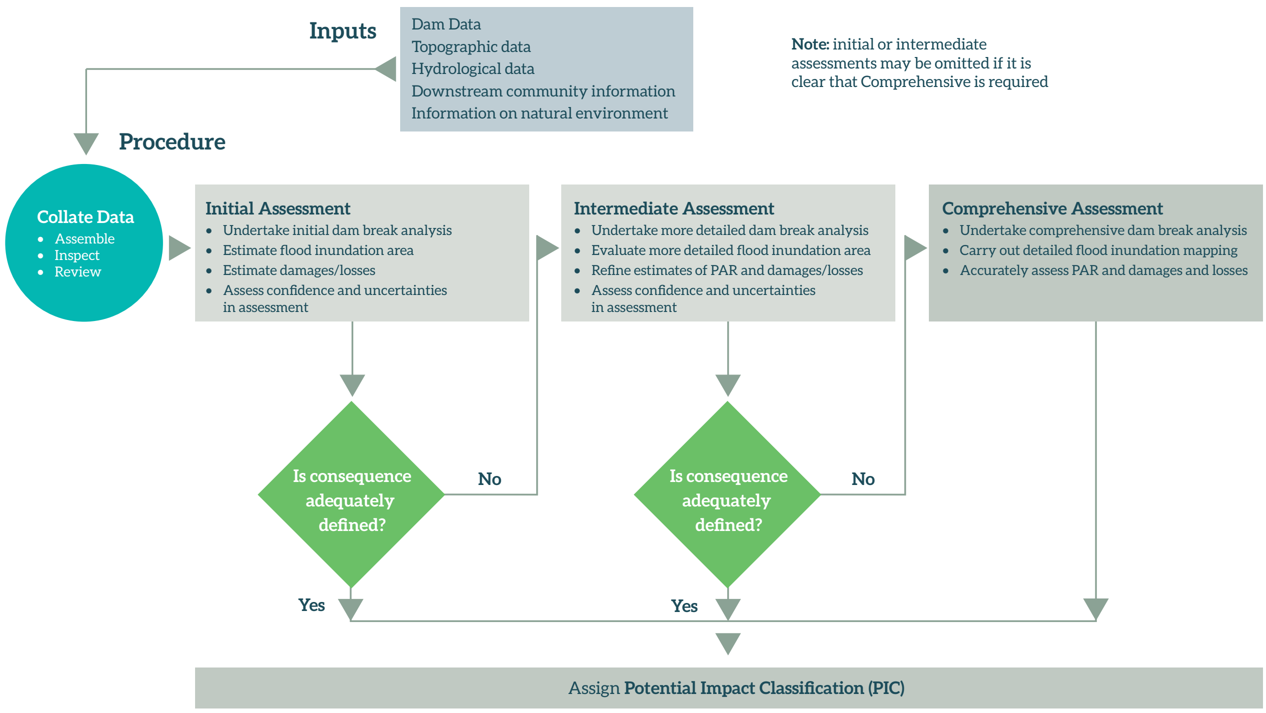


*Figure 2.1: Overview of the selection process for different levels of assessment for a dam-break flood hazard and consequence assessment*

### 2.2.1.1 Initial

An initial dam-break flood hazard and consequence assessment may be sufficient to determine the PIC of a dam based on existing knowledge and information. This could be from an estimation of the magnitude of a potential dam-break flood supported by basic calculations to determine the peak breach outflow, and use of topographic maps and aerial photographs to evaluate the flood path and its potential impacts on people, buildings, infrastructure, historical and cultural places, and the environment.

Such an assessment should be completed conservatively and is often restricted to the consideration of a hypothetical, conservative potential failure mode that results in dam failure. However, the initial assessment may raise uncertainties (e.g. in open flat areas and where buildings, infrastructure or occupied locations are close to the edge of inundation) that can only be resolved by undertaking an intermediate or comprehensive assessment.

Initial assessments can be justified for dams when there is little doubt as to the dam's PIC (in terms of potential failure impact to the downstream Population at Risk, Potential Loss of Life, and damage level to community buildings, critical or major infrastructure, historical or cultural places and the environment). The cost of a higher level of assessment may be deemed unnecessary in relation to the potential benefits of a higher level of assessment.

Initial assessments may also be appropriate as a first level screening for dams anticipated to have a Medium or High PIC, and prior to completion of an intermediate or comprehensive assessment which would be needed to develop flood inundation maps for emergency preparedness plan documents.

#### 2.2.1.2 Intermediate

An intermediate dam-break flood hazard and consequence assessment requires a more quantitative assessment of the magnitude of the potential dam-break flood hazard and the downstream consequences compared to an initial assessment. An intermediate level assessment should include the estimation of breach parameters to a greater level of detail (e.g. considering breach size and development time appropriate to the dam type and the nature of the foundation) and some dam-break flood routing, usually with the aid of a computational hydraulic model, to establish the likely extent of downstream flood inundation from which the Population at Risk, Potential Loss of Life, and damage levels. The assessment of damage levels includes damages to community buildings, critical or major infrastructure, historical or cultural places, and the environment.

However, if there continues to be a lack of certainty or confidence in the results of an intermediate assessment, then a comprehensive assessment should be completed. For example, a comprehensive assessment may be required to determine the PIC where the results of an intermediate assessment indicate that the PIC is on the borderline between Low and Medium, or Medium and High.

#### 2.2.1.3 Comprehensive

A comprehensive assessment is typically required for dams that have high consequences, and therefore require detailed consequence outputs for emergency planning and preparedness, or the development of risk reduction measures. A comprehensive assessment may also be required to establish the PIC of a dam where it is borderline between Low and Medium, or Medium and High.

The process for a comprehensive dam-break flood hazard and consequence assessment is similar to that for an intermediate assessment. However, the completion of a comprehensive assessment usually requires the identification and consideration of potential failure modes (refer section 2.2.5), dam-break flood routing, mapping of the extent of flood inundation, and evaluation of the peak flood depth, flow velocity, time of flood arrival, time of flood peak, and inundation duration at key locations (e.g. buildings and infrastructure). It would usually require the completion of a detailed dam-break consequence assessment, unless the PIC was clearly above the threshold for a High PIC dam and detailed information on the dam-break consequence was not required.

### 2.2.2 Process for initial assessments

The following process should be considered for initial dam-break flood hazard and consequence assessments:

- Collate readily available and existing information, including details about the dam, downstream topographic data, and hydrological data.
- Estimate the peak dam breach outflows for 'sunny day' and 'rainy day' failure scenarios as appropriate to the dam type (e.g. using an approach such as Froehlich, 2016a, for embankment dams).
- Estimate the resulting downstream flood inundation extent using engineering judgement and inspection of downstream topographic maps and aerial photographs, supported by limited hydraulic calculations as required.
- Estimate the Population at Risk, Potential Loss of life, and damage levels according to the categories listed in Table 2.2, based on general information available from existing topographic maps, inspection of aerial photographs and supplemented with local knowledge.
- Population at Risk and Potential Loss of Life are estimated within broad range categories (refer to Table 2.6) based on judgement which considers the dam-break flood flow characteristics at locations where the presence of people can be reasonably expected. Note that where Population at Risk and Potential Loss of Life estimates do not clearly fit within one of the categories listed in the PIC determination tables, further assessment at an intermediate or comprehensive level would normally be required.
- Assess the dam PIC based on the estimated Population at Risk, Potential Loss of Life, and assessed damage levels.
- Identify and communicate any uncertainties that may need to be resolved by an intermediate or comprehensive assessment.

### 2.2.3 Process for intermediate and comprehensive assessments

The following process should be considered for intermediate and comprehensive dam-break flood hazard and consequence assessments:

- Collate information relevant to assess the effects of a potential dam failure.
- Identify and build an understanding of the typical initiating events and mechanisms by which the dam could fail (potential failure modes should be identified and considered for a comprehensive level of assessment).
- Estimate the dam breach characteristics and the magnitude of the breach outflow flood (peak discharge, time to peak discharge, and time to empty the impounded reservoir). If the various potential failure modes result in different locations or types of breach, it may be necessary to estimate breach characteristics for more than one breach. The steps outlined below apply for each selected breach.
- Evaluate the movement and spread of the flood released by a dam failure and the resulting downstream inundation (flood travel times, peak flow depths and velocities, and the extent of flood inundation).
- Estimate damages to buildings, critical or major infrastructure, historical and cultural places and environmental damages (refer guidance in section 2.4.2).
- Estimate the Population at Risk and the Potential Loss of Life (refer guidance in section 2.4.3).
- Assess the dam PIC based on the estimated Population at Risk, Potential Loss of Life, and assessed damage levels (refer guidance in section 3).
- Communicate the potential consequences in an easily understood form for use by relevant parties for the particular dam as needed (such as the dam Owner, regulators, and emergency agencies, e.g. Civil Defence).

These processes are discussed more fully in the following sections. FEMA (2013) and Appendix A of ANCOLD (2012) provide further information on methods for undertaking the differing levels of dam-break flood hazard and consequence assessment.

### 2.2.4 Collation of relevant data

Relevant data should be collated for a dam-break flood hazard and consequence assessment including information on:

- The dam and its impounded reservoir.
- The topography downstream of the dam.
- Hydrological data.
- The downstream community.
- Historical and cultural places.
- The natural environment.

Table 2.1 summarises the information in each of the above categories that may be required to be collated. The level of detail required for this information will be influenced by the level of dam-break flood hazard and consequence assessment being undertaken.

Table 2.1: Information that may be required for dam-break flood hazard and consequence assessments

| Type of data | Specific information |
|---|---|
| Dam and reservoir | • Layout of reservoir and/or river system<br>• Reservoir capacity (including reservoir depth/storage information if available)<br>• Reservoir bathymetry<br>• Layout of dam and appurtenant structures<br>• Type of dam (construction materials)<br>• Dam dimensions (maximum height, crest width and length, crest level)<br>• Spillway characteristics, dimensions, crest level and flood capacity<br>• Low-level outlet dimensions, layout, inlet and outlet invert levels<br>• Dam foundation conditions<br>• Dam history (age, level of engineering in original design, operational history including any dam safety incidents/issues)<br>• Dam potential failure modes (where they exist, or develop as appropriate)<br>• Breach characteristics for each relevant potential breach |
| Topographic data | • Characteristics of downstream valley (shape and slope) or plain (slope and direction of slope)<br>• Maps (appropriate scale topographic maps)<br>• Topographic data in digital terrain model form (primarily for intermediate and comprehensive level assessments)<br>• Surveyed river / stream cross-section data<br>• Potential controls on downstream flood flows (bridges, culverts, road embankments, other dams, gorges, and vegetation)<br>• Downstream dams and reservoirs<br>• Major downstream tributaries |
| Hydrological data | • Hydrological characteristics of catchment<br>• Recorded rainfall or streamflow data<br>• Flood inflow estimates for reservoir<br>• Flood estimates for downstream tributaries<br>• Historic flood information (levels and flows) |
| Downstream community | • Locations and sizes of downstream centres of population<br>• Temporal patterns of population (itinerants)<br>• Locations and types of community facilities (e.g. schools, hospitals, other institutions, residential dwellings, industrial, commercial and retail areas, camping areas)<br>• Potentially affected infrastructure (e.g. roads, bridges, airports, railway lines, water, flood protection assets, power and communication systems)<br>• Emergency service facilities (Police, Fire, Ambulance, Civil Defence)<br>• Hazardous substance processing or storage facilities<br>• Land use and development types |
| Cultural places* | • Historical or cultural places listed on the New Zealand Heritage List / Rārangi Kōrero<br>• Historic sites listed on the Department of Conservations National Register |
| Natural environment* | Vegetation type and cover<br>Waterways and wetlands<br>Rare or endangered species habitats<br>River morphology<br>Other features of environmental significance (e.g. national parks, conservation areas, regional parks, reserves) |
| *An Assessment of Environmental Effects report for a new dam or existing dam can be a valuable source of information for evaluation of consequences to the natural environment and cultural and heritage sites. | |

### 2.2.5 Potential dam failure modes

An understanding of the initiating events and mechanisms that can lead to a dam failure (potential failure modes) is important for dam-break flood hazard and consequence assessments. The potential failure modes for a dam will influence the nature of breach development and the conditions under which downstream consequences of failure are evaluated. The identification and assessment of potential failure modes is addressed in Module 3: Investigation, Design and Analysis and Module 5: Dam Safety Management.

Detailed consideration of the most credible potential failure modes for a given dam can be used to obtain an improved understanding of the likely breach characteristics and development of the breach outflow hydrograph. For example, the breach characteristics and outflow hydrograph for a failure of a concrete dam would be different from that for a failure of an embankment dam. There are many and varied dam arrangements, each with their own unique features that require careful consideration when identifying potential failure modes and determining likely breach characteristics and resulting outflow hydrographs.

Credible potential failure modes for a dam should be used to develop 'sunny day' and 'rainy day' dam failure scenarios. In general, the potential failure modes that lead to the largest downstream flooding, for both the 'sunny day' and 'rainy day' scenarios, should be selected.

### 2.2.6 Cascade failure

If one or more dams are located downstream of the dam being analysed, the dam-break flood hazard assessment should consider the potential for a cascade failure where the failure of the upstream dam could cause overtopping and failure of the downstream dam(s). In some cases, this can have a 'domino' effect causing multiple dams in a chain or 'run-of-river' system to fail.

As an example, in Figure 2.2 the failure of Dam C could cause a cascade failure of Dams D and E. In such a situation the assessment of the consequences of dam failure should include the cumulative effects of any downstream dam failures. Conversely, there are situations where the existence of a downstream dam can result in reduced downstream consequences. This occurs where the dimensions of the downstream reservoir (including the available freeboard at the downstream dam) are such that the reservoir provides sufficient attenuation, or even complete containment, of the discharge resulting from an upstream dam failure. As an example, in Figure 2.2 the discharge from failure of Dam B could be contained within the downstream reservoir impounded by Dam C, without a failure of Dam C, if the reservoir contained sufficient flood storage above normal reservoir operating level.

Ultimately, each dam and its upstream and downstream environment will be unique and should be reviewed on its own merits.

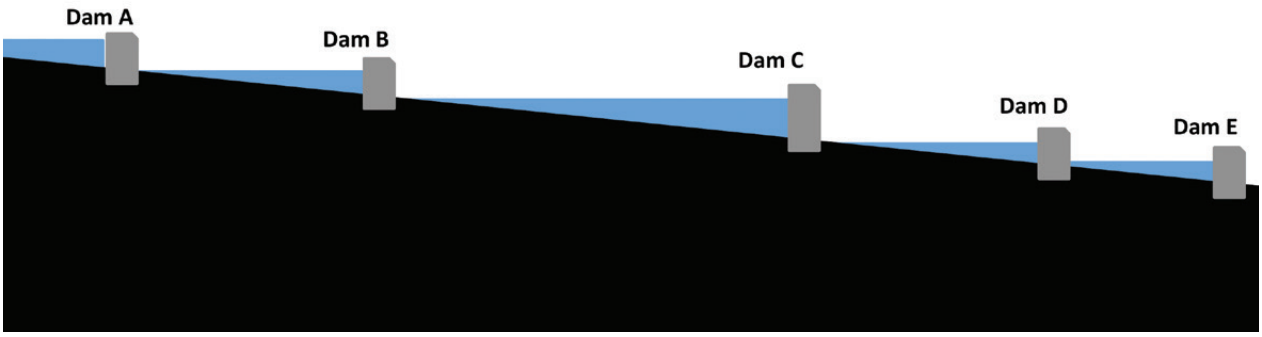


*Figure 2.2: Example multi-dam system with the potential for a cascade failure*

### 2.2.7 Records and documentation

Both dam-break flood hazard and consequence assessment involve elements of judgement. It is therefore important that the methods and rationale used in the estimation methodologies are thoroughly documented with sufficient evidence to justify and ensure transparency of the outputs. Further guidance on information management as part of a Dam Safety Management System is provided in Module 5, section 4.9.

## 2.3 Dam-break flood hazard assessment

### 2.3.1 Process

Figure 2.3 provides an overview of the dam-break flood hazard assessment process. The following sub-sections provide guidelines for each step in the process. These sub-sections relate primarily to dam-break flood hazard assessments for water retaining dams. Refer to section 5.9 for discussion on tailings storage facilities.

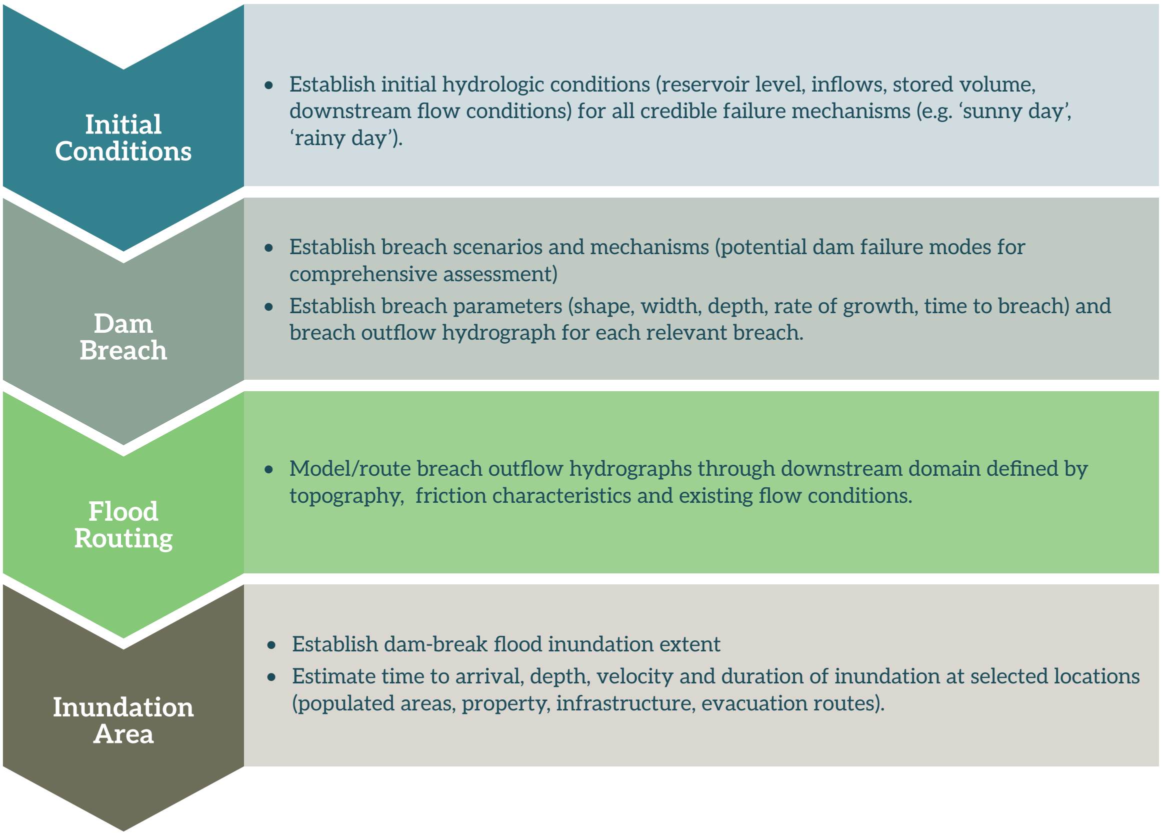


*Figure 2.3: Overview of the dam-break flood hazard assessment process*

### 2.3.2 Purpose

A dam-break flood hazard assessment evaluates the rate of release of the reservoir storage volume through a hypothetical breach and estimates the movement and spread of the resulting flood wave downstream. The objective of the assessment is to determine the characteristics of the dam-break flood wave and the likely downstream effects of a hypothetical dam failure. The flood wave characteristics of most interest are the maximum extent of downstream flood inundation, the time of flood arrival, the time to flood peak, the peak flood depth, the peak flow velocity, the maximum value of the product of depth and velocity and the duration of inundation at key locations. The effects of greatest interest are to people (including potential life loss) and the damage to buildings, infrastructure, historical and cultural places, and the environment.

The dam-break flood hazard assessment should extend downstream to a point where the effects of a dam-break flood become negligible. Refer to section 5.4 for further discussion on selection of the downstream extent of a dam-break study.

### 2.3.3 Initial hydrologic conditions

Evaluation of the rate of release of the reservoir storage volume through a hypothetical breach (the breach outflow hydrograph) and the movement and spread of the resulting dam-break flood wave (flood wave routing) requires the evaluation of initial hydrologic conditions, and the estimation of likely breach size and its rate of development. The key hydrologic parameters to consider are reservoir level, reservoir inflow, stored volume, and downstream flow conditions.

For all assessments, the following two failure scenarios should typically be considered (except for flood detention dams, as outlined in section 5.7):

- 'Sunny day' failure – the dam failure occurs when the reservoir is full and under normal inflow conditions.
- 'Rainy day' failure – the dam failure occurs under flood inflow conditions.

For comprehensive assessments, each identified credible potential failure mode and the specific breach characteristic of those potential failure modes should be assessed to develop the worst case 'sunny day' and 'rainy day' dam failure scenarios.

It is important that both 'sunny day' and 'rainy day' scenarios are considered as there may be a significant difference in the consequence arising from each that is not immediately obvious. For example, while flood depths and extent are likely to be greater for a 'rainy day' failure, downstream communities may be more exposed to the hazard resulting from a 'sunny day' failure because people may be more likely to be present around watercourses (e.g. for recreational purposes) at the time of failure than under 'rainy day' failure conditions. As noted in section 1.3, the incremental increase in flooding due to a hypothetical 'rainy day' dam-break flood may be lesser, or have lesser consequences, than the flood resulting from a hypothetical 'sunny day' dam failure.

Reservoir inflows and levels, and downstream watercourse flows, should be those most likely to occur coincident with an assumed potential dam failure mode. For example, for a 'sunny day' failure, the assumption of the reservoir being at spillway level or at the maximum normal operating reservoir level and median annual flow conditions in the downstream channel (including tributary watercourses) is reasonable.

For a 'rainy day' dam failure, it is important to identify the hydrological base case against which the 'rainy day' failure scenario should be compared. For new dams, or existing dams, where the PIC has yet to be established, the Inflow Design Flood (IDF) is not defined until the consequences of dam failure have been assessed and the PIC assigned. The IDF therefore cannot initially be used in the assessment. If failure is assumed to be due to overtopping of the dam crest, it is recommended that the Dam Crest Flood is used as the base flood for carrying out the consequence assessment. If a peak flood level lower than the dam crest level is likely to cause failure of the dam, such as excessive seepage through an embankment crest above core level or due to instability of a concrete dam, then this flood should be used for the base flow conditions.

For a 'rainy day' dam failure, it is also important to take account of the tributary inflows from catchments downstream of the dam. Judgement should be exercised to define the magnitude of concurrent tributary inflows relative to the magnitude of the selected IDF taking account of the relative size of the tributary catchments and the nature of the storm giving rise to the assumed 'rainy day' dam failure. For example, while a Probable Maximum Flood (PMF) may be assumed as the IDF for a hypothetical 'rainy day' dam failure, the downstream tributary catchments could be located well downstream from the dam catchment. The centre of the storm causing the assumed 'rainy day' failure could be sufficiently far away from these tributary catchments that it is appropriate to assume concurrent inflows of lesser magnitude from the tributary catchments.

In some cases, there may not be a credible 'rainy day' failure scenario (e.g. dams impounding off-river storage reservoirs) and this should be stated in the dam-break flood hazard assessment report. Equally, for structures such as flood detention dams there may not be a credible 'sunny day' scenario (refer section 5.7 for further information on flood detention dams).

### 2.3.4 Dam breach characteristics

#### 2.3.4.1 Considerations

The magnitude of the dam-break flood resulting from a hypothetical dam breach depends on the dam type, the breach location within the dam structure, the breach size and the rate of breach development. The breach characteristics are determined by considering likely initiating events and analysing potential failure modes. Estimation of the breach shape, size, and timing requires consideration of the dam type:

- Earthfill and rockfill embankment dams – tend to fail in a progressive manner. Once a breach has initiated, the outflow gradually erodes part of the dam until the reservoir is emptied or the outflow becomes insufficient to further erode the breach. Unless the impounded reservoir is extremely large and the dam small, an eroded breach may be limited to a part of an earthfill or rockfill dam. Concrete structures embedded in the embankment may limit the breach growth, while soft foundations may allow the breach to extend beyond the limit of the dam foundation.
- Concrete faced rockfill dams – may sustain considerable discharge through the rockfill before the rockfill starts to erode due to concentrated leakage. When the eroded rockfill material forming part of the embankment can no longer support the upstream face, an abrupt failure of the concrete face slab will occur allowing a breach to develop. So long as the upstream face slab does not fail, seepage outflows may be able to be safely accommodated by the downstream rockfill.
- Concrete gravity dams – tend to fail in an abrupt manner with failure assumed to occur near-instantaneously. Case histories show that many concrete gravity dam failures have involved foundation discontinuities or weaknesses. A potential failure mode analysis should be used to estimate the breach size. Reports indicate that more than one third of historical concrete dam failures have resulted in breach widths greater than 30 percent of the dam length (Veale and Davison, 2013).
- Concrete arch dams – also tend to fail in an abrupt manner with failure assumed to occur near-instantaneously. Based on case histories, concrete arch dams are more likely to fail in their entirety, usually due to abutment failure and the subsequent loss of arch support.

#### 2.3.4.2 Key parameters

Key parameters for describing breach development include the breach shape, width and depth, the rate of growth over time, and the time to reach the ultimate or critical breach depth. Generally, for dams impounding very large volume reservoirs, the critical parameter for determining the size of a dam-break flood is the ultimate breach size. For dams impounding very small reservoirs, the reservoir drawdown rate may be quite fast, and the critical parameters determining the size of a dam-break flood are the rate of breach erosion over time and the reservoir storage volume. For canal embankments, parameters influencing the size of a canal breach flood may include the concurrent canal flow (inflows may or may not be able to be controlled), the rate of breach erosion over time, the ultimate breach size and the critical flow capacity of the canal cross-section.

The estimation of breach parameters for dams is an inexact but very important aspect of dam-break flood evaluation. Fortunately, there are considerable empirical data which can be used to estimate breach parameters. In addition, there are mathematical models which can be used to predict the development of a breach over time and the subsequent dam-break flood hydrograph.

The identification and assessment of potential failure modes will provide information on the nature and likely location(s) of hypothetical dam breaches. For embankment dams, geotechnical assessments should provide information on likely erosion mechanisms and erosion rates for embankment materials. For earthfill and rockfill embankment dams it is common to assume a trapezoidal breach shape and a linear rate of breach growth. However, the best guide for estimating breach parameters is to use data from historical failures. Wahl (1998) and Froehlich (2016a, 2016b) provide guidance on breach parameter estimation and a comprehensive dataset of dam, reservoir, and breach parameters from historical embankment dam failures. Veale & Davison (2013) provide a database of concrete dam failures and useful guidance on estimating breach geometries for concrete gravity dam failures.

Due to the inexact nature of breach parameter selection for a hypothetical dam failure, sensitivity analyses should be considered to assess the effects of different breach sizes and rates of development on:

- The peak discharge and duration.
- The ensuing effects of the dam-break flood on the downstream area.

Consideration should be given to 'ground-truthing' peak breach outflow predictions against historical failure data for dams of similar composition, size and reservoir storage capacity. This should be done prior to specifying the breach parameters that are to be used in mathematical dam-break flood models and undertaking sensitivity analyses of dam breach outflow hydrograph predictions to breach parameter estimates.

## 2.3.5 Dam breach outflow hydrograph

### 2.3.5.1 General

A dam breach outflow hydrograph describes the rate that the stored volume is released from the reservoir through the breach with time. While it is generally sufficient to estimate the peak breach outflow using empirically-based methods (such as those described by Wahl, 1998, and Froehlich, 2016a, for embankment dams) for an initial dam-break flood hazard assessment, a more rigorous breach outflow hydrograph should be estimated for intermediate and comprehensive assessments. The characterisation of a breach outflow hydrograph requires an understanding of a dam's potential failure modes, the likely size of a breach, the rate of breach development, and the hydraulic behaviour of the outflow for a given breach geometry, initial reservoir level, and downstream topography.

### 2.3.5.2 Estimation methods and considerations

Methods for evaluating a breach outflow hydrograph include:

- Simple triangular-shaped hydrograph approximations based on an estimated peak breach outflow and the total reservoir storage volume.
- Reservoir routing based on a level reservoir assumption and a modified weir outflow relationship for flow through a developing breach.
- Analytical solutions for a hypothetical failure of a concrete gravity or arch dam.
- Flood routing models based on commercial software programmes in which the breach formation parameters and the geometry of the downstream channel are defined.

There are several factors other than the shape and size of a breach, the breach formation time and the rate of breach growth that influence a dam breach outflow hydrograph. The following should be considered:

- The size and shape of the upstream reservoir, and whether drawdown of the reservoir should be modelled with a level pool or dynamic approach (Goodell & Wahlin, 2009).
- Whether or not inflows can be controlled, which is important for diversion structures or canals where inflows are large relative to stored volumes.
- The downstream tailwater level at the time of dam failure.
- The variation in downstream tailwater level as a dam breach develops over time.
- The downstream topography.

Figure 2.4 provides an example breach outflow hydrograph for a 'sunny day' failure of an earthfill or rockfill embankment dam. The hydrograph reflects a progressive dam failure where the size of the dam breach gradually increases over time as the breach outflow erodes more dam material. Eventually a peak outflow condition is reached. The peak outflow is a representation of either:

- The 'equilibrium' breach size, where the combination of reservoir elevation and breach size produce the maximum outflow that will be achieved, and further erosion may occur but the decreasing reservoir level will result in a lesser discharge, or
- The 'maximum' or 'ultimate' breach size, where the breach reaches a maximum size when the reservoir outflow becomes insufficient to erode it further (laterally or deeper).

The ‘equilibrium’ breach size is the typical control for dams with lesser reservoir volumes and the ‘maximum’ breach size is the typical control for dams with larger reservoir volumes.

In either case, the reservoir will continue to drain until it is either empty (where the breach is eroded down to the breach invert level) or it reaches the invert of the eroded breach (where the breach is formed over a part of the dam height). Throughout the entire breach development process for an earthfill or rockfill dam, the level of the upstream reservoir remains approximately horizontal with weir type outflow occurring through the dam breach.

In contrast to earthfill or rockfill dams, the breach outflow hydrograph for a sudden (near-instantaneous) concrete dam failure has a different shape to that shown in Figure 2.4, with the peak outflow occurring at a time close to zero as shown in Figure 2.5. The evaluation of such hydrographs requires special consideration as the assumptions of a level reservoir surface and weir type outflow through the dam breach are no longer valid. An analytical solution may be required to evaluate the breach outflow hydrograph. USACE (1997) provides guidance for relatively long and narrow rectangular channels where the dam is completely removed. A concrete dam failure will produce a much higher peak breach outflow than an earthfill or rockfill dam for the same reservoir storage volume, dam height, and maximum breach size.

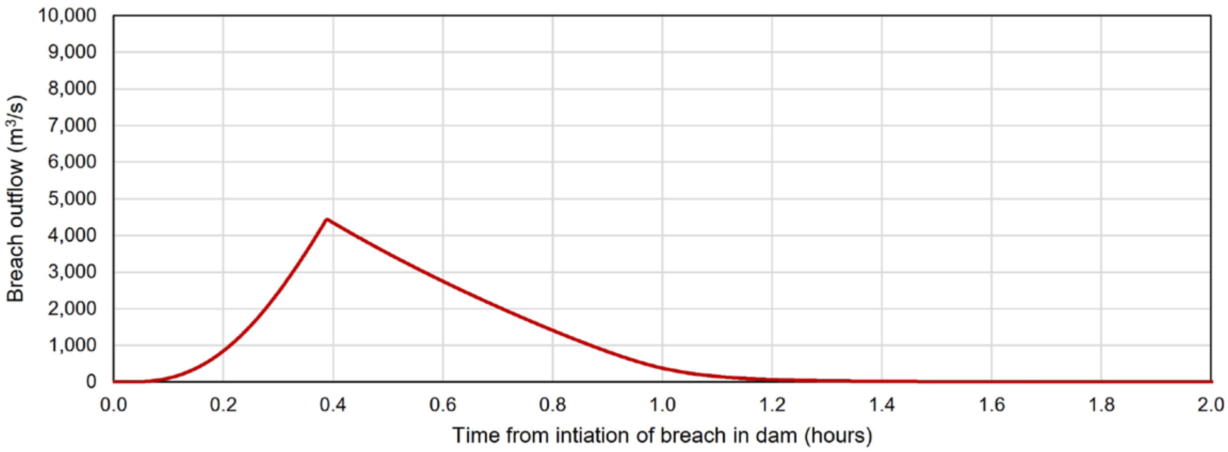


*Figure 2.4: Example breach outflow hydrograph for a ‘sunny day’ failure of an earthfill or rockfill embankment dam*

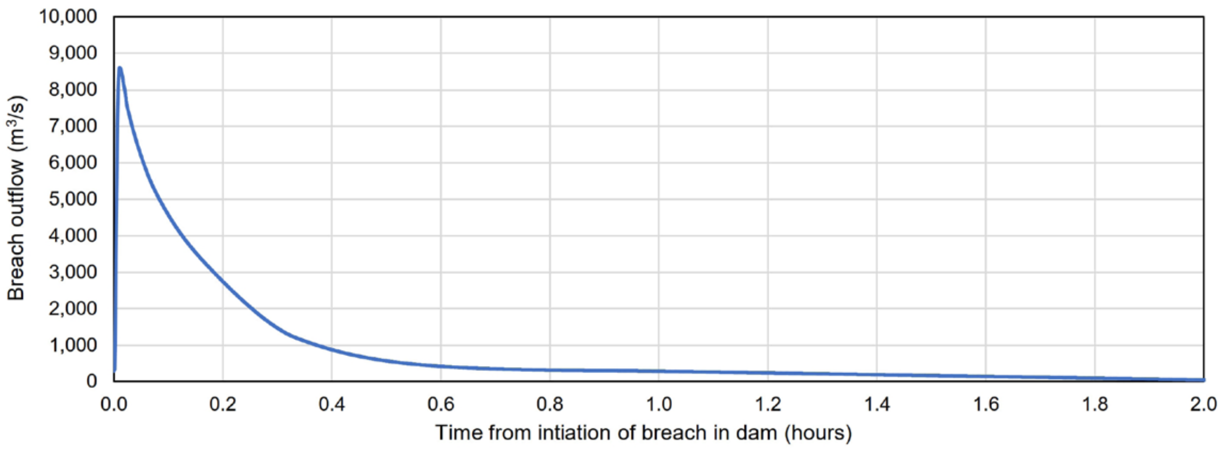


*Figure 2.5: Example breach outflow hydrograph for a ‘sunny day’ failure of a concrete gravity or concrete arch dam*

### 2.3.6 Flood wave routing

The process of evaluating the extent of flood inundation by tracking the downstream propagation of a dam-break flood wave is referred to as flood routing. Flood routing methods range from the simple translation of a peak flood discharge (including estimation of flood peak attenuation) to the use of computational hydraulic modelling. The method should be appropriate to the type of dam-break flood hazard assessment being completed (initial, intermediate, or comprehensive) and the level of accuracy required.

The key input to any flood wave routing analysis is the description of the downstream domain through which a hypothetical dam-break flood wave will flow. At a simple level this information can be obtained from topographical maps, or at a more detailed level the information can be obtained from site or aerial-based survey or scanning methods. As a dam-break flood is commonly several orders of magnitude larger than any historic natural flood event, experience and judgment is required in defining the downstream domain from available topographic data and other information. As such, while historic flood levels and flow characteristics provide useful data to inform the assessment, care should be exercised in assuming such characteristics will persist for larger dam-break flood flows.

The other key input to any flood routing analysis is an assessment of the frictional characteristics of the downstream domain as defined by its surface roughness characteristics. Experience and judgment are required. A site visit is very informative for making an assessment of surface roughness characteristics, as well as understanding the downstream topography and any other features that could affect the movement of a dam-break flood wave through the downstream domain. Land use maps and data are useful for assisting in determining the surface roughness and therefore likely flow characteristics within the project area.

The selected flood routing method is then applied to the defined domain to evaluate the movement of the dam-break flood wave downstream. Sensitivity analyses should be used to assess the potential variations in flood travel times and peak depths that result from uncertainty in the frictional characteristics of the domain. For off-stream storage dams and canal embankments, the downstream domain may not be a defined channel (as for a dam impounding a waterway) and different considerations may be required.

Backwater effects from hydraulic structures, with the potential to obstruct the path of the dam-break flood wave (e.g. bridges, road and rail embankments, culverts, stopbanks etc.) need to be carefully considered and included in the model as required. For example, bridge waterways and culverts could be assumed to block due to snagging of woody debris or sediment build-up, and road or river embankments could be assumed to fail due to overtopping flows. Assumptions regarding the behaviour of hydraulic structures need to be documented in the modelling report (refer section 2.2.7). Sensitivity analyses may be required to understand the impact of the assumed behaviour of hydraulic structures on estimated dam-break flood characteristics (i.e. flood travel times, peak flow depths and velocities, and the extent of downstream flood inundation).

### 2.3.7 Flood wave routing software

Comprehensive dam-break flood hazard assessments require analytical or computational hydraulic modelling methods. These methods employ detailed hydrodynamic evaluation of a dam breach outflow hydrograph and routing of the resulting flood wave downstream. Various commercial computational hydraulic modelling software packages are available for such purposes.

The breach development component of a software package evaluates the breach outflow hydrograph based on a prescribed breach development description (breach shape, initial size, final size and development time), the assumption of a horizontal upstream water surface as the upstream reservoir drains, and the assumption of weir outflow through the breach. As such, the breach development component is generally not suitable for the evaluation of near-instantaneous concrete dam failures. The flood routing component of a software package routes the resulting dam breach flood through the downstream valley and floodplains accounting for the effects of downstream domain friction, tributary watercourses, and hydraulic controls such as gorges, bridges and dams.

Separate software packages may be used to perform each of the above functions where they are appropriately coupled.

Computational hydraulic modelling software packages are typically one-dimensional (1D), two-dimensional

(2D) or a linked 1D-2D model. Further description of these types of models is provided in Book 6, Chapter 4 of Australian Rainfall and Runoff (ARR) (Ball et al., 2019). A 1D modelling approach is appropriate where the downstream flood path is formed by a clearly defined valley and the direction of flow is assumed to be predominantly parallel to the valley. 1D computational hydraulic modelling tools define the downstream domain by means of channel cross-sections. The channel cross-sections are used as calculation nodes at which flood levels and discharges are evaluated over the course of the passage of a flood wave. A 2D modelling approach is more appropriate where the downstream flood path for a flood wave crosses a floodplain, where the dam breach outflow may not travel by an obvious flow channel, or where the exact location of the flood path is uncertain. 2D computational hydraulic modelling packages define the downstream topography by means of a grid, typically consisting of triangular and/or quadrilateral shaped cells, with each cell having a specified constant ground level and differing directions of inflow and outflow across each cell face. Such models provide outputs of flood depth, water level, and velocity at each grid cell as a function of time.

### 2.3.8 Dam-break flood inundation mapping

Dam-break flood inundation maps show the maximum extent of inundation resulting from a hypothetical dam-break flood. These inundation maps are necessary for the assessment of downstream flood inundation effects (refer Figure 2.6). Inundation maps and supporting dam-break flood information also form an essential part of an Emergency Action Plan (refer Module 6: Emergency Preparedness). For emergency planning and preparedness, and interaction with regulators and emergency response agencies, the inundation maps that are developed and used should be based on the potential failure modes that produce the maximum peak outflows for the 'sunny day' and 'rainy day' dam failure scenarios (typically a breach through the maximum section). However, for risk assessments and/or a more complete understanding of the consequences of a dam failure, the development of inundation maps for other credible potential failure modes may be required.

To enable an assessment of the consequences of dam failure to be completed, the maps should show the locations of all buildings, infrastructure and other property, and provide details of flood arrival times, times to flood peak, and peak flood depths or levels at key locations of interest. It is important to choose locations of interest that are representative of areas where the expected consequences would be significant, such as populated or developed areas and key infrastructure such as bridges and roads that provide evacuation routes.

Inundation maps should be produced for both 'sunny day' and 'rainy day' dam failure scenarios (except for flood detention dams, as outlined in section 5.7). 'Rainy day' failure flood inundation maps should identify the underlying extent of the base flood assumed to give rise to the hypothetical dam failure, but without that failure occurring.

The scale of any required inundation mapping will depend on the characteristics of the dam and downstream catchment, and the magnitude of the hypothetical dam-break flood. Standard 1:50,000 scale Land Information New Zealand (LINZ) topographic maps are typically adequate as base maps. However, when preparing maps for input to an Emergency Action Plan, it is recommended that Civil Defence Emergency Management (CDEM) and other end users of the maps are consulted to check that the maps are sufficient for their purposes. FEMA (2013) provides guidance on the preparation of dam-break flood inundation maps for differing levels of assessment and accuracy.

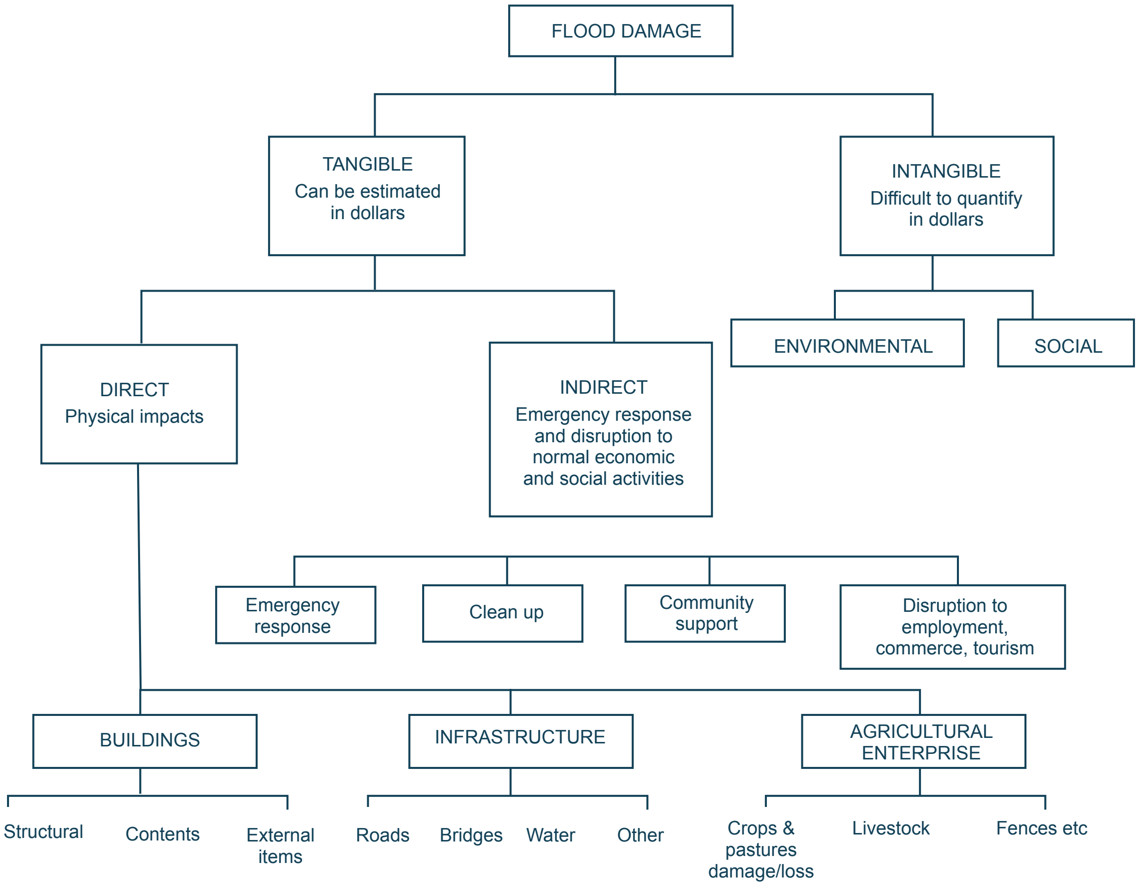


*Figure 2.7: Flood damage classifications (from Stephens, 2019)*

In some cases, a dam Owner may wish to understand specific types, or even the full range, of consequences such as those outlined in Figure 2.7 (e.g. for consenting, consultation, insurance or other purposes). However, for PIC assessment purposes, the objective of a consequence assessment is to determine the damage level exclusively for the following 'specified categories' listed in Table 2.2 and summarised as follows:

- Community buildings (i.e. households, commercial or industrial and community facilities).
- Historical or cultural sites.
- Critical or major infrastructure (including the time to restore operation of the damaged infrastructure).
- Natural environment.

Additionally, potential impacts to life safety, which are measured by the Population at Risk and Potential Loss of Life, are required to be estimated.

The guidance on consequence assessment presented in the following sections is limited to the processes used to determine damage levels for the categories listed in Table 2.2 and the processes to assess potential impacts to life safety for PIC assessment purposes. The following section 2.4.2 outlines guidance to estimate damage levels for the categories listed in the Table 2.2. Section 2.4.3 outlines guidance to estimate potential life safety impacts for PIC assessment purposes. The process to determine a dam's PIC is provided in section 3.

*Table 2.2: Determination of Assessed Damage Level*

| Damage Level | Specified categories | | | | |
|---|---|---|---|---|---|
| | Community[1] | Cultural | Critical or major infrastructure[1] | | Natural environment |
| | | | Damage | Time to restore to operation[2] | |
| Catastrophic | One or more of the following apply:<br>• 50 or more household units rendered uninhabitable.<br>• 20 or more commercial or industrial facilities rendered inoperable.<br>• 2 or more community facilities rendered inoperable or uninhabitable. | Irreparable loss to 2 or more historical or cultural sites. | Two or more critical or major infrastructure facilities rendered inoperable. | One year or more. | Extensive and widespread damage, with permanent, irreparable effects on the natural environment. |
| Major | One or more of the following apply:<br>• 4 or more but less than 50 household units rendered uninhabitable.<br>• 5 or more but less than 20 commercial or industrial facilities rendered inoperable.<br>• 1 community facility rendered inoperable or uninhabitable. | One or both of the following apply:<br>• irreparable loss to 1 historical or cultural site.<br>• loss to 1 or more historical or cultural sites where it is possible, but impracticable, to fully restore the site. | One critical or major infrastructure facility is rendered inoperable. | Three months or more but less than 1 year. | Extensive and widespread damage where it is possible, but impracticable, to fully restore or repair the damage. |
| Moderate | One or more of the following apply:<br>1 or more but less than 4 household units rendered uninhabitable.<br>1 or more but less than 5 commercial or industrial facilities rendered inoperable.<br>loss of some functionality of one or more community facilities. | Significant loss to 1 or more historical or cultural sites where it is practicable to restore the site. | One or more critical or major infrastructure facilities are affected by the loss of some functionality. | Less than 3 months. | Significant damage that is practicable to restore or repair. |
| Minimal | Minor damage that does not materially affect the functionality of any household unit, commercial or industrial facility, or community facility (or no damage). | Loss to 1 or more historical or cultural sites that will require minor restoration only (or no loss to any historical or cultural site). | Minor damage to 1 or more critical or major infrastructure facilities (or no damage). | One week or less. | Only minor rehabilitation or restoration may be required or recovery is possible without intervention (or no damage). |

Notes:

1. 'Rendered uninhabitable' in respect of the community damage category and 'rendered inoperable' in respect of the critical and major infrastructure damage category should be interpreted as meaning 'damaged beyond repair or destroyed'.
2. The estimated time required to repair the damage sufficiently to return the critical or major infrastructure to the normal operation that the infrastructure had immediately before the failure of the dam.

## 2.4.2 Assessment of damage levels

### 2.4.2.1 Determination of damage levels

For initial level dam-break consequence assessments, the estimation of damage levels involves the preliminary identification of buildings, cultural and heritage sites, critical and major infrastructure, and environmental areas within the expected downstream extent of dam-break flood inundation. The initial assessment process uses information from topographic maps and aerial photographs. The damage to identified assets is then qualitatively assessed according to each of the four damage level descriptions provided in Table 2.2. Initial assessments should adopt a conservative approach and, depending on the results, findings may need to be confirmed through more detailed assessments at an intermediate or comprehensive level.

For intermediate and comprehensive level dam-break consequence assessments, the estimation of damages for each of the four categories listed in Table 2.2 typically utilises dam-break flood inundation information (e.g. flood inundation extents, maximum flood depths, maximum flow velocities and/or maximum values of the product of flood depth and flow velocity, DV) in combination with geospatial information (e.g. topographic maps, aerial photos, land parcel boundaries, District Plan land use maps etc.) to identify affected assets within the dam-break flood inundation extent. By overlaying this information, typically in a Geographic Information System (GIS) environment, the damage to each asset from the dam-break flood water can be estimated based on the degree of flooding at each asset. Note that a site inspection may be necessary to verify the characteristics of individual assets where it is not obvious from available geospatial information. Figure 2.8 provides a basic illustration of a dam-break flood inundation extent and the location of assets immediately downstream for an example dam failure scenario.

Note that any consequence assessment should be based on current land use. District Plan land use maps show allowable land use, not current use. A site visit can be useful in clarifying current land use within a dam-break flood inundation area.

The processes described above can be broken down into two components: identification and analysis. Table 2.3 lists the activities involved in each of these components.

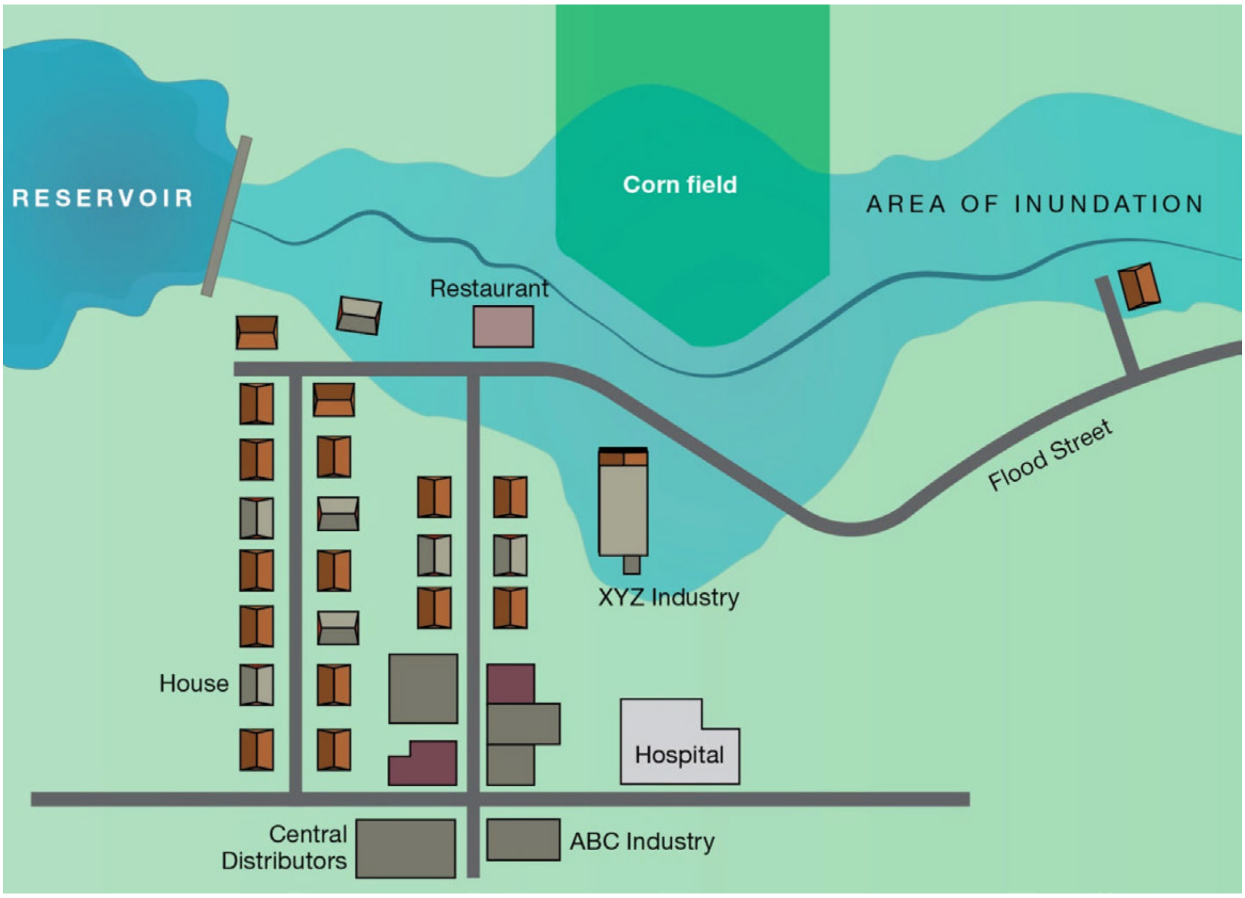


*Figure 2.8: Example of dam-break flood inundation area in relation to downstream assets (from FEMA, 2012)*

*Table 2.3: Activities involved in damage level assessments*

| Component | Activity |
|---|---|
| Identification | • Identifying the extent of inundation associated with each dam-break flood scenario, refer guidance in section 2.3.<br>• Identifying the forcefulness of the floodwater and its destructive power (i.e. flood depth and velocity information), refer guidance in section 2.3.<br>• Identifying the inventory of assets (primarily buildings, infrastructure, transport systems and other potentially affected locations) that will be inundated.<br>• Identifying environmental areas/sites potentially subject to damage.<br>• Identifying cultural and heritage areas/sites potentially subject to damage. |
| Analysis | • Estimating impact of each dam-break flood scenario in terms of damage to buildings (i.e. residential dwellings and commercial, industrial or community facilities) and critical or major infrastructure.<br>• Estimating damages to environmental areas/sites.<br>• Estimating the damages to cultural and heritage areas/sites. |

For all assessment levels (i.e. initial, intermediate, comprehensive), potential damages should be grouped into the four 'specified categories' listed in Table 2.2 so that the appropriate damage level can be assigned (i.e. minimal, moderate, major, catastrophic). The highest damage level determined (across all four 'specified categories' listed in Table 2.2) is selected for use in the classification of a dam (refer section 3).

For a 'rainy day' dam failure, the damage levels for PIC assessment purposes should be based on the total damages estimated for the dam failure occurring under flood conditions minus the estimated damages caused by the same flood conditions without dam failure (i.e. the incremental damages resulting from the additional flood inundation caused by the dam-break flood).

#### 2.4.2.2 Damage to community buildings

For PIC assessment purposes, the degree of damage to each identified community building (i.e. residential dwellings, commercial, industrial and community facilities) needs to be established according to the descriptions provided in Table 2.2, as either:

- Rendered uninhabitable or inoperable.
- Loss of functionality.
- Minor damage that does not materially affect the functionality.
- No damage.

Estimation of the degree of damage to community buildings only considers the direct impact of a hypothetical dam-break flood on a structure. No estimate of the life safety of people inside or outside the building is required, as this is covered independently under the assessment of Population at Risk and Potential Loss of Life (refer section 2.4.3).

For intermediate and comprehensive level assessments, where dam-break flood inundation depth and/or velocity information is available, the degree of damage to buildings can be established using building stability curves. Such curves relate the flow characteristics (e.g. maximum flood depth and/or maximum flow velocity) to the degree of damage expected for different building types. The following information sources provide building damage curves which may be useful for estimating the potential damage to buildings.

- The National Institute of Weather and Atmosphere (NIWA, 2010) provides potential damage curves as a function of building type and flooding depth, based on observed data from floods and tsunamis in New Zealand, Australia, and the Pacific. Using this information, 'damage states' DS0 to DS4 can be assigned to each flood affected building. For each damage state, different repair actions would be required to restore the structure to its pre-flood condition. Table 2.4 lists these damage states with their description, as well as the interpretation of the damage states relative to the descriptions provided in Table 2.2. Note that when assessing building damage states using the NIWA (2010) approach, flood depths are relative to the building floor level (and not the lowest ground level at the site).

*Table 2.4: Building damage states from NIWA (2010) related to building damage descriptors from Table 2.2*

| NIWA (2010) Damage State[1] | NIWA (2010) Damage State Description | Table 2.2 Building Damage Description |
|---|---|---|
| DS0 | Insignificant | No damage |
| DS1 | Light — Non-structural damage, or minor non-structural damage | Minor damage that does not materially affect the functionality |
| DS2 | Moderate — Reparable structural damage | Loss of functionality |
| DS3 | Severe — Irreparable structural damage | Rendered uninhabitable or inoperable |
| DS4 | Collapse — Structural integrity fails | Rendered uninhabitable or inoperable |

Notes:

1. Refer to NIWA (2010) for method to determine damage states as a function of flood depth (relative to building floor level) for different building types.

- Smith et al. (2014) provides thresholds for building stability in floods based on flood depth and velocity, from a comprehensive review of building stability thresholds from numerous publications. Figure 2.9 shows the combined hazard flood curves from Smith et al. (2014) which categorise flood hazard into six hazard categories (H1 to H6). The thresholds for these categories are based on peak flood depth and velocity at a given building. Table 2.5 describes these five thresholds as well as the interpretation of them relative to the damage states provided listed in Table 2.2. This method is also suitable to determine the damage level to buildings. It differs from the NIWA (2010) approach, because it is informed by the influence of both flood depth and flow velocity at a building.

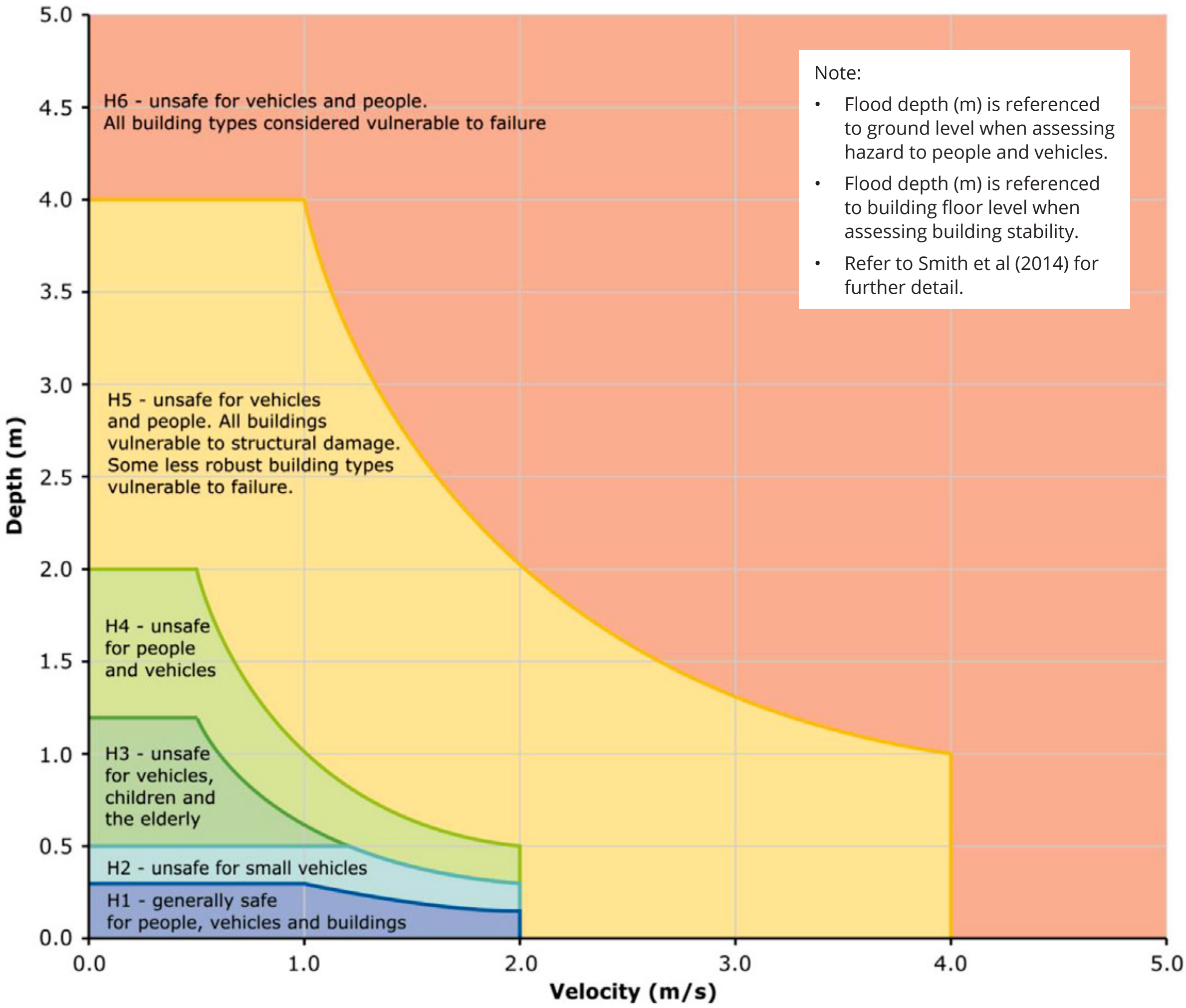


*Figure 2.9: Combined flood hazard curves (from Smith et al., 2014).*

*Table 2.5: Hazard thresholds (from Smith et al., 2014) related to building damage descriptors from Table 2.2*

| Smith et al (2014) Hazard threshold[1] | Smith et al (2014) Hazard threshold description | Table 2.2 Building damage description |
|---|---|---|
| H1 | Generally safe for vehicles, people and buildings | Minor damage that does not materially affect the functionality |
| H2 | Unsafe for small vehicles. | Loss of functionality |
| H3 | Unsafe for vehicles, children and the elderly. | Loss of functionality |
| H4 | Unsafe for vehicles and people. | Loss of functionality |
| H5 | Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust buildings subject to failure. | Rendered uninhabitable or inoperable |
| H6 | Unsafe for vehicles and people. All building types considered vulnerable to failure. | Rendered uninhabitable or inoperable |

Notes:

1. Refer to Smith et al. (2014) and Figure 2.9 for flood depth and velocities that relate to different hazard thresholds for buildings.

#### 2.4.2.3 Damage to cultural sites

For PIC assessment purposes, the degree of damage to each identified cultural place (i.e. historical and cultural sites) needs to be established according to the descriptions provided in Table 2.2, as either:

- Irreparable loss.
- Loss where it is possible, but impracticable, to fully restore the site.
- Significant loss where it is practicable to restore the site.
- Minor loss that will require minor restoration only.
- No loss.

Identification of cultural places should be restricted to those places which form a significant and valued part of Aotearoa New Zealand's historical and cultural heritage and which are either:

- Listed on the New Zealand Heritage List/Rārangi Kōrero.
- Listed on the Department of Conservation website entitled 'National Register of heritage sites managed by DOC'.

The intent is that only historical or cultural sites that have already been identified and designated as heritage sites of national or regional significance should be considered, rather than seeking out and introducing new ones.

The degree of damage to cultural sites which are buildings could be established using the same methodology outlined in section 2.4.2.2. Where a cultural site is not related to a building (e.g. a site of archaeological significance, cemetery or urupā), the degree of damage will need to be established using judgement which considers the magnitude of the dam-break flood wave at the site. However, if the assessment of damage level could significantly influence the PIC of a dam, or if a more comprehensive assessment is required for other reasons, consideration should be given to involving a cultural specialist to assist with evaluating the potential damage to the site.

#### 2.4.2.4 Damage to critical or major infrastructure

For PIC assessment purposes, the degree of damage to identified items of critical or major infrastructure needs to be established according to the descriptions provided in Table 2.2, as either:

- Rendered inoperable.
- Affected by the loss of some functionality.
- Minor damage.
- No damage.

Critical or major infrastructure is restricted to the following definitions provided in the Regulations (2022):

(a) a building or other infrastructure operated or used by a lifeline utility within the meaning of section 4 of the Civil Defence Emergency Management Act 2002.

(b) a hospital building that is likely to be needed in an emergency (within the meaning of section 4 of the Civil Defence Emergency Management Act 2002 to provide—

   (i) emergency medical services; or

   (ii) ancillary services that are essential for the provision of emergency medical services.

(c) a building that is used to provide emergency response services (for example, policing, fire, ambulance, or rescue services)

(d) buildings or infrastructure that are essential to the containment of a hazardous substance (as defined by section 2 of the Hazardous Substances and New Organisms Act 1996):

(e) the dam, another dam, or flood protection works if the service the dam, other dam, or flood protection works provide is critical to the community (for example, energy supply, drinking water storage, wastewater treatment, flood detention dams) and that service cannot be reasonably provided by alternative means.

Critical or major infrastructure, as defined above, includes essential utility systems and components of transportation networks that serve communities. Therefore, any potential damage to such infrastructure from dam failure needs to be identified.

For the purposes of PIC assessment, the interpretation adopted in these Guidelines is that critical or major infrastructure associated with lifeline utilities are related to network mains and nodes rather than local connections. For example:

- In respect of electricity generation assets, loss of a relatively small generation facility is unlikely to directly cause power availability constraints locally or nationally due to the interconnected national grid and the general surplus of generation capacity in comparison to demand.
- In respect of electricity transmission assets, loss of a local/district powerline is not normally considered as 'critical or major infrastructure' as it is not considered to be a network main. However, loss or damage to a Transpower National Grid transmission line or substation would be considered as 'critical or major infrastructure' for PIC assessment purposes.
- In respect of roads, only state highways and other roads critical for connecting communities are considered to be 'critical or major infrastructure'. This excludes local roads unless they provide the sole link to a community.
- In respect of other lifeline utilities (e.g. water, sewerage, gas, telecommunications and rail), only those related to network mains should be considered for PIC assessment purposes.

It is acknowledged that lifeline utilities (entities) as defined in the Civil Defence Emergency Management Act 2002 will own, operate and use a variety of infrastructure, not all of which are essential to providing lifeline services. Only those items of infrastructure which are essential to providing lifeline services are considered to be 'critical or major infrastructure'.

It should be recognised that there is a high level of dependence by other lifeline utilities on roading networks. For example, water, sewerage, power and telecommunications services all use the road corridor and often also rely on structures such as road bridges to run cables or pipelines across. A failure of part of the road network may not only result in the consequential loss of another service, but also make access more difficult to repair and restore the service.

The degree of damage to critical or major infrastructure assets which are buildings could be established using the same methodology outlined in section 2.4.2.2. Where critical or major infrastructure is not related to a building (e.g. roads, bridges) the degree of damage will need to be established using judgement which considers the magnitude of the dam-break flood wave at the location of the specific infrastructure asset.

#### 2.4.2.5 Damage to natural environment

For PIC assessment purposes, the degree of damage to the natural environment needs to be established according to the descriptions provided in Table 2.2, as either:

- Extensive and widespread damage, with permanent, irreparable effects.
- Extensive and widespread damage where it is possible, but impracticable, to fully restore or repair the damage.
- Significant damage that is practicable to restore or repair.
- Minor rehabilitation or restoration may be required, or recovery is possible without intervention.
- No damage.

The natural environment will be affected by maximum flood depths, maximum flow velocities, and duration of inundation over the flooded area. Potential damage to the following environmental aspects should be considered:

- Waterways, wetlands.
- Flora and fauna.
- Rare or endangered species.

- Deposition of sediment (e.g. release of sediments trapped behind the dam and/or from erosion of embankment materials during dam failure).
- Erosion of river and/or floodplain areas.
- Reduction of visual amenity (e.g. loss of natural landscape features, including the reservoir itself).
- Contamination, particularly in the case of tailings dams and dams associated with wastewater treatment.

Environmental information within the dam-break flood inundation extent is generally sourced from topographic maps, internet searches, discussion with local agencies and organisations, District Planning maps, and searches of Department of Conservation databases.

The damage level to the natural environment for PIC assessment purposes is generally determined qualitatively. This assessment relies on judgement informed by the known damage sustained during significant historic natural flood events and considers the magnitude of the dam-break flood at the location of any identified environmental feature or aspect. However, when the assessment of these damages could significantly influence the PIC of the dam, or if a more comprehensive assessment is required for other reasons, then consideration should be given to involving an environmental specialist. This specialist can assess the full range of environmental attributes and assist with evaluating potential damage levels.

## 2.4.3 Population at Risk and Potential Loss of Life

### 2.4.3.1 Definitions

The table used to determine a dam's PIC is provided in Table 2.6 and introduces the terms Population at Risk (PAR) and Potential Loss of Life. The definitions of these two terms are provided in the Regulations (2022) as follows:

- Population at Risk: the number of people likely to be affected by an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam (assuming that no person takes any action to evacuate).
- Potential Loss of Life: the number of people expected to lose their life as a result of an uncontrolled release of all or part of the stored water or other fluid due to a failure of the dam.

These two terms, Population at Risk and Potential Loss of Life, provide metrics for assessing the potential life safety impacts of a hypothetical dam failure event. For PIC assessment purposes, they are required to be quantified into the categories listed in Table 2.6, that is:

For Population at Risk:

- 0 persons at risk.
- 1 to 10 persons at risk.
- 11 to 100 persons at risk.
- More than 100 persons at risk.

For Potential Loss of Life:

- No persons.
- One person.
- Two or more persons.

With respect to the definition of PAR, the interpretation adopted in these Guidelines of 'likely to be affected' is people who are directly exposed to dam-break flood inundation which is potentially hazardous to life (i.e. has potential life safety impacts). Other persons who are either indirectly affected (for example through economic loss) or not exposed to flood inundation are excluded from a PAR estimate. Refer to section 2.4.3.3 for guidance on flood hazard thresholds which are considered to be potentially hazardous to life.

With reference to Table 2.6, it is important to note that a dam is assigned a Medium or High Potential Impact Classification (PIC) if loss of life is expected to occur due to a hypothetical dam failure, irrespective of other damages or effects which might occur. An expected loss of one human life is sufficient to require a Medium PIC classification for a dam while an expected loss of two or more human lives is sufficient to require a High PIC classification.

The following guidance related to PAR and Potential Loss of Life is focused on procedures and methods for quantifying these parameters into the categories listed in Table 2.6 for PIC assessment purposes. It should be noted that alternative methods for quantifying PAR and Potential Loss of Life may be required for other purposes (e.g. for establishing the effectiveness of emergency response or for quantitative risk assessment where annualised life loss estimates are required). Such alternative methods are not covered by these Guidelines.

*Table 2.6: Determination of Potential Impact Classification (PIC)*

| Assesseddamagelevel | Population at Risk (PAR) | | | | Potential Loss of Life |
|---|---|---|---|---|---|
| | 0 | 1 to 10 | 11 to 100 | 100+ | |
| Catastrophic | High | High | High | High | No persons |
| | N/A[1] | High | High | High | One person |
| | N/A[1] | High | High | High | Two or more persons |
| Major | Medium | Medium | High | High | No persons |
| | N/A[1] | Medium | High | High | One person |
| | N/A[1] | High | High | High | Two or more persons |
| Moderate | Low | Low | Medium | Medium | No persons |
| | N/A[1] | Medium | Medium | Medium | One person |
| | N/A[1] | High | High | High | Two or more persons |
| Minimal | Low | Low | Low | Low | No persons |
| | N/A[1] | Medium | Medium | Medium | One person |
| | N/A[1] | High | High | High | Two or more persons |

Notes:
1. Not applicable. Population at risk is zero therefore no Potential Loss of Life.

### 2.4.3.2 General principles

Some general principles for estimation of PAR and Potential Loss of Life for PIC assessment purposes are given below. The following sections 2.4.3.3 and 2.4.3.4 provide further information on methodologies for estimation of PAR and Potential Loss of Life.

- The failure of any dam or water-retaining structure, no matter how small, could represent a danger to human life downstream. A situation can always be imagined where PAR and Potential Loss of Life is identified regardless of how remote the location of the dam or how remote the likelihood of persons being affected by its hypothetical failure. However, postulating every conceivable circumstance that might place a person in the dam-break flood inundation area should not be the basis for estimating PAR and Potential Loss of Life for PIC assessment purposes.
- Methods for Potential Loss of Life estimation outlined in these Guidelines are only intended for PIC assessment purposes. Estimates of Potential Loss of Life have a high degree of uncertainty and limitations in these estimates must be clearly stated if used for any other purpose
- PAR and Potential Loss of Life estimates should be considered for areas of any type that are known to be normally occupied. Examples of such normally occupied areas that are recommended to be considered are listed in Table 2.7, and further described in section 2.4.3.3.
- In evaluating PAR and Potential Loss of Life estimates for PIC assessment purposes, no allowances for evacuation, early warning systems, or other emergency actions by the adversely impacted population should be considered. This is because it could lead to dam Owners relying on untested assumptions about the effectiveness of emergency procedures and the responsiveness of emergency authorities in a dam failure situation to potentially lower the PIC of their dam. Emergency procedures should not be a substitute for appropriate design, construction, operation and maintenance practices and actions for dam structures (FEMA, 2004).

- Where the PAR and Potential Loss of Life in a 'rainy day' dam failure scenario is required to be estimated, the PAR and Potential Loss of Life should be estimated separately for both the 'base flood without dam failure' and the 'base flood with dam failure' cases. An estimate of the incremental PAR and Potential Loss of Life for the 'rainy day' dam failure scenario can then be obtained by subtracting the estimate for the 'base flood without dam failure' case from the estimate for the 'base flood with dam failure' case.
- In some cases, the PIC of a dam can be determined without the need for Potential Loss of Life estimates. For example, and with reference to Table 2.6, if a damage level of 'major' has been estimated in combination with a PAR of 10 to 100, the dam has a High PIC regardless of any Potential Loss of Life estimate. In such cases, a Potential Loss of Life estimate would not be required to determine the dam's PIC. A PAR estimate is required in all cases, unless a 'catastrophic' damage level is determined using the methods previously described in section 2.4.2.

#### 2.4.3.3 Population at Risk

Estimation of PAR generally involves identifying buildings and other places of occupancy within the expected dam-break flood inundation zone from topographic maps and aerial photographs. Typical occupancy rates for each identified building and place of occupancy are assigned from user judgement and the PAR estimated within a broad range (e.g. 0, 1 to 10, 10 to 100, >100). Where any PAR estimate lies close to the boundary of one of these ranges, then assessment at a more detailed level should be considered.

For initial level assessments, a coarse estimate of PAR can be made. For example, it may conservatively be assumed that all people within the expected dam-break flood inundation area are counted as part of the PAR regardless of life safety impact. For intermediate and comprehensive level assessments, estimation of PAR will generally need to be established through a more detailed assessment of the life safety impact on all people within the expected dam-break flood inundation zone.

The typical procedure for intermediate and comprehensive level assessments of PAR should involve:

**Identifying buildings and places of occupation within the dam-break flood inundation area**

Building and places of occupation in the dam-break flood inundation area should be identified using a combination of topographic maps, aerial photographs, local information and internet searches and/or site inspections as appropriate. This is most efficiently done with a Geographic Information System (GIS).

When identifying places of occupation, both permanent and temporary populations should be considered. Permanent populations are those linked to a fixed location on a permanent basis (e.g. persons present in residential dwellings, places of work, schools and other regularly occupied community facilities, hospitals, and industrial, commercial, and retail premises). Temporary populations are considered to be those that do not usually live or work within the dam-break flood inundation area but are present temporarily in the area (e.g. recreational users of recognised tracks, tourist or fishing spots, campers in recognised camping areas, road and rail users, seasonal workers, attendees at sports events or festivals). The possible presence of the dam Owner's staff and contractors within the dam-break flood path should also be considered.

Table 2.7 includes descriptions of buildings and places of occupation that should be considered to identify permanent and temporary populations within the dam-break flood inundation area. Special consideration may be required if other buildings or places of occupation are identified within the dam-break flood inundation area but not included in Table 2.7.

**Assigning occupancy rates to each building and place of occupation**

Table 2.7 provides guidance on assignment of occupancy rates to buildings and places of occupation identified within the dam-break flood inundation area. In many cases, occupancy rates may need to be determined by verification with local information or a site inspection. The documentation of the dam-break consequence assessment should justify the occupancy rates used.

When assigning occupancy rates, it is important that they do not double count people (e.g. people both living in and working in the hypothetical dam-break flood inundation zone).

**Determining time categories**

A dam failure could hypothetically occur at any time of day, day of the week, or season. However, both permanent and temporary populations within a dam-break flood inundation area will vary depending on the time of day, day of the week, and season as people move around for work, school, recreation, or other reasons. To deal with this mobility issue, it is recommended that several time-based scenarios should be considered to identify the period of greatest consequence. The time-based scenario that results in the largest PAR should be used as the basis for subsequent PIC assessment.

The selection of time-based scenarios will be dependent on the range of buildings and places of occupation located within the dam-break flood inundation area. Consideration of different time-based scenarios will require appropriate adjustment of occupancy rates for day/night, weekday/weekend and summer/winter seasonal situations. Such occupancy rates should reflect a reasonable 'snapshot' view of the number of people present within the dam-break flood inundation area for each time-based scenario considered. Such occupancy rates should reflect a reasonable 'snapshot' view of the number of people present within the dam-break flood inundation area for each time-based scenario considered (i.e. not skewed by very low-frequency, high population events such as an annual angling competition or a running event).

Land that is temporarily used on a short term or intermittent basis (e.g. land used for outdoor events, or campgrounds which have a large summertime population but only a small wintertime population) may require special consideration. The time-based scenario which considers the greatest period of consequence should be used with occupancy rates related to the peak occupancy for those times (i.e. a full campground for summer day/night periods but near empty for winter day/night periods). Local information on such areas is likely to be required to determine the occupancy rates for different time periods.

**Evaluating flood hazard at each building and place of occupation**

The flood hazard at each building and place of occupation is evaluated by extracting computational hydraulic model simulation outputs of maximum flood depth and velocity at each building and place of occupation for each dam-break flood scenario considered (e.g. 'sunny day' failure and 'rainy day' failure scenarios with and without dam failure).

**Determining the PAR**

Figure 2.9 (previously introduced in section 2.4.2.2) defines flood hazard classes for people, buildings, and vehicles sourced from Smith et al. (2014) which have been developed from extensive laboratory tests as well as field observations from natural flood events. The hazard assessment methodology defined by this information is widely used by government agencies and industry in both Australia and New Zealand for assessing natural flood hazards and has been incorporated into the Australian Rainfall and Runoff (ARR) national guideline document A Guide to Flood Estimation, Book 6 Flood Hydraulics (Ball et al., 2019).

People in buildings or places of occupation are included in the PAR if the dam-break flood hazard exceeds the 'H2' category shown in Figure 2.9. Categories greater than 'H2' reflect a degree of flood hazard which most people (including adults, children and the elderly) would not normally be able to safely withstand.

People in vehicles are included in the PAR if the dam-break flood hazard exceeds the 'H1' category shown in Figure 2.9. Categories greater than 'H1' are considered unsafe for small passenger vehicles.

The assessment procedure described above is typically carried out to determine the total PAR for each dam-break flood scenario analysed (e.g. 'sunny day' and 'rainy day' dam failure scenarios) as well as for each of the time-periods selected. Where PAR in a 'rainy day' dam failure scenario is required to be estimated, the PAR should be estimated separately for both the 'base flood without dam failure' and the 'base flood with dam failure' cases. An estimate of the incremental PAR for the 'rainy day' dam failure scenario can then be obtained by subtracting the estimate for the 'base flood without dam failure' case from the estimate for the 'base flood with dam failure' case. In all cases, it is recommended that total PAR estimates are rounded to the nearest whole number.

In all cases, judgement should be exercised to check that PAR estimates are reasonable for land within the potential dam-break flood inundation zone which is temporarily used on a short term or intermittent basis

*Table 2.7: Guidance for assigning occupancy rates for different places of occupation by permanent and temporary populations*

| Place of occupation | Description | Guidance on assigning occupancy rates |
|---|---|---|
| Permanent populations in habitable structures | Any structure that is occupied or maintained in a condition that allows it to be occupied by humans. This includes residential dwellings, commercial buildings, industrial buildings and community facilities such as schools, childcare facilities, churches and other public facilities such as libraries and swimming pools. | Residential dwelling occupancy rates are typically derived from demographic (Census) data for the area.<br>• Occupancy rates for other habitable structures can be obtained from a variety of sources, including:<br>• Local information (e.g. discussion with regional or local councils, local residents or community groups)<br>• Site inspections<br>• Typical occupancy rates for commercial office or retail buildings (e.g. persons per m2 of building floor area). |
| Temporary populations in recreational areas | Designated areas that attract people for recreational activities. Some designated recreational areas along rivers, streams and their floodplains feature man-made improvements and structures such as boat ramps, public toilets, buildings, and large established campgrounds. Other designated recreation areas along rivers, streams and their floodplains attract people by providing opportunities for fishing, swimming, hiking, rafting, kayaking, etc. Recreational facilities in urban areas can be parks, playgrounds, sports fields, golf courses and other similar open-air facilities designed and intended to attract people | Occupancy rates for recreation areas are typically site specific and should be sourced from local information (e.g. discussion with regional or local councils, Fish & Game New Zealand, Department of Conservation, local residents or community groups). In some cases, it may be necessary to conduct surveys of the downstream area, over a period of time, to determine the temporary population.<br>Where site specific occupancy rates are not available, typical occupancy rates (e.g. persons per km2 of land area) from references such as King & Cousins (2015) may be considered. |
| Temporary populations in agricultural and horticultural areas | People working on agricultural or horticultural land | Occupancy rates for agricultural and horticultural land are typically site specific and should be sourced from local information (e.g. discussion with regional or local councils or land owners).<br>Where site specific occupancy rates are not available, typical occupancy rates (e.g. persons per km2 of land area) from references such as King & Cousins (2015) may be considered. |
| Temporary populations on roads, cycleways and railways | People travelling on designated transportation routes | Temporary populations on transportation routes should be estimated by methods which consider the average daily traffic count (AADT) on each transportation route and the length of route exposed. Examples of such methods are summarised in Appendix 11 of DNRME (2018). |

#### 2.4.3.4 Potential Loss of Life

**General**

The PAR approach outlined in section 2.4.3.3 only identifies the number of people likely to be directly exposed to dam-break flood inundation that could cause physical injury or a threat to life safety. An important subset of the PAR is an estimate of the number of fatalities that could be expected to occur during a hypothetical dam-break flood. This is termed 'Potential Loss of Life' in the Regulations (2022).

Potential Loss of Life estimates are inherently difficult to develop. They depend on many uncertain and variable factors, such as the dam breach parameters, the topography of the area downstream of a dam, flood wave travel time, depth of flow, flow velocity, time of day, the amount of warning time, the responsiveness of people to evacuate when warned, the presence of suitable evacuation routes, historical patterns of human activity, and the general mobility of the population.

No simple, reliable, or universally applicable methodology is available for estimation of Potential Loss of Life. Different methods can produce very different estimates. However, in all cases, there are two components to the question of whether Potential Loss of Life could occur in a hypothetical dam failure situation:

- Would the presence of people be reasonably expected at a location of interest?
- Are the flow characteristics expected to be lethal at this location in the event of dam failure?

Due to the inherent uncertainties in Potential Loss of Life estimation methods, the assumptions, reasoning, and any supporting calculations used to derive estimates should be clearly documented.

The following sections outline guidance on different commonly practiced methods of estimation of Potential Loss of Life for PIC assessment purposes. For the reasons outlined in section 2.4.3.2, no allowances for evacuation, early warning systems, or other emergency actions by the adversely impacted population should be considered when evaluating Potential Loss of Life for PIC assessment purposes.

**Qualitative assessment**

Estimation of Potential Loss of Life may involve a qualitative approach which considers the population present within buildings and in other places of occupancy within the expected dam-break flood inundation area, and the anticipated level of flood hazard at each populated location. Informed judgement is required to infer whether potentially lethal flooding conditions would occur in the areas identified as contributing to the PAR, and to establish if loss of life is expected to be 'no persons', 'one person' or 'two or more persons' based on the Potential Loss of Life categories listed in Table 2.6. In such cases, it is always prudent to adopt a conservative approach, with the assumptions and reasoning clearly documented.

A qualitative assessment may be appropriate for estimation of Potential Loss of Life where it is self-evident that failure of a particular dam could cause the Potential Loss of Life to be either 'no persons' (i.e. a small dam in a remote area with negligible PAR downstream) or 'two or more persons' (e.g. a large dam immediately upstream of an urban area within the dam-break flood inundation zone reflecting a large PAR).

A qualitative assessment should be considered as an initial approach for assessing Potential Loss of Life. However, where the Potential Loss of Life cannot be clearly established as 'no persons', 'one person' or 'two or more persons', then a quantitative approach (as described below) can be used.

In general, a qualitative assessment of Potential Loss of Life should be sufficient for PIC assessment purposes in many cases. Reliance on quantitative assessment approaches (as described below) can be misleading and deceptive due to the inherent uncertainties in the methodologies and their inputs.

**Reclamation Consequence Estimating Methodology (RCEM)**

To estimate possible life loss from a hypothetical dam failure in support of a portfolio dam safety risk assessment, the United Sates Bureau of Reclamation (USBR) uses an empirical methodology known as the Reclamation Consequence Estimating Methodology (RCEM). Note that USBR uses the RCEM Potential Loss of Life estimates in support of dam safety risk assessments (refer Module 7, section 5.4) and not for life loss estimates for PIC assessment purposes (Feinberg et al., 2016).

The RCEM method is documented in USBR (2015) and the methodology is not reproduced in these Guidelines. In general, the RCEM method estimates loss of life using the product of flood depth and velocity (referred to as DV), at locations where a component of the PAR has been identified, from curves fitted to fatality rate data derived from case histories of historic dam failure and natural flash flood events. Different fatality rates are provided for two emergency warning time categories, 'little to no warning' and 'adequate warning'.

If the RCEM method is used to estimate Potential Loss of Life for PIC assessment purposes, typically for comprehensive assessment levels, the following application principles should apply:

- Fatality rates provided in USBR (2015) for the upper bound of the 'suggested limit' for the 'little to no warning' category should be used.
- Where Potential Loss of Life values estimated using the RCEM method are near the threshold of 'one person' or 'two or more persons' and could change the PIC from Low to Medium or Medium to High, sensitivity testing of key inputs and assumptions should be considered to provide greater confidence in the estimate. In all cases, judgement should be exercised to check results are reasonable.
- When using the RCEM method, Potential Loss of Life estimates are commonly not a whole number. Potential Loss of Life values should be rounded to the nearest whole number for PIC assessment purposes (e.g. a value between 0.5 and 1 should be considered as equal to 1). Note that a Potential Loss of Life value of less than 1 should not be interpreted as a numerical probability.

**Advanced modelling tools**

In addition to the methods listed above, more advanced modelling tools have been developed to estimate Potential Loss of Life from natural and/or dam failure floods (e.g. LifeSim developed by the US Army Corps of Engineers and the Life Safety Model (LSM) originally developed by BC Hydro and now marketed by HR Wallingford).

Both the LifeSim and LSM models provide a spatially distributed, dynamic simulation of a developing flood situation. This means they simulate the passage of a hypothetical flood event over time (considering warning and mobilisation of people potentially exposed to the flood hazard) and predict the likely spatial distribution of impacted people and property. These models are referred to as 'agent-based' simulators as they can simulate the response of individual people, buildings and vehicles (i.e. agents) in a floodplain and their interaction with a hypothetical dam-break or natural flood event. They use outputs from two-dimensional computational hydraulic models (e.g. depth and velocity information as a function of time) and couple them in a Geographic Information System (GIS) environment with a simulator that models the interaction of these agents with the floodwaters. This simulated interaction is based on mathematical models which include representations of human and vehicle stability and the structural vulnerability of buildings in floodwaters.

These more advanced models can be used for comprehensive level assessments and where detailed estimates of Potential Loss of Life may be required for densely populated areas downstream of a dam. However, as discussed above, qualitative inference may be able to be used to establish the Potential Loss of Life in the latter circumstance sufficiently to establish a dam's PIC classification without having to resort to such advanced methods.

LifeSim or LSM models are well suited to assist with exploring options for improving the effectiveness of emergency planning and response, and to provide inputs to quantitative risk assessments.

If a LifeSim or LSM model is used to estimate loss of life for PIC assessment purposes, Potential Loss of Life estimates should be evaluated explicitly from simulations where the population downstream of the dam receives no warning for evacuation.

Both the LifeSim and LSM models deal with uncertainty in input data through use of Monte Carlo sampling. As such, these models output a range of Potential Loss of Life values (e.g. minimum, 25th quartile, median, 75th quartile and maximum values). Where Potential Loss of Life estimates obtained using LifeSim or LSM models are near the threshold of 'one person' or 'two or more persons' and could change the PIC from Low to Medium or Medium to High, judgement is required to determine which value within the range is appropriate for PIC assessment purposes.

**Other quantitative assessment tools**

Other quantitative methods, outside of the RCEM, LifeSim, and LSM methods listed above, may be appropriate to estimate Potential Loss of Life for PIC assessment purposes. Any such methods need to be an established and industry accepted practice and considered appropriate by a Technical Specialist.

The same application principles described above for the RCEM methodology should apply to other quantitative methods for estimating Potential Loss of Life for PIC assessment purposes.

### 2.4.4 Uncertainties in the consequence assessment process

Dam-break consequence assessments typically involve a number of inputs (of varying levels of detail) and assumptions which require elements of judgement. Where uncertainties arise from the consequence assessment which could affect the PIC, sensitivity testing for key inputs and assumptions should be considered to provide greater confidence in the assigned PIC.

In all cases, the documentation for dam-break and consequence assessments should explain assumptions made, methodologies used and identify the sources of the information consulted (also refer section 2.2.7 Records and documentation).

# 3. Dam Potential Impact Classification

## 3.1 Method

A dam's PIC indicates the potential consequences of a hypothetical dam failure and serves as the basis for recommended design, construction, and operational safety criteria outlined in these Guidelines.

Table 2.6 provides the framework for determination of a dam's PIC. The three key inputs to the table are:

- The assessed damage level (refer section 2.4.2).
- The assessed Population at Risk (PAR) (refer section 2.4.3).
- The assessed Potential Loss of Life (refer section 2.4.3).

Table 2.6 is used to determine a dam's PIC by aligning the assessed damage level with the assessed PAR and Potential Loss of Life.

## 3.2 Using the Potential Impact Classification

Using the method outlined in section 3.1, a dam is assigned a PIC based on the consequences of its failure.

The PIC for a dam has two primary uses:

- Application of the dam safety requirements included in the Building Act (2004) and Regulations (2022) (refer Module 1: Legal Requirements). The PIC for a dam should be based on the worst-case consequence assessment resulting from hypothetical 'sunny day' and 'rainy day' failures. The Act (2004) and Regulations (2022) include a number of specific dam safety requirements for dams that are linked to the PIC (refer Module 5: Dam Safety Management and Module 6: Emergency Preparedness).
- The determination of appropriate design proficiencies, design loadings, quality assurance procedures, investigation and design methods, construction expertise, and commissioning procedures (refer Module 3: Investigation, Design and Analysis). The use of PIC for these aspects of dam development and rehabilitation is not required by the Act (2004) or Regulations (2022) but has been a longstanding practice in New Zealand.

Subsidiary dams and appurtenant structures, which also support the reservoir, should also be allocated a PIC which reflects the consequences of their failure (refer section 4).

## 3.3 Review of dam Potential Impact Classification

It is important to note that a dam's PIC may change over its lifespan due to the nature and occupation of the downstream area, or land use in the upstream catchment. For a tailings dam, the PIC may change during various stages of development, operation and closure. PICs should therefore be reviewed every five years, or whenever modifications to dams or their operational procedures could result in changes to the downstream consequences of a dam failure. Section 139 of the Act (2004) requires that a dam's PIC must be reviewed:

- Within 5 years after the regional authority approves, or is deemed to approve, the classification, and;
- After the first review, at intervals of not more than 5 years.
- Any time building work that requires a building consent is carried out on the dam, and;
- Any time building work results, or could result, in a change of the potential impact of a failure of the dam on people, buildings, infrastructure, historical and cultural places, and the environment.

Note that where a dam or appurtenant structure has previously been assessed as High PIC, and where a consequence assessment is not otherwise required for emergency preparedness or risk assessment purposes, the Owner may elect not to complete a PIC review on the basis that the dam classification cannot be increased. However, there may be legislative requirements for the completion of PIC reviews and Owners should refer to Module 1: Legal Requirements.

The following questions should be considered during the review of a dam's PIC:

- Are the assumed potential failure modes and dam breach characteristics still appropriate?
- Have there been any changes to operational use that might affect assumptions incorporated in the previous PIC determination?
- Have there been any changes to downstream populations, property characteristics, or infrastructure?

# 4. Subsidiary dams, canals and appurtenant structures

In situations where a dam has a subsidiary dam (e.g. a saddle dam), or a separate appurtenant structure, the consequences of a potential failure of each structure (main and subsidiary dam(s) and appurtenant structure(s)) should be assessed and each should be classified with its own PIC. This recognises that while the structures share the same reservoir, they may have very different failure consequences, as determined by their inherent features and potential breach outflow paths. The same applies to embankment 'fill' sections of a canal, where each section (and each side) of the 'fill' embankment could have a different PIC. Examples with different features and dam-break flow paths are shown in Figure 4.1 for a dam with a saddle dam and in Figure 4.2 for a canal with multiple embankment 'fill' sections.

Consequence assessments for subsidiary dams, appurtenant structures, and canal 'fill' sections should carefully consider potential failure modes and possible failure locations, and clearly establish the dam-break flow paths and consequences for each structure (or constituent components which may include gates and valves).

Similarly, saddle dams that block low sections of natural ground around the perimeter of a reservoir, and have potential failure modes that could result in the uncontrolled release of the reservoir contents, should be evaluated for consequences of failure. Natural saddle dams could also be present along reservoir shorelines and should also be evaluated.

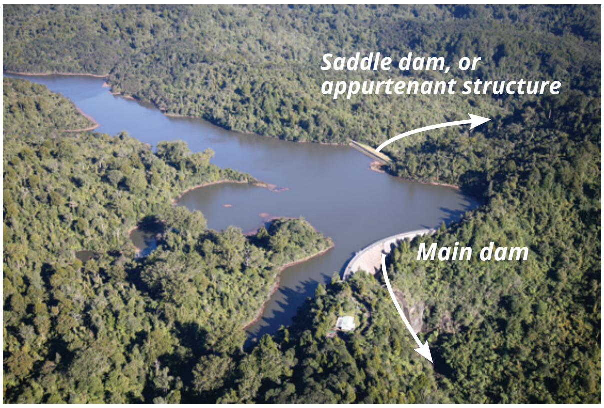


*Figure 4.1: Example of main and subsidiary dams with different features and dam-break flow paths (provided by Watercare Services).*

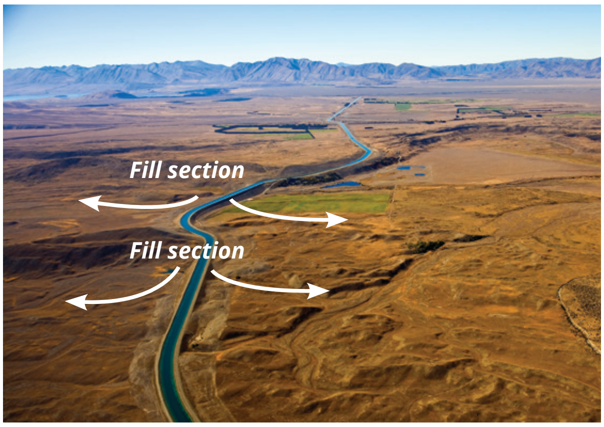


*Figure 4.2: Example of canal 'fill' sections with different features and dam-break flow paths (provided by Meridian Energy)*

# 5. Issues to consider in dam-break flood hazard and consequence assessments

There are a number of factors that can lead to erroneous dam-break flood hazard and consequence assessments, thereby affecting the classification of a dam. The following insights are provided to reduce the likelihood of erroneous consequence assessments and dam potential impact classifications.

## 5.1 Choosing the right level of assessment

The level of consequence assessment should be commensurate with the indicated potential consequences of a dam failure. Typically, an iterative approach is appropriate, starting with initial qualitative analyses. Based on the results, decisions can then be made to proceed to more detailed levels of semi-quantitative and quantitative assessment. Refer to section 2.2.1 for further guidance on levels of assessment.

Choosing an appropriate level of topographical information is also important and will have a significant bearing on the modelling of a dam-break flood wave. Where computational hydraulic modelling is considered to be warranted, the topographical information should be of a high enough resolution (e.g. a 1m Digital Elevation Model based on LiDAR topographic survey data) to allow the downstream area and potential dam-break flood inundation zone to be accurately represented in any model.

## 5.2 Concrete gravity and arch dams

Most dam breach modules within commercially available flood wave routing software packages assume that dam breach development occurs gradually over time. This assumption implies that quasi-steady weir flow occurs through the breach and that the surface of the reservoir remains approximately level as it drains through the breach. These behaviours are only appropriate for the failure of earthfill or rockfill dams.

For concrete gravity and arch dams, breach development occurs near instantaneously and the assumptions of quasi-steady weir flow through a breach and an approximately level reservoir surface as the reservoir drains through the breach are invalid. Special consideration needs to be given to the evaluation of a dam breach outflow hydrograph for a hypothetical failure of a concrete gravity or arch dam. The use of approximate analytical solutions is recommended for the evaluation of instantaneous or near instantaneous dam failures. USACE (1997) provides guidance for relatively long and narrow rectangular channels where the dam is completely removed.

## 5.3 Backwater effects in side valleys

It is important to consider the backflow of a dam-break flood wave and consequential inundation of side valleys (tributary waterways that join the main valley) downstream of a dam. While on initial appearance it may not seem likely that flooding could occur in downstream tributary valleys against the natural direction of flow, these valleys can be affected by significant back-flooding. In some cases, the flood inundation may extend for several hundreds of metres or even kilometres depending on the valley slope.

In such situations, it is important to choose the right level of topographical information and ensure that side valleys are adequately covered within the domain of a computational hydraulic model.

## 5.4 Choosing the downstream extent of the assessment

When assessing dam failure consequences, it is important to choose an appropriate downstream extent for the flood hazard or consequence assessment. Not extending the downstream extent far enough can exclude effects further downstream and underestimate the population at risk and the level of damage.

An example is where a downstream river valley meets an open body of water. It should not be assumed that the body of water will not be affected by a dam-break flood wave passing through it. While the peak flow depths and velocities resulting from a dam break-flood wave through an open body of water may be significantly reduced, there could still be implications for recreational users on, or near, these water bodies. An understanding of the characteristics of the breach outflow hydrograph resulting from a hypothetical dam failure, and the hydraulic behaviour of the dam-break flood wave through the body of water, are necessary to assess the likely effects of a dam failure on the body of water.

Care should also be exercised in selecting an appropriate downstream boundary condition for a computational hydraulic model for a dam-break flood hazard assessment. For example, for a tidal estuary, it may be appropriate to assume a constant water level corresponding to peak tide level if the size of the estuary is large relative to the size of the reservoir affected by the assumed dam failure. However, if the size of the tidal estuary is small relative to the size of the affected reservoir, then it may be necessary to shift the location of the downstream boundary in the model well beyond the mouth of the estuary into the open sea. For the 'rainy day' dam-break scenario, the effect of storm surge on the tidal boundary condition for a computational hydraulic model should also be considered.

The downstream extent of study should be established using the following criteria based on FEMA (2013):

- Dam breach flood flows are contained within a large downstream reservoir with no further downstream flooding;
- Dam breach flood flows are confined within the downstream channel; or
- Dam breach flood flows enter a bay or ocean (and downstream of any tidal estuary areas).
- The dam breach flood hazard is within the 'H1' hazard threshold shown in Figure 2.9 and only affects a remote or sparsely populated area.

## 5.5 Time of day considerations

Consideration should be given to times during both normal working hours and after normal working hours, as the time of day can have a significant influence on the Population at Risk (PAR) exposed to a dam failure. For example, if the downstream area contains schools and commercial/retail areas, then the PAR may be much higher during normal working hours than after normal working hours. All consequence assessments used for determining the PIC of a dam should be based on the largest PAR, whether it occurs during normal working hours or outside of normal working hours. The methodology outlined in section 2.4.3.3 provides a suitable framework for the estimation of population at risk taking into consideration temporal population movements.

## 5.6 Development changes

Development or a change in land use (e.g. conversion of farmland to residential subdivisions) or change in landform (e.g. due to mining activities) downstream of a dam can have marked effects on the consequences of dam failure and therefore the dam's PIC. Owners should periodically review their dam classifications to ensure they properly reflect any development changes in downstream catchments. As outlined in section 3.3, PICs should be reviewed every 5 years, or whenever modifications to dams or their operational procedures could result in changes to the downstream consequences of a hypothetical dam failure.

## 5.7 Flood detention dams

Flood detention dams usually only impound water during storm inflow events, although some such dams may impound a small permanent storage volume with an ability to store additional flood volume during storm conditions. For flood detention dams which do not have a permanent storage volume, there are no plausible 'sunny day' dam failure scenarios and consideration must be given to credible 'rainy day' dam failure scenarios. For flood detention dams which do have a small permanent storage volume, consideration must be given to both 'sunny day' and 'rainy day' failure scenarios which are credible.

Credible 'sunny day' failure scenarios for flood detention dams with a small permanent storage volume could include an internal erosion failure resulting from concentrated leakage along a crack through the dam body either adjacent to a concrete / fill interface or in the bulk fill material itself.

With flood detention dams, it is important to recognise that there is an inconsistency between the Inflow Design Flood (IDF) typically used for the design of flood detention dams in an urban environment (i.e. stormwater design standards) and the recommended Inflow Design Flood from a dam safety perspective (see Table 4.1a and Table 4.1b of Module 3). The IDFs from this table are a function of the PIC of a dam, the downstream PAR impacted by a hypothetical failure of that dam, and the Potential Loss of Life arising from the dam failure.

The 'rainy day' failure scenarios considered may include the following cases:

- Failure during a moderate reservoir inflow flood (e.g. a 1 in 100 Annual Exceedance Probability (AEP)) at the 'full impoundment' condition with no dam crest overspill and unblocked outlets.
- Failure during the IDF with a small amount of dam crest overspill.

The first case represents one typically used for stormwater design purposes. The second case represents a typical 'rainy day' failure scenario applied to other types of dams for PIC purposes and is extreme in stormwater management terms. It should include consideration of the potential for blockage or partial blockage of outlets by flood-transported debris.

The 'no dam failure' scenario corresponding to each of these 'rainy day' dam failure scenarios also needs to be considered as it provides the base case from which the incremental effects of the 'rainy day' dam failure are determined.

For both a 'rainy day' dam failure scenario and the corresponding 'no dam failure' scenario, careful consideration needs to be given to tributary inflows downstream of the flood detention dam (refer also to section 2.3.4).

The selection of the extreme IDF for the second 'rainy day' failure scenario above may require an initial estimation of the PIC of a flood detention dam and the use of Table 4.1a and Table 4.1b in Module 3 to determine a suitable AEP for the IDF. A preliminary consequence assessment can then be carried out and a feedback loop applied to check the initial PIC estimate and revise it if necessary. A final consequence assessment can then be completed to confirm the PIC of the dam.

It should be noted that it is not necessarily the most extreme IDF scenario that gives rise to the worst incremental consequences downstream for a 'rainy day' dam failure. Sometimes it is the 'rainy day' dam-break flood resulting from a smaller IDF which produces the worst incremental consequences downstream in terms of maximum incremental flood depths and extents.

The more extreme AEP values recommended for IDF selection in Table 4.1a and Table 4.1b of Module 3 significantly exceed those typically used for urban stormwater design. This will require extrapolation of the rainfall frequency data applied to any rainfall/runoff model used to evaluate the required IDF hydrograph.

The establishment of credible potential failure modes for a flood detention dam needs to consider a range of factors including:

- Possible blockage of the primary outlet facility by debris.
- The potential for failure due to internal erosion mechanisms. These could occur adjacent to the primary outlet facility, through the dam body, or through the dam foundation.
- The maximum reservoir impoundment level.
- The duration of impoundment relative to the time for a dam breach to be initiated and then progressively develop.
- The magnitude and duration of discharge from any secondary overflow spillway.
- The duration of any dam overtopping.
- The slope of the downstream face of the dam and the maximum flow velocities down that face.
- The erodibility of the dam materials and any grass cover.

Flood detention dams are frequently located in urban areas with a dense concentration of population downstream. In such cases, the dam-break consequence assessment needs to consider the complexity of the range of building types and places of occupation in an urban setting. People, property, and other features on the reservoir rim upstream of the dam may be impacted due to the rise in reservoir water level under extreme flood conditions. While these impacts should be considered in any general flood hazard assessment, the incremental impacts in a hypothetical 'rainy day' dam-break flood situation relative to the base flood situation could be negligible assuming that dam failure is initiated at the base flood peak. Therefore, it may not be necessary to include these reservoir rim impacts as part of the dam-break flood hazard and consequence assessment process.

## 5.8 Dams with a large operational range

For dams with a large operational range (e.g. in the order of metres or tens of metres) that may vary from one extreme to the other seasonally or more frequently, the potential consequences of failure should be assessed assuming the impounded reservoir is full at its maximum design level at the time of dam failure.

## 5.9 Tailings dams and dams with highly sedimented reservoirs

Tailings storage facilities (TSF) can incorporate dam structures which impound by-products of mining, industrial, and agricultural operations, often storing a zone of supernatant liquid on top of the tailing deposits (i.e. a supernatant pond). The properties of tailing deposits vary greatly between different TSFs but, in general, the tailings exist as a mixture of water and solids. The physical properties of the tailings can also change over the lifecycle of a TSF due to a reduction in water content, consolidation and desiccation, or due to chemical effects.

A hypothetical failure of a dam retaining tailings at a TSF needs special consideration as the contents of the tailings pond may flow differently to water (i.e. as a non-Newtonian fluid) and contain potentially hazardous substances. The rheometric properties of the tailings material could also influence the dam breach geometry, the released volume in the breach outflow, the peak discharge, the flood wave propagation, and inundation extents.

Apart from the hazard resulting from propagation of the dam-break flood downstream, the release of the tailings material could also contaminate the downstream flood inundation area and have an adverse impact on the environment. The potential consequences of long-term ecological damage from contamination due to the release of tailings material into a downstream watercourse and valley should be taken into account when assessing the PIC of a tailings dam.

Dam-break flood hazard and consequence assessments for TSFs should be conducted using established and industry recommended practice such as that contained in the Canadian Dam Association guidance document Tailings Dam Breach Analysis (CDA, 2021).

Similar considerations may apply for water storage, irrigation, and hydroelectric dams that have accumulated large amounts of sediment (and potentially hazardous substances) in their reservoirs.

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**A technical interest group of Engineering New Zealand**
PO Box 12 241, Wellington 6144, New Zealand
**nzsold.org.nz**