Department of Natural Resources, Mines and Energy

Guideline for failure impact assessment of water dams

November 2018

Queensland Government

This publication has been compiled by Dam Safety, Department of Natural Resources, Mines and Energy.

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Summary

In accordance with Queensland state law, a Failure Impact Assessment (FIA) is the instrument used to establish if a dam poses a hazard to human life and requires regulation.

The regulating agency is Queensland Government's Department of Natural Resources Mines and Energy (DNRME), which uses the provisions of the *Water Supply (Safety and Reliability) Act 2008* to describe a dam requiring regulation as being "referable".

An FIA is prepared, executed and reported in accordance with this guideline.

This latest revision of the guideline reflects legislative changes, captures experience gained by DNRME and the broader industry and incorporates enhanced knowledge from the wider dam safety industry regarding dam failure studies.

How to use this Guideline

Section	Description	Intended Readers
Introduction	The introduction describes the context of a failure impact assessment, its purpose and if/when it is required. The legislative requirements and background, roles and responsibilities and summary of costs associated with a failure impact assessment are also described.	Primarily dam owners, decision makers and those wishing to understand the context and justification of the failure impact assessment.
Methodology	The methodology outlines simplified and comprehensive methodologies for undertaking a failure impact assessment. It is structured according to the expected sequential steps required to complete the failure impact assessment i.e. scoping, establishment of dam failure scenarios, flooding assessment and submission.	Primarily technical specialists and relevantly skilled engineers who undertake or certify the failure impact assessment.
References	References to scientific literature and industry guidelines, which form the basis and justification for the failure impact assessment purpose and methodology, are provided. Many of the analysis techniques and tools described may be superseded in future; periodic review of the engineering literature is recommended.	
Appendix 1 FIA Submission Checklist	Appendix 1 provides a checklist to be filled in prior to submission on an FIA. The FIA submission should consider attaching this checklist to the FIA Report.	
Appendix 2 FIA Report Checklist	Appendix 2 provides a suggested heading list for a failure impact assessment report and a checklist of key facts and analysis outputs recommended for inclusion.	
Appendix 3 Template for RPEQ certification	Appendix 3 provides a template statement of certification that must be submitted by an RPEQ as part of the FIA submission.	
Other Appendices	Other appendices are provided to support the guideline.	

Version History

Version	Date	Comment
1	April 2002	Original approval
2	December 2012	A simple update of the April 2002 guidelines updating the name of the department and the new legislation references. There are no fundamental changes to the basic failure impact assessment process methodology.
3	October 2018	This latest version reflects legislative changes that have occurred, captures experience gained by DNRME and the broader industry and incorporates enhanced knowledge from the wider dam safety industry regarding dam failure studies. Significant changes in this version of the guideline include: the increased dam size criteria triggering the requirement for a failure impact assessment introduced by legislative amendments in 2012[1] legislative amendments in 2017 that provide for the exclusion of certain population at risk (PAR) when determining the failure impact rating of a dam relaxation of hydraulic impact criteria to reflect the lower relative risk to individuals exposed to flow having lower depth times velocity values while not specifically required for FIA, guidance is provided for assessing potential impacts of dam failure on transient populations driving on major roads The Q_{BREACH} methodology has been adjusted based on internal assessments.

[1] The previous / new criteria have changed from (1) more than 8m / 10m in height with a storage capacity of more than 500ML / 1500ML and (2) more than 8m / 10m in height with a storage capacity of more than 250ML / 750ML and a catchment area that is more than three times its maximum surface area.

Glossary

Term (Abbreviation)	Description
Abutment	The part of a valley side wall against which a dam is constructed. Right and left abutments are designated as one looks downstream.
Acceptable Flood Capacity (AFC)	The flood capacity which the dam is required to safely pass. Consideration of acceptable flood capacity is a requirement once the dam becomes referable. A guideline for acceptable flood capacity is available on the DNRME website.
Adopted middle thread distance (AMTD)	The distance (km) measured along the middle of a watercourse that a specific point in the watercourse is from the watercourse's mouth or junction with the main watercourse (Australian Water Information Dictionary, Bureau of Meteorology, 2017).
ANCOLD	The Australian National Committee On Large Dams (ANCOLD) is a voluntary industry association with an interest in dams in Australia, formed in 1937, and with ties to the International Commission on Large Dams (ICOLD, which has representation across 100 member countries). ANCOLD prepares and issues guidelines which represent best engineering practice relating to dam safety.
Annual average daily traffic (AADT)	The average number of vehicles per day over a calendar year.
Annual exceedance probability (AEP)	The probability that a given magnitude of event will be exceeded in any one year.
Australian rainfall and runoff (ARR)	A guideline for flood hydrology in Australia.
Bathymetric surveys	A type of survey used to map the shape of the terrain and contours of land underwater. This can be used to calculate the storage curve or volume of a dam.
Catchment	A catchment is an area where water is collected by the natural landscape. The land surface that drains into a dam or to a common point.
Category 1 failure impact rating	A category of referable dam under the Act that has been determined to have a population at risk of 2 or more persons but not more than 100 persons.
Category 2 failure impact rating	A category of referable dam under the Act that has been determined to have a population at risk greater than 100 persons.
Chief executive	The Director-General, Department of Natural Resources Mines and Energy (also known as the 'regulator for dam safety').
Comprehensive assessment	A more thorough and complex assessment, generally more definitive and therefore less conservative than a simplified assessment. A comprehensive FIA assessment would usually include detailed dam failure analyses and one or two-dimensional hydraulic modelling.
Critical case (critical dam failure scenario, incorporating critical flood case)	The dam failure scenario which produces the highest consequence. Note that smaller flood events (into and/or below the dam) can produce the critical dam failure scenario (i.e. not always the PMF or DCF).
Critical flood event	The no-failure flood event which, when combined with the dam failure event, causes the highest consequence (and PAR).

Term (Abbreviation)	Description
Dam	A dam means: works that include a barrier, whether permanent or temporary, that does or could impound water; and the storage area created by the works The term includes an embankment or other structure that controls the flow of water and is incidental to works mentioned in the dot point above. The term does not include the following: a rainwater tank a water tank constructed of steel or concrete or a combination of steel and concrete a water tank constructed of fibreglass, plastic or similar material *See* referable dam for further exclusions relevant to FIA.
Dam crest failure	A dam crest failure is a failure that occurs when the water level is at or overtops the dam crest level.
Dam crest flood (DCF)	The flood event which, when routed through the storage with the storage initially at full supply level, results in a still water level in the storage at the dam crest level, excluding wind and wave effects.
Dam crest level	The dam crest level: for an embankment dam, is the lowest point of the embankment crest for a concrete dam, is the level of the non-overflow section of the dam, excluding handrails and parapets if they cannot store water against them for a concrete faced rockfill dam, is the lowest point of the crest structure
Dam failure flood	The flood event produced by a dam failure. (For an embankment dam, called a dam breach flood.) Dam failure flooding can include contribution from flooding from both upstream and downstream catchments.
Dam failure PAR	The number of persons, calculated using methodologies described in this guideline, whose safety will be at risk if the dam or the proposed dam after its construction fails. Dam failure PAR are persons who are not at risk by a flood event but are at risk when the same flood event is accompanied by a dam failure event. It can be considered as Total PAR minus the PAR affected by a no-failure flood event immediately prior to dam failure (subject to water depth and flood hazard thresholds). This term is consistent with the term “dambreak PAR” in ANCOLD (2012). The guidelines also refer to dam failure PAR as just “PAR”. This guideline provides the criteria and exclusions that define dam failure PAR. *See* Sections 1.4 and 2.4.5.
Dam failure scenario	*See* Failure scenario
Dam operator	The person/s or organisation responsible for the operation of a dam and works associated with the dam.
Dam owner	The person/s or organisation that owns the land on which a dam is constructed or is to be constructed.

Term (Abbreviation)	Description
	For the purposes of FIA an owner is any of the following: the registered proprietor of the land (relevant for freehold land) the lessee or licensee under the *Land Act 1994* of the land (relevant for non-freehold land that is, State land) the holder of a mineral development license or mining lease under the *Mineral Resources Act 1989* the person or body of persons who for the time being, has lawful control of the land, on trust or otherwise the person who is entitled to receive rents and profits of the land
Development	Under the *Planning Act 2016*, development is any of the following: carrying out– building work; or plumbing or drainage work; or operational work; or reconfiguring a lot; or making a material change of use of premises
Development assessment	Assessment of a development application against relevant policies, guidelines and state codes.
Development condition	A condition that forms part of a development permit or approval. Dam safety conditions are taken to apply as development conditions.
Development permit	A development permit is the part of a decision notice for a development application that authorises the carrying out of the assessable development to the extent stated in the decision notice.
DNRME	Department of Natural Resources, Mines and Energy Note that the Department of Energy and Water Supply (DEWS) was renamed as the Department of Natural Resources Mines and Energy (DNRME) in 2017.
Dwelling	*See* Place of occupation
Emergency action plan (EAP)	An EAP provides guidance for actions required as a result of hazardous situations or emergency events occurring at a referable dam. There is a legislative requirement for all referable dams to have an EAP. A guideline for EAPs is available on the DNRME website.
Failure	The physical collapse of all or part of a dam, or the uncontrolled release of any of its contents.
Failure impact assessment (FIA)	An assessment undertaken to determine the potential consequences of failure for a dam.
Failure impact criteria	The limits of depth and/or depth times velocity, which when exceeded at a location by water released as a result of an assumed dam failure, result in persons being considered at risk at that location.
Failure impact rating	A category 1 or 2 failure impact rating is allocated depending on the maximum population at risk assessed based on assumption of failure of a dam. Dams with category 1 or 2 failure impact ratings are referable dams under the Act.

Term (Abbreviation)	Description
Failure impact zone	The zones(s) downstream of the dam where there may be potential PAR.
Failure scenario	A specific, feasible dam failure mode combined with a specific flood event that is used to assess PAR.
Foundation	The material upon which a dam structure is placed.
Full supply level (FSL)	The level of the water surface of the dam reservoir when the water storage is at maximum operating level not affected by a flood event.
Hazardous waste	Any substance, whether liquid, solid or gaseous, derived by, or resulting from, the processing of minerals that tends to destroy life or impair or endanger health; or ash resulting from the process of power generation.
Height	For a dam, means the measurement of the difference in level between the natural bed of the watercourse at the downstream toe or, if not across a watercourse, between the lowest elevation of the outside limit and the top of the dam.
Hydraulic modelling	Hydraulic modelling is a mathematical representation (usually resolved numerically and applied in a digital computer) of a water/sewer/storm system, which is used to simulate and analyse the system's hydraulic behaviour. In particular to rivers and floodplains, hydraulic modelling predicts water levels and velocities (as opposed to hydrologic modelling, which generally only predicts discharge).
Hydrodynamic modelling	Similar description to hydraulic modelling, considers the time dependent variations in hydraulic behaviour.
Hydrological modelling	A hydrological model is a simplified, conceptual representation of the watershed and catchment flow sections of the hydrologic cycle. Hydrologic modelling predicts runoff (discharge, as opposed to hydraulic modelling which also predicts water levels and velocities).
Incident	An event that does not endanger the integrity of the dam and downstream property or life but which could, in other circumstances, deteriorate into a serious situation. It might be described as a “near miss” Examples of incidents include: rapid change in seepage overtopping of earth embankment excessive beaching excessive embankment erosion spillway or bywash erosion or blockage excessive cracking or displacement in concrete dams and spillways sliding, rotation or settlement of the dam malfunction of gates or crest bags vandalism
Incremental population at risk	Not used in this guideline. *See* population at risk (PAR).
Inspection	A careful and critical examination of all physical aspects of a dam.
Lake	See reservoir.
Levee bank	A levee is an artificial embankment or concrete / steel structure, for which the objective is to protect land or property from flooding to a

Term (Abbreviation)	Description
	particular probability standard, by confining relevant floods to the primary watercourses nearby.
Light detection and ranging (LiDAR)	Remote sensing technology that measures distance and therefore relative locations by illuminating a target with a laser. Commonly used to make high resolution maps.
Megalitres	A unit of capacity equal to one million litres, or a thousand cubic metres of volume.
No-failure flooding	Flooding that occurs without a dam failure event. It includes runoff from the catchment upstream of the dam (and may include influence of gate operations) as well as runoff from the downstream catchment and any tributaries.
Non-referable dam	Any dam that does not have a Category 1 or Category 2 failure impact rating. This includes those not required to be failure impact assessed and those where a dam failure impact identified PAR to be less than two. Such dams may have a requirement imposed for a further failure impact assessment.
Notices	A written notice provided to the dam owner by the chief executive. There are a number of notices that the chief executive may give to the dam owner in relation to failure impact assessments. These include: A *compliance notice* may be given for failure to prepare and submit a failure impact assessment or a further assessment to the chief executive for acceptance. A *notice* may be given for any existing dam or a dam being constructed to require the dam to be failure impact assessed. A *notice* is given when the chief executive accepts the failure impact assessment An *information notice* is given when the chief executive requires a review of a failure impact assessment. An *information notice* is given when the chief executive rejects a failure impact assessment. A *referable dam notice (RDN)* is given to the dam owner when the chief executive reasonably believes a dam would, if it were failure impact assessed, have a category 1 or category 2 failure impact rating. When the chief executive decides to give a referable dam notice, an *information notice* outlining the decision is also given.
Place of occupation	A house, workplace, dwelling, building or other place where people congregate for any extended period of time.
Plinth	Refers to the plan projection on the ground of a building or other place of occupation. This is not necessarily a habitable floor level.
Population at risk (excluded)	There are exclusions to the assignment of PAR, *see* Section 2.4.5.
Population at risk (PAR)	*See* dam failure PAR.
Probable maximum flood (PMF)	The flood resulting from probable maximum precipitation coupled with catchment conditions that are optimal for generating maximum runoff.
Probable maximum precipitation (PMP)	The theoretical greatest depth of precipitation for a given duration that is, based on meteorological methods of maximisation, physically possible over a particular catchment area.

Term (Abbreviation)	Description
Referable dam	A dam, or proposed dam after its construction, for which: a failure impact assessment is required to be carried out under the Act, and the assessment states the dam has or the proposed dam after its construction will have a category 1 or 2 failure impact rating, and the chief executive has under the Act, accepted the assessment Also, a dam that is below the size criteria specified in the Act and reasonably believed by the chief executive to have a category 1 or 2 rating becomes referable as a result of a referable dam notice (RDN) issued by the chief executive under the Act when the dam owner does not submit an FIA in response to the RDN within the time specified in that RDN. The following cannot be considered to be a referable dam: a dam containing or proposed dam that after its construction will contain, hazardous waste a weir, unless the weir has a variable flow control structure on the crest of the weir A referable dam is one that would, in the event of failure, put a population of 2 or more people at risk. Referable dams are regulated for dam safety purposes.
Referable dam notice (RDN)	See Notices.
Registered professional engineer of Queensland (RPEQ)	Professional engineers, who carry out professional engineering services, must be registered under the *Professional Engineers Act 2002*.
Reservoir	The body of water impounded by a dam.
Ring tank	A dam that is totally enclosed by embankments surrounding the water storage and does not have a separate contributing catchment. Also referred to as: turkey's nest offstream storage pumped storage
Simplified assessment	An assessment using simplified tools and/or models involving approximations to determine outcomes. In general a simplified assessment will provide a more conservative assessment compared to a comprehensive assessment. A simplified assessment can be used when the result is clear and the effort does not warrant a comprehensive assessment.
Spillway	A weir, channel, conduit, tunnel, gate or other structure designed to permit discharges from the reservoir when storage levels rise above the full supply level. Can include secondary and auxiliary spillways.
Spillway adequacy	*See* acceptable flood capacity.
State Assessment and Referral Agency (SARA)	A co-ordinated, whole-of-government approach to the assessment of development applications in Queensland. SARA is the central agency for lodgement and for state approvals for development decisions.
Storage capacity	The capacity of water ordinarily stored upstream of a dam during normal operations of that dam.
Sunny day failure	A dam failure event that occurs without a wet weather event.

Term (Abbreviation)	Description
Tailwater	Water level immediately downstream of the dam structure.
The Act	The *Water Supply (Safety and Reliability) Act 2008*.
Total PAR	Total PAR are persons who are at risk when a no-failure flood event is accompanied by a dam failure event.
Weir	A barrier constructed across a watercourse below the banks of the watercourse that hinders or obstructs the flow of water in the watercourse, but does not cause a substantial difference in water level (upstream to downstream) by the stage when the water is about overflow the banks.
Workplace	Under s. 8 of the *Work Health and Safety Act 2011*, a workplace is a place where work is carried out for a business or undertaking and includes any place where a worker goes, or is likely to be, while at work.

1 Introduction

1.1 Purpose of a failure impact assessment

The primary purpose of a failure impact assessment is to establish if a dam is considered to be 'referable' in accordance with the provisions of the *Water Supply (Safety and Reliability) Act 2008* (the Act) and, if so, what is the category of failure impact rating of the dam.

A referable dam is regulated under the Act for dam safety purposes. Dam safety conditions are applied, and the owner establishes a dam safety program to deliver appropriate design and operational management based on risks associated with any potential failure. Dams are monitored and audited and an emergency action plan is required under the Act.

1.2 What is a failure impact assessment

A failure impact assessment (FIA) of a water dam in Queensland is a consequence or hazard assessment used to establish whether there are people whose safety will be at risk in the event of a dam failure.

A failure impact assessment firstly assumes that the dam fails in a manner consistent with the type of dam. It then makes a worst case determination of the resulting consequences or hazards. It does not consider the likelihood of the dam failure occurring.

More details of what is necessary for a failure impact assessment are contained in the methodology (Section 2).

1.3 What is a dam failure

A dam is considered to have failed when:

- a part or all of the dam physically collapses, for example, when–
    - the earth wall slumps or a pipe forms through the embankment
    - part of the wall erodes when overtopped
    - foundation weakness removes a section of a concrete dam wall

Or:

- there is an uncontrolled release of any of the contents from the dam, for example, when–
    - a gate or valve fails
    - an outlet pipe breaks

Dam failures can occur with or without a wet weather event. A sunny day failure occurs when a dam fails without a wet weather event. A flood failure occurs when a dam fails with a flood event, which can result in flooding from both the dam catchment and catchments and tributaries downstream.

1.4 What are population at risk (dam failure PAR, or PAR)

There are key terms relating to population at risk, described in Table 1. Section 2.4.5 describes how to assess PAR.

Table 1: Key terms describing population at risk

Term	Description
Total PAR	Total PAR are persons who are at risk when a no-failure flood event is accompanied by a dam failure event.
No-failure flooding	Flooding that occurs without a dam failure event. It includes runoff from the catchment upstream of the dam (and may include influence of gate operations) as well as runoff from the downstream catchment and any tributaries. This guideline also refers to no-failure flooding as just "flooding".
Dam failure PAR (or just "PAR")	The number of persons, calculated using methodologies described in this guideline, whose safety will be at risk if the dam or the proposed dam after its construction fails. Dam failure PAR are persons who are not at risk by a flood event but are at risk when the same flood event is accompanied by a dam failure event. It can be considered as Total PAR minus the PAR affected by a no-failure flood event immediately prior to dam failure (subject to water depth and flood hazard thresholds). This term is consistent with the term "dambreak PAR" in ANCOLD (2012). The guidelines also refer to dam failure PAR as just "PAR". This guideline provides the criteria and exclusions that define dam failure PAR.

1.5 What is a failure impact rating (FIR)

A failure impact rating (Table 2) is assigned to a dam according to dam failure PAR, which is a key outcome of the FIA process.

Table 2: Failure impact rating criteria[2]

Criteria	Referable?	Failure impact rating (FIR)
PAR < 2	No	No failure impact rating
2 ≤ PAR ≤ 100	Yes	Category 1 failure impact rating
PAR > 100	Yes	Category 2 failure impact rating

1.6 Failure impact assessment process

The failure impact assessment process is detailed in Section 2. It considers the following broad steps:

- Scoping Exercise
- Dam Failure Scenarios
- Flooding Assessment
- FIA Submission

[2] PAR in this table refers to Dam Failure PAR.

FIA submission should consider the checklist provided in **Appendix 1,** contain a report that considers including contents provided in **Appendix 2**, and must include a statement of certification from an RPEQ (see **Appendix 3**).

Following submission the chief executive performs an internal assessment that will result in three alternative outcomes:

1. Reject
2. Review
3. Accept

If the accepted FIA results in a dam being referable then subsequent regulatory conditions may become required, including dam safety conditions and an emergency action plan (EAP).

1.7 Relevant legislation

1.7.1 Water Supply (Safety and Reliability) Act

The safety of water dams in Queensland is regulated under the *Water Supply (Safety and Reliability) Act 2008* (the Act). Under the Act, the chief executive of the Department of Natural Resources, Mines and Energy (DNRME) is responsible for the regulation of referable dams in Queensland.

The Act requires owners of certain dams, both proposed and existing, to undertake a failure impact assessment of their dam. The failure impact assessment is designed to identify any potential threat to people living downstream of the dam from unexpected flooding caused by dam failure.

The Act also requires that a failure impact assessment be certified by an independent Registered Professional Engineer of Queensland (RPEQ) before it is submitted to the chief executive.

This guideline has been developed and issued by the chief executive, in accordance with sections 342(1)(b), 346(3)(a) and 572 of the Act. It provides information to dam owners of their statutory obligation to submit a failure impact assessment for acceptance. It also provides guidance to the dam owner and their certifying RPEQ on the process for undertaking and certifying the assessment.

Dam owners should refer to the full text of the Act to determine if their dam is subject to this legislation.

If there are inconsistencies between this guideline and the Act, the Act prevails to the extent of any inconsistency.

1.7.2 Professional Engineers Act

It is a requirement of the *Professional Engineers Act 2002* that professional engineering services in Queensland or for Queensland, are carried out by a RPEQ, or alternatively by a person who carries out the services under the direct supervision of a RPEQ who is ultimately responsible.

Many aspects of a failure impact assessment can be considered as a professional engineering service and as such should be performed by, or directly supervised by, an engineer with appropriate qualifications and is an RPEQ.

Further information is available, visit www.bpeq.qld.gov.au.

1.7.3 Work Health and Safety Act

The *Work Health and Safety Act 2011* (WHS Act) provides a framework to protect the health, safety and welfare of all workers at work. It also protects the health and safety of all other people who might be affected by the work.

All workers are protected by the WHS Act, including:

- employees
- contractors
- subcontractors
- outworkers
- apprentices and trainees
- work experience students
- volunteers
- employers who perform work

The WHS Act also provides protection for the general public so that their health and safety is not placed at risk by work activities.

The WHS Act places the primary health and safety duty on a person conducting a business or undertaking (PCBU). The PCBU must ensure, as far as is reasonably practicable, the health and safety of workers at the workplace. Duties are also placed on officers of a PCBU, workers and other persons at a workplace.

Under the Act any population on the same workplace as the dam are excluded from being considered as PAR (see Section 2.4.5.4 and section 346 of the Act).

1.7.4 Environmental Protection Act

The Environmental Protection Act 1994 (EP Act) is a key element of Queensland's environmental legal system. Its objective is to protect Queensland's environment while allowing for development that improves the total quality of life, both now and in the future, in a way that maintains ecological processes (ecologically sustainable development).

Structures that store hazardous waste or other materials that may have potential environmental impacts if released are regulated under the Environmental Protection Act 1994. They are excluded from FIA requirements (see Section 1.10 and section 340 of the Act).

1.7.5 Planning Act

Once an FIA is accepted for a proposed dam, and the dam is referable, application must be made under the *Planning Act 2016* for a development permit to construct the dam. Safety conditions would normally be attached to any development permit issued for a referable dam.

For more information, see Section 2.5.

1.8 Responsibilities

1.8.1 Of the dam owner

It is the responsibility of the dam owner to arrange for the preparation and submission of an FIA. FIAs submitted to the chief executive must be certified by an independent RPEQ.

A dam owner may be prosecuted for failing to carry out and submit an FIA as required. Penalties may also apply if a person gives false or misleading information to the certifying RPEQ.

1.8.2 Of the certifying RPEQ

An FIA must be certified by an independent registered professional engineer (RPEQ).

The RPEQ is responsible for certifying the accuracy and content of the assessment, reflecting upon the contents of this guideline and the Act.

- The certifying RPEQ must ensure that they comply with the *Professional Engineers Act 2002*, which requires (among other requirements) competence in the specific field of engineering being investigated and direct supervision of all engineering services performed.
- The certifying RPEQ must exercise professional judgement when applying any relevant methodology.
- The assumptions and procedures adopted for the FIA must be documented and justified, particularly where there are departures from this guideline.
- Evidence in support of particular methods or conclusions must be from published and preferably peer-reviewed technical papers.
- Anecdotal evidence is not acceptable as justification.
- Penalties apply if the RPEQ certifies a failure impact assessment that contains information that they know is false or misleading.
- The certifying RPEQ cannot be:
    - the owner (of the dam being assessed)
    - an employee of the owner
    - the operator (of the dam being assessed)
    - an employee of the operator

1.9 When is an FIA required

The requirement to do an FIA is automatically triggered for a water dam under s.343 of the Act if certain criteria is met. Some of these require relevant height and size criteria to be considered.

The height and size criteria are:

- More than 10m in height with a storage capacity of more than 1500ML
- More than 10m in height with a storage capacity of more than 750ML and a catchment area that is more than three times its maximum surface area at full supply level

The following conditions require an FIA:

- Proposed dam that meets the height and size criteria (above)
- Existing dam (not previously assessed) that meets the height and size criteria (above).

- Existing non-referable dam that already meets the height and size criteria (above) with proposed works to increase the storage capacity by more than 10%.
- Existing referable dam with proposed works to increase the storage capacity by more than 10%.
- An existing dam that does not exceed the height and size criteria where proposed works will increase its size so that it does meet the height and size criteria.
- Where a dam has been previously assessed and the FIA has been accepted by the chief executive, a new FIA needs to be submitted to the chief executive by the date nominated in the notice accepting the FIA.
- The chief executive gives the dam owner a notice under s.343(5) of the Act.
- The chief executive gives the dam owner a notice under s.342A(2) of the Act and the Dam Owner wishes to contest that assessment.
- If the dam owner considers that their referable water dam should no longer be referable then a new FIA is required to justify such a position. If that assessment indicates that the dam is no longer referable and that assessment is accepted by the chief executive, the dam will no longer be referable.

Note that the FIA process is not complete until it has been submitted and accepted by the chief executive. Any construction, upgrades or other works that require an FIA cannot commence without an accepted FIA.

1.10 When is an FIA not required (legislative exclusions)

Table 3 provides criteria that negate the requirement for an FIA because they cannot be referable under the Act, irrespective of their size.

Table 3: Criteria for an FIA not being required

Criteria	Description
Dam contains hazardous waste	Structures that store hazardous waste or other materials that may have potential environmental impacts if released are regulated under the *Environmental Protection Act 1994*. Note however that a water supply dam on an industrial site or a mine site may still require an FIA under the Act.
Most weirs[3]	A weir with a variable flow control structure (for example, an inflatable rubber bag or gates) on the crest of the weir may require an FIA.

1.11 Complexity and costs associated with an FIA

The level of detail and analysis associated with an FIA should reflect the complexity of the specific problem and how clearly the failure impact rating can be categorised. Additional applications the FIA outputs may be applied to should also be considered, noting that if the dam becomes referable the outputs can provide valuable knowledge on the consequences of failure for the dam. This information can then be applied to subsequent Emergency Action

[3] See Glossary for a definition of a weir.

Plans (EAPs) requirements or other planning, emergency response and risk mitigation strategies.

The methodology adopted for the FIA should be a balance between what the certifying RPEQ considers necessary and the reasonable cost of the process considering the risk profile of the dam.

See Section 2.2 for further discussion on scoping an FIA.

In most cases the dam owner must pay for all costs associated with preparing and certifying an FIA. The only exception to this is when the chief executive issues a referable dam notice (RDN), deeming a dam to be referable, or issues a notice to the dam owner directing them to undertake an FIA.

Subsequently, the submitted FIA concludes that a dam is not referable and that FIA is accepted by the chief executive. Under these circumstances the chief executive must pay the reasonable cost of preparing and certifying the FIA. The dam owner must retain suitable records to substantiate such costs. Section 348 of the Act provides further details.

1.12 Applicability of FIA outputs

The primary intent of an FIA is for statutory purposes to identify a category for referable dam status. The assumptions, methodologies and criteria described in this guideline reflect this.

Dam failure modelling and impact assessment is also undertaken for other purposes and can be more detailed. In particular, methods that consider risk (and not just consequence) can provide more relevant information for quantitative risk assessments, establishing acceptable flood capacity and informing effectiveness of emergency response. ANCOLD (2012), DNRME (2017a) and DNRME (2017b) provide further guidance.

The FIA methodology presented in this document may differ from quantitative risk assessments and emergency response purposes. Points of difference between them and FIA include:

- Quantitative risk assessment:
    - The application of a factor FV = 1.3 in the simplified breach analysis (see **Appendix 5**) may be conservative.
    - Flooding events for FIA do not incorporate likelihood of concurrence (Section 2.4.3).
    - PAR on roads (if applied) does not distinguish between voluntary and involuntary risks (**Appendix 11**).
    - Occupancy rates may vary depending on the time of day and season (**Appendix 4**).
- Emergency response:
    - Total PAR must be identified, not just dam failure PAR.
    - Additional aspects, such as time after dam failure and more refined hazard classifications, may be of significant value.
    - Selection of flooding events that coincide with a dam failure event may require review.

1.13 Comparison to ANCOLD's Guidelines on the Consequence Categories for Dams

These FIA guidelines deviate from the ANCOLD guidelines (ANCOLD, 2012). This deviation is primarily driven by the specific legislative purpose of the FIA guidelines, particularly the need for clear and unambiguous thresholds to identify dams which need to be regulated.

A summary of key differences is provided in Table 4.

Table 4: Comparison with ANCOLD guidelines

Aspect	FIA guidelines	ANCOLD guidelines (ANCOLD, 2012)
Extent of consequence assessment	Only risk to human life (PAR) considered.	Considers risk to human life (PAR) and damage and loss, including: property damage effects on businesses credibility and political impact health, social and economic disruption environment
Applicability	Only applicable to water dams.	Applicable to all dams and similar structures.
Meaning of PAR	Dam failure PAR are persons who are not at risk by a flood event but are at risk when the same flood event is accompanied by a dam failure event. It can be considered as Total PAR minus the PAR affected by a no-failure flood event immediately prior to dam failure (subject to water depth and flood hazard thresholds). This definition aligns with the concept of Dambreak PAR in the ANCOLD guidelines, although there are differences in threshold calculations (see Section 2.4.5).	Two definitions are considered. **Total PAR** is within the total flood inundation area for each scenario. For an "initial assessment" or an "intermediate assessment", Total PAR is reported. **Dambreak PAR**, which is Total PAR minus: PAR affected by pre-dam break flood water, defined by DV > 0.6m²/s, D_{max} >1.2m or V_{max}>1.5m/s PAR who have had at least 12 hours warning of the event. For a "comprehensive assessment", Dambreak PAR is reported.
PAR thresholds	As per Table 1 and analysis logic described in Figure 3.	A threshold is applied to exclude PAR affected by pre-dam break flood water. Otherwise, there is no threshold depth or velocity considered (just "wet" or "not wet"). Note that the previous ANCOLD guideline revision included the 300mm threshold applied in the FIA guideline.
PAR exclusions	If the PAR is on a workplace at which the dam is situated, or on the same parcel of land on which the dam is situated, or on a mine or coal mine at which the dam is situated, the PAR is ignored.	No specific exclusions.

Aspect	FIA guidelines	ANCOLD guidelines (ANCOLD, 2012)
Use of PLL (probable loss of life)	Not considered.	PLL can be used instead of PAR as alternative method to determine Consequence Category (Table 3 or Table 4 of ANCOLD guideline).
Consideration of itinerants	Not mandatory, but methods to incorporate into PAR calculations are provided.	Recommends that “itinerants should be included in the estimation of PAR based on their probability of being in the flood-affected zone”.

2 Methodology

2.1 Introduction

The recommended methodology to prepare, submit and act upon an FIA considers the following broad steps:

1. Scoping Exercise

- This is required to determine the need for, scope and complexity of the FIA. Background information and data is collated and a site inspection is performed. If the FIA is to proceed then an RPEQ is engaged.

2. Dam failure scenarios

- An assessment of the failure modes for the dam considering design, construction details and the drivers of dam failure. The scenarios need to consider flood events from upstream of the dam to generate outflow hydrographs for the flooding assessment.

3. Flooding assessment

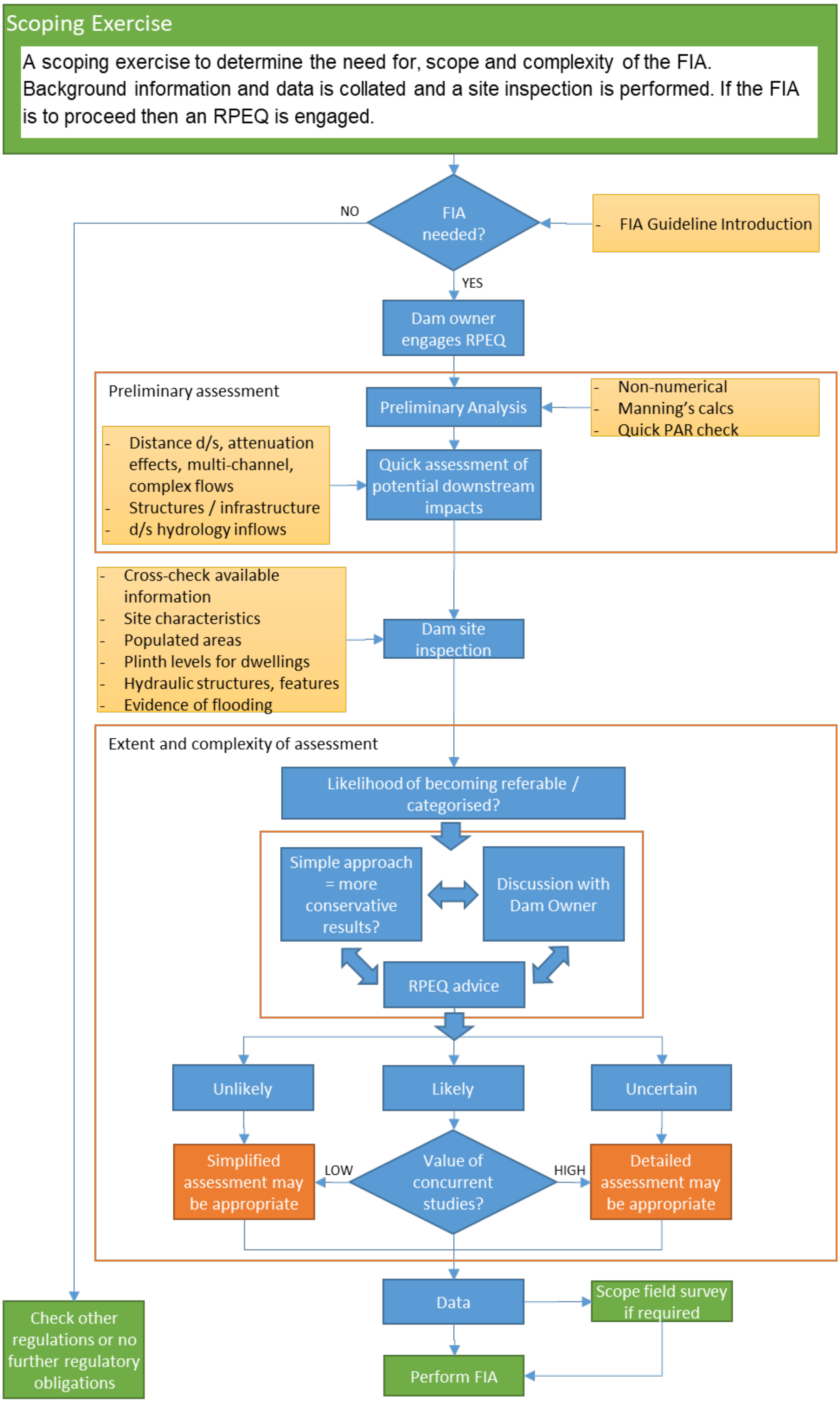
- Using analysis methods (often numerical modelling), establish downstream flooding characteristics, threshold water depths and velocities necessary to identify PAR for each dam failure scenario. The highest PAR value from the scenarios is the critical PAR.

4. **FIA submission**

- Submission to the regulator and, if criteria are satisfied, the dam becoming referable and regulated under the provisions of the Act. The failure impact rating assigned to a referable dam (none, category 1 or category 2) assists the chief executive in setting safety conditions appropriate for each dam and the timing for further FIAs.

The following sections describe the methodology for each of the above steps. A flowchart is provided at the front of each section, with sub-headings providing details for each step within the flowchart process.

2.2 Scoping Exercise



2.2.1 Is an FIA needed?

Reasons and criteria for initiating the FIA are provided in Section 1.9 (and legislative exclusions in Section 1.10).

2.2.2 Engage and discuss with RPEQ

The dam owner needs to engage an independent RPEQ to oversee and certify the assessment. It is recommended that the RPEQ be engaged at the commencement of the scoping exercise.

The dam owner and certifying RPEQ need to come to an agreement regarding the nature of the assessment. This agreement should define the scope of work necessary to be confident that all regulatory obligations have been met and that the RPEQ is comfortable to certify. The activities to be considered include:

- The dam site and the impacted area needs to be inspected at least once (see Section 2.2.4).
- Data needs to be collected and its appropriateness and accuracy assessed (see Section 2.2.6).
- The dam failure impact zone for the critical failure scenario must be identified and an adequate assessment of the PAR determined from this assessment (see Sections 2.3 and 2.4).
- The FIA must be certified by the independent RPEQ and submitted to the chief executive (see Section 2.5).

2.2.3 Preliminary Assessment

The preliminary assessment estimates the expected failure impact zones for the dam. A failure impact zone is the extent downstream of the dam where there may be potential PAR. The extent of any preliminary assessments required is site specific, depending on the nature of the dam and downstream area.

Methods and techniques are available to approximate the failure impact zone, typically assuming simple failure mechanisms and normal depth / uniform flow conditions downstream (discussed in more detail in Section 2.3 and 2.4). Aspects such as complex overland flow paths, structures and infrastructure in the downstream catchment and downstream hydrology and flooding may be significant and may need to be factored into the preliminary assessment. See Section 2.2.5 for further discussion on FIA extent and complexity.

Table 5 provides a rough guide for an initial assessment of failure impact zone. The numbers in this table are intended as a guide only and the distances may be substantially greater or lesser, depending on the dam and downstream channel. It is anticipated that any preliminary assessment will be conservative and may need to be confirmed through subsequent more comprehensive assessments depending on the results.

Table 5: Indicative failure impact zone distances (based on dam failure studies)

Storage (ML)	Indicative total distance downstream from dam (km)
20,000	Up to 60km
2,000	Up to 20km
200	Up to 5km

2.2.4 Dam site inspection

Site inspections by the RPEQ or representatives of the RPEQ are mandatory to identify all areas that could be potentially affected by dam failure.

They ensure that the FIA is based on correct and up-to-date information. Site inspections also provide an appreciation of the site characteristics and the currency and adequacy of available data. While it's not essential that the certifying RPEQ attends the site inspection, it is desirable. It is expected that the date(s) and name(s) of the personnel involved, who are representatives of the RPEQ, be included in the FIA.

In some circumstances, site inspections may be limited to an aerial inspection of the area using aircraft or drones. This approach may be appropriate for investigating dams in remote areas with few dwellings and where it could easily be established that those dwellings are either within or outside the failure impact zone.

Depending upon the anticipated outcome of the analyses, more rigour may be required for the inspection. This may occur where the FIA suggests a borderline result and the owner wishes to justify the adoption of a specific rating, or where the dam is clearly referable and more detailed analysis is justified for subsequent EAP, AFC and dam design analyses.

Site inspections should consider:

- Accuracy of available mapping, aerial photography or satellite imagery used.
- Existence of buildings and other populated areas (for example, roads or camping facilities) to calculate the PAR and justify the failure impact rating identified.
- Plinth (relevant datum) levels for places of occupation in the failure impact zone (see Section 2.4).
- Other storages on the same watercourse or potential failure path.
- Catchment modification works (for example, levees) or the presence of hydraulic structures.
- Nature of the downstream watercourse for estimation of roughness values.
- Site characteristics (for example, soil types to justify assumptions made for alternative breaking calculations).
- Evidence of previous floods (for example, debris marks, which could assist in calibrating the model to a previous event).

The certifying RPEQ must be satisfied that the inspection of the site has accounted for all relevant impact areas within the failure impact zone to justify the failure impact rating determined.

The RPEQ must include a statement to this effect in the certification (see **Appendix 3**).

2.2.5 Extent and complexity of assessment

Methodologies for undertaking FIA range from simplified to comprehensive.

For all FIAs, the certifying RPEQ will be responsible for the analyses and conclusions drawn.

The type of assessment undertaken may depend on the following:

(a) Circumstances and available data	• The type of assessment may be dependent on the circumstances and the data that is available. In most cases, some form of numerical analysis will be required to determine the dam failure impacts on any PAR.
(b) The costs involved	• Simpler assessments should cost less than the more complex comprehensive assessments. • However, a more conservative outcome is expected when undertaking a simplified assessment.
(c) The certainty of the outcome	• If a simpler assessment clearly demonstrates that a dam does not have any PAR, then a more comprehensive assessment will not be required. • If a simpler assessment predicts PAR that is marginal for determining the referable status of the dam (no PAR, category 1 or category 2, see Section 1.5) a more comprehensive assessment may be justified.
(d) The minimum level of assessment the RPEQ considers is necessary for certification	• In their discussions, the dam owner and the certifying RPEQ should come to an agreement regarding the nature of the assessment. • The RPEQ should endeavour to balance what they are prepared to certify as a responsible professional against what the dam owner needs to do to satisfy their regulatory obligations. • The RPEQ should also be mindful of the financial impact of the assessment on the dam owner whilst ensuring that it is undertaken to an appropriate level of rigour.
(e) The value of concurrent studies	• If a dam becomes referable there are regulatory and design requirements to consider, including dam design and capacity considerations and emergency response plans. If it is likely that the dam is to become referable it may be beneficial to incorporate more detailed analyses to address these requirements. • Numerical modelling tools and other applications are often used to inform floodplain management and emergency response investigations. Incorporating FIA information, or at least the consequence analyses required of an FIA submission into these flood related studies provides

opportunities to streamline effort and, importantly, improve overall resilience on a floodplain.

    - For example, if dam failure scenarios are incorporated into the scope of a floodplain management plan then the consequences of dam failure can be factored into the broader issues of land zoning, infrastructure planning, identification of evacuation routes and emergency response procedures.

- Note comments in Section 1.12 relating to applicability of FIA outputs.

Simplified methodologies (see Section 2.3 and 2.4) are designed to be more conservative than the comprehensive methodologies. These assessments may be a useful starting point to obtain a quick, cost-effective indication of the potential dam failure impacts, and may be adequate for the final assessment in some cases.

Dam owners should discuss with the certifying RPEQ the type of assessment to be adopted, the extent and complexity of the analysis and/or any modelling required for the assessment of their dam.

Following this assessment, it may then be necessary to proceed to a more comprehensive analysis. This is particularly the case in situations with a borderline PAR, where the dam owner may wish to justify the adoption of a lower failure impact rating, or clearly establish whether or not the dam is referable.

Methodologies additional to those described in the guidelines may exist and be applicable to a particular FIA.

2.2.6 Data collection

A wide array of information may need to be collected to determine the potential effects of a dam failure. The necessary extent and accuracy of the data collected will be dependent on the type of assessment being undertaken and the circumstances of the particular dam.

The data types set out in Table 6 should be considered when preparing an FIA. It should be noted that, for the relevant circumstances of smaller or low consequence dams, some of the complexity and particular items set out below may be unnecessary.

The certifying RPEQ must consider the appropriateness and accuracy of all information adopted for the assessment as part of their certification.

Table 6: Data types to consider when preparing an FIA

Type of information	Description
Dam storage information	Information should be gathered that outlines the physical dimensions and properties of the dam. This information is required to determine potential dam failure characteristics and flooding effects. Examples:

Type of information	Description
	• the type of dam and location (including latitude and longitude) • the spillway type and adequacy (including any flood control facilities such as gates and secondary spillways) • the dimensions of the dam such as height, length of embankments and the width of the crest • the storage capacity to full supply level and to the crest of the dam (storage capacity curve) • the purpose of the dam and a description of the surrounding catchment • comments on the design, foundations and any unusual conditions (including the embankment zoning, if known, and the condition of components and materials) • consideration as to possible causes and modes of failure (for example, inadequate spillway capacity, potential for piping of embankment, earthquake effects or blockage of outlets) • any previous design studies or reports
Dam structure information for failure assessment	Information to inform identification of likely modes and locations of dam failure for a given structure. • dam failure characteristics including break base width, side slopes, depth and development • the potential for cascade failures • type of embankment material and how this affects break dimensions and break development times; for example, granular materials will tend to scour faster, and smaller, high plasticity clay embankments may take longer to erode • geometry of the valley and if this has the potential to confine the break • erodibility of dam foundation material • location of the break and whether it produces the largest impact to nearby buildings • spillway discharge rating curve • storage capacity versus height curves • inflows into the dam
Topographic information	Sufficient topographic information must be obtained to accurately determine: • The shape and slope of the terrain downstream of all potential failure locations. • Any significant controls on the downstream flow such as culverts, vegetation, weirs, bridges, embankments, surface roughness and temporary storage on the floodplains. • Locations of major downstream tributaries. Topographic information sources include: • site survey obtained through traditional methods, total stations or real time kinematic (RTK) • aerial survey, such as LiDAR obtained from aircraft flyover or drones • surveys or digital elevation models from previous investigations • orthographic, topographic, military and cadastral plans • road maps • satellite imagery or aerial photography • information from residents, agencies or community groups

Type of information	Description
	• historic imagery features available in mapping websites may be useful to obtain information regarding site changes over time
River channel bathymetry	Bed levels in river beds (i.e. under water) are less easily obtained from remote sensed sources and often require a dedicated hydrographic survey to obtain. **Appendix 7**, and in particular Table 17, provides a guide to minimum spatial resolution and downstream extent of a model applied to dam failure analysis; this provides a guide to the required resolution of cross-sectional data.
Flooding and rainfall-runoff information	Floods due to dam failure are generally significantly larger than other extreme flood events. They can rise very rapidly with steep wave fronts and carry large amounts of debris and sediment. Hydrologic and hydraulic information should be obtained through appropriate analytical techniques, or the best available sources. These may include: • Australian Rainfall and Runoff guidelines (ARR 2016) • Other recognised design rainfall sources for bench-marking • previous flood studies and FIAs • historical flooding and rainfall information • evidence of previous floods (for example, debris marks, which could assist in calibrating the model to a previous event) • information from residents, agencies or community groups For dams with a larger catchment size (for example, more than 1000–2000 ha), it may be necessary to undertake more detailed hydrological assessments of the dam and downstream catchments. Recognised models include RORB, XP-RAFTS, URBS and WBNM. Many local governments undertake flood studies of their area. These can be a useful starting point for hydrological analysis. Note that such studies typically target peak discharge from a catchment; some adjustments to better understand peak volumes, which are often critical to FIA, may be required.
Hydraulic information	Potential historic sources of hydraulic information for dams may be obtained from: • previous FIAs • previous studies (for example, local government flood models) • local knowledge Many local governments undertake flood studies of their area. These can be a useful starting point for analysis, however consideration should be given to potential limitations. For example, such studies may focus on a particular spatial location and may not have the resolution or features in the areas of interest to the FIA. A number of standard software packages are available for hydraulically simulating the flow of dam discharges. These include HEC-RAS, TUFLOW and MIKE FLOOD.
Downstream community information	Downstream community information in the failure impact zone needs to be collected and considered to identify PAR. Information should be gathered for all populated areas within the failure impact zone including buildings, recreational

<table>
<tr><th>Type of information</th><th>Description</th></tr>
<tr><td></td><td>areas or roads. Once identified, the equivalent population of these can be estimated (see Appendix 4).

Downstream community information may be obtained from:

• site inspections
• satellite imagery or aerial photography
• local websites (for example, local government, Australian Bureau of Statistics)
• FIAs or emergency action plans for existing dams
• Google Street View photography
• information from residents, agencies or community groups

ANCOLD Guidelines on the Consequence Categories for Dams (October 2012) suggest that an initial estimate of dwellings that may be in the failure impact zone can be made by identifying buildings “within a height above the stream bed of between one third (1/3) and one half (1/2) of the dam height”. However, this needs to be confirmed as part of the analysis.

For dams in remote areas, where temporary workers (who are not determined to be excluded PAR under the Act) may live in buildings such as dongas or shipping containers, it can be difficult to identify habitable dwellings. Before undertaking a site inspection, remotely sourced imagery may be useful to identify features such as vehicle or tyre tracks, air-conditioners and TV aerials or satellite dishes, which could suggest the building is occupied.</td></tr>
<tr><td>Plinth levels</td><td>The plinth level is generally taken to be the level where the footing of the building meets the natural ground level. See Section 2.4.5.3.

The plinth levels for all buildings in a failure impact zone should be established using appropriate spatial information (topographic information, overlaid by the locations of buildings described in downstream community information). This can be a significant task, especially for dams upstream of large urban or suburban areas. GIS related techniques are available to overlay cadastre with filtered LiDAR data to identify plinth levels over large spatial extents. In some cases, plinth level information may need to be manually extracted from spatial datasets or site survey.

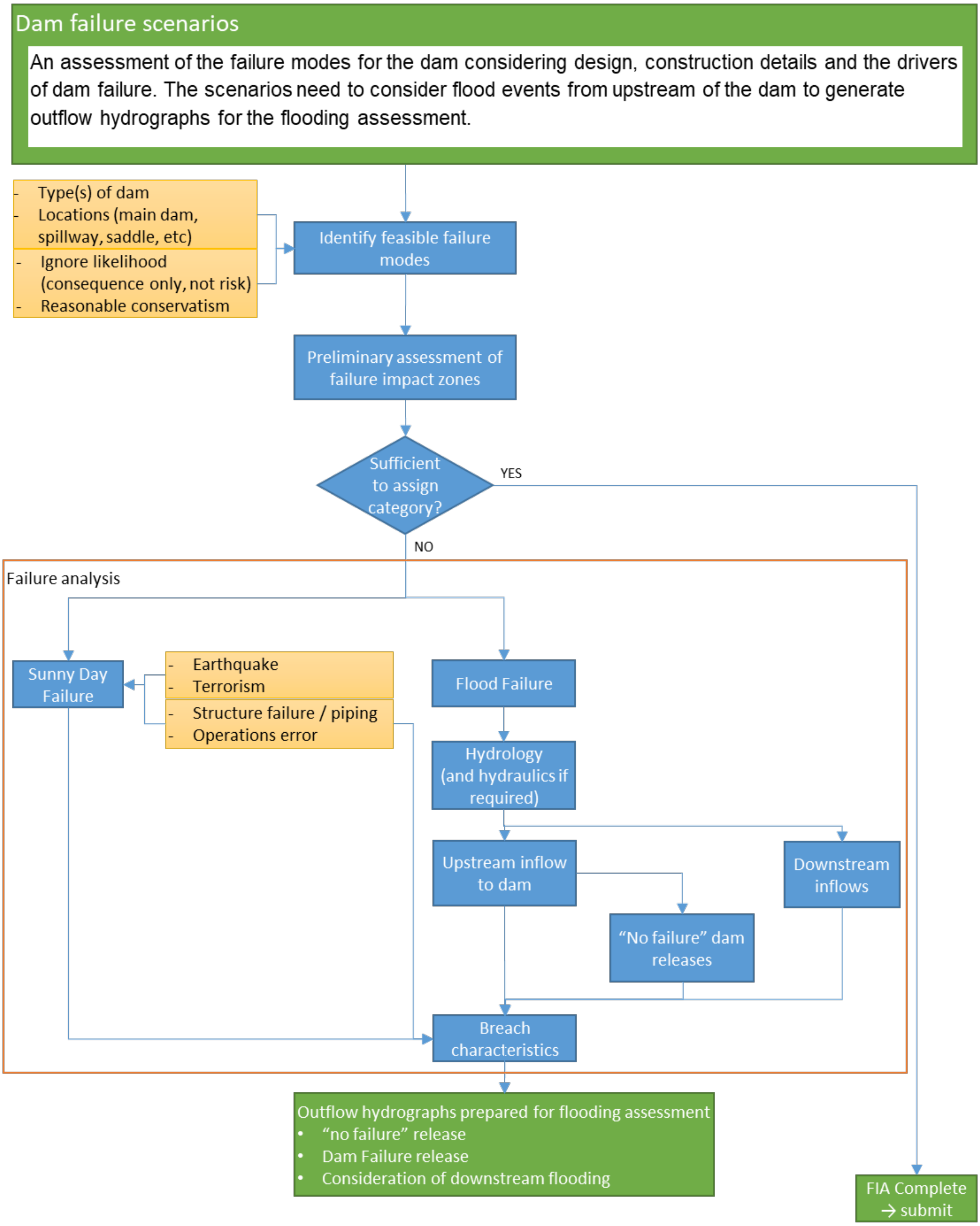
Plinth levels for all buildings in the failure impact zone should be obtained where it is feasible to do so. If obtaining these levels for all buildings is not feasible, a targeted assessment should be conducted that considers:

• High risk or critical potential PAR should be prioritised and the plinth levels accurately measured. This may include those immediately downstream of a dam or immediately adjacent to a major flow path.
• Plinth levels should be measured for selected buildings that are considered representative of the full range of buildings in the failure impact zone. An emphasis should be placed on high, low and typical plinth levels in each discrete spatial extent.
• Plinth levels for remaining buildings are estimated from the best available data sources.

The number of directly measured plinth levels, and methods to estimate levels for remaining buildings, should be described and justified in the FIA.</td></tr>
</table>

Type of information	Description
Verification of data during site inspection	Site inspections are essential to verify the currency of the information. Aspects to consider include: • A potential limitation with making use of remotely sourced information is that it may not contain recent developments (for example, houses or other places of occupation). • Confirmation of assumptions made as part of any hydrology and hydraulics assessments. • Verification of assumptions made about the downstream community. This ensures that the information in the FIA is current and enables the identification of dwellings obscured by trees, cloud shadows or poor quality image detail. • Verification of any applicable PAR exclusion types e.g. residents on the parcel of land on which the dam is situated or PAR at a workplace at which a dam is situated.

2.3 Dam Failure Scenarios



2.3.1 Identification of feasible failure modes

Dam failure analysis identifies feasible dam failure modes that would cause maximum consequence (i.e. the critical failure mode). These failure modes therefore need to consider:

- The physical characteristics of a failure mode (i.e. how a dam, or component of a dam, fails given its design and construction material).
  - The dam failure analysis should initially examine the structure (or proposed structure) and gather any relevant information, including service histories, design reports and design reviews. This information can inform identification of likely modes and locations of breaks for a given structure.
- The specific location on the dam structure of the failure.
  - An illustration of this is provided in Figure 1.
- The magnitude of the events that will cause maximum consequence (which may not be the dam crest flood or PMF).
  - See Section 2.4.3 for more information.

Principal dam failure modes to be considered are summarised in Table 7. **Appendix 6** describes failure modes for a range of dam types.

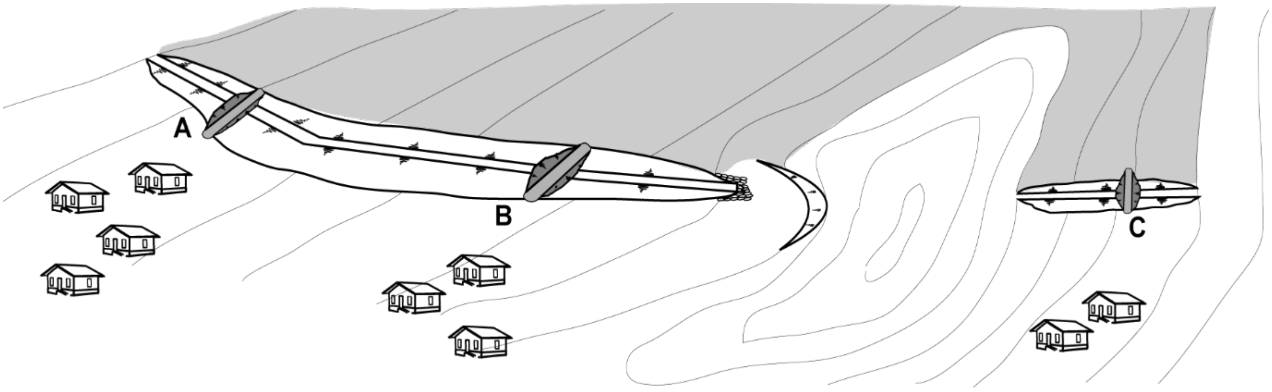
When considering the feasibility of a particular failure mode, dam engineers skilled in geology, geotechnical or structural aspects should be consulted.

Table 7: Summary of feasible dam failure modes to consider as part of scenarios in a failure analysis

Failure mode	Description
Sunny day failure	The failure flood occurs with the storage at full supply level (FSL) without a wet weather event.
Dam crest flood	A failure occurs during a flood event that just causes overtopping of the dam crest. This can also occur, with or without a wet weather event, where there is pumping into a storage and pumps fail to stop.
Dam failure with water level at level of PMF	If the PMF does not overtop the dam, assume the dam fails with the water at the lake level resulting from the PMF.
Intermediate lake level failure events	In some situations a reasonable failure mode is an intermediate failure event between FSL and dam crest level, producing flood levels up to the plinth level of downstream locations, and then dam failure occurs. This could occur through piping or slip failure for embankment dams or structural failure for mass concrete, and may produce higher PAR than a dam crest failure.
Failure in specific location(s) – particularly on an embankment dam	Failure occurs in a specific location on dam structure that results in maximum failure impacts downstream. This consideration is particularly important for dams that have long embankments or for ring tanks, any type of dam with a saddle dam/s, and therefore the dam could fail at various locations. This is most important to consider when potential PAR is close to the dam. It may be necessary to try several failure locations to ensure that the highest PAR has been identified, remembering to recalculate the break dimensions and hydrograph for each failure trial. See also Figure 1.
Multiple Dams Cascade Failure	See Section 2.3.2.
Failure of flow control structures	If the dam has the capability to significantly vary flood discharges through crest gates, sluices or some other type of variable flow control structures, the possibility of either failure or malfunction of these structures must be considered. **Appendix 6** covers some aspects of gated dam failures.
Other	Other causes of failure include: • storage rim instability • erosion due to poor materials and construction design and specification • factors such as deterioration, old age, design or construction faults and poor maintenance • damage due to fire, wind (for example, causing beaching leading to a breach) and escape of water into mining tunnels/shafts beneath reservoirs • vandalism • terrorism

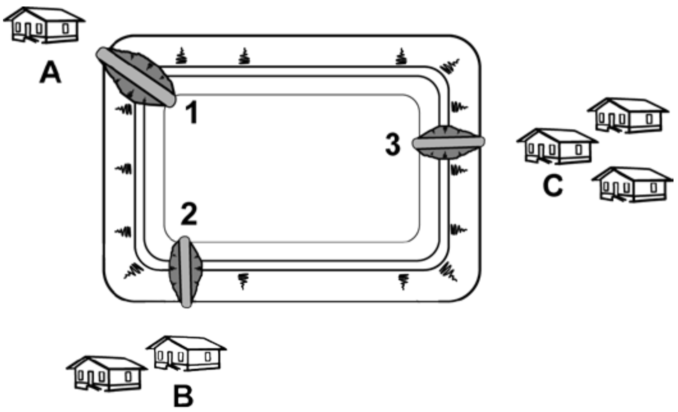
Figure 1: Illustration of identification of locations of feasible failure modes for embankment dams

Consider a dam with a long embankment, a saddle dam and multiple buildings downstream:



- Breaches at locations A, B and C are assumed in order to find the highest PAR.
- The breach calculations at each of these locations are adjusted to account for the embankment height at the location and the quantity of water released.
- In most cases, simultaneous failures would not need to be considered.

Consider a ring tank surrounded by properties:



- Breaches at locations 1, 2 and 3 are assumed in order to find the highest PAR (to properties at A, B and C).
- The location that affects the greatest number of buildings will be the critical breach location for the dam (based on the information provided in the figure, this is likely to be from failure at location 3).
- In most cases, simultaneous failures would not need to be considered.
- Breach calculations at each location are adjusted to account for the embankment height at the location and the quantity of water released.

2.3.2 Multiple dam impacts (cascade dam failure)

In instances where two or more dams exist on the same watercourse it must be considered whether the failure of an upstream dam triggers the failure of downstream dams.

Figure 2 provides an example of a cascade failure:

- If the dam failure discharge from dam A contributes to a dam failure at dam B that causes PAR at location C, both dams A and B will be considered referable.
- Dam B may still be referable, but not as a result of a cascade failure event, assuming that the only potential PAR is at location C.

Figure 2: Cascade failure example for two dams on the same watercourse

2.3.3 Preliminary assessment of failure impact zone

The primary purpose of the FIA is to establish whether or not a dam is referable and, if it is, what failure impact rating it has. If this purpose can be clearly established using a simplified assessment then more comprehensive analyses may not be justified.

A preliminary analysis to assist with this could include:

- A quick assessment of PAR, such as identification and population check of townships downstream of the dam, etc.
- Review of existing reports, especially floodplain management plans.
- Simplified hydrologic / hydraulic assessments to establish preliminary estimates of extents of downstream inundation and what locations may be impacted.

2.3.4 Initial assessment of FIR

Failure Impact Rating (FIR) may be clear at this stage and no further analysis is required. For example, if there is a sizeable township immediately downstream of the dam with numerous residences on low-lying sections of floodplain, identification of PAR may be obvious and simple methods can robustly demonstrate PAR numbers.

On the other hand, if PAR is less clear, or if the estimation of PAR does not clearly provide an FIA categorisation, more detailed analyses may be warranted.

2.3.5 Hydrology

Inflows from catchments both upstream and downstream of the dam are needed to define flood events, onto which dam failures are superimposed.

It is important that hydrological analyses are fit-for-purpose, make use of all relevant available data and other supporting information. Sources of hydrological information include:

- Australian Rainfall and Runoff guidelines and design rainfall data.
- Other recognised design rainfall sources for benchmarking.
- Previous flood studies in the dam catchment or adjacent catchments.
- Historical flooding and rainfall information, including evidence of previous floods and information from residents, agencies or community groups.
- Daily rainfall / pluviograph records and streamflow gauging records (various sources).
- Various hydrological analysis methodologies, including numerical modelling[4].

FIAs only consider consequence of failure (not likelihood) and require identification of events that will cause the highest PAR, which may not necessarily be the largest flood event. Further discussion on identifying critical flood events is provided in Section 2.4.3.

Validation of hydrological analyses is recommended (see **Appendix 7**).

2.3.6 Failure analysis

Appendix 6 describes approaches that may be applied in estimating dam failure parameters. Other methodologies are available, both simplified and complex, that may be applicable to FIA. In all cases, justification for the adopted approach must be provided in the FIA report.

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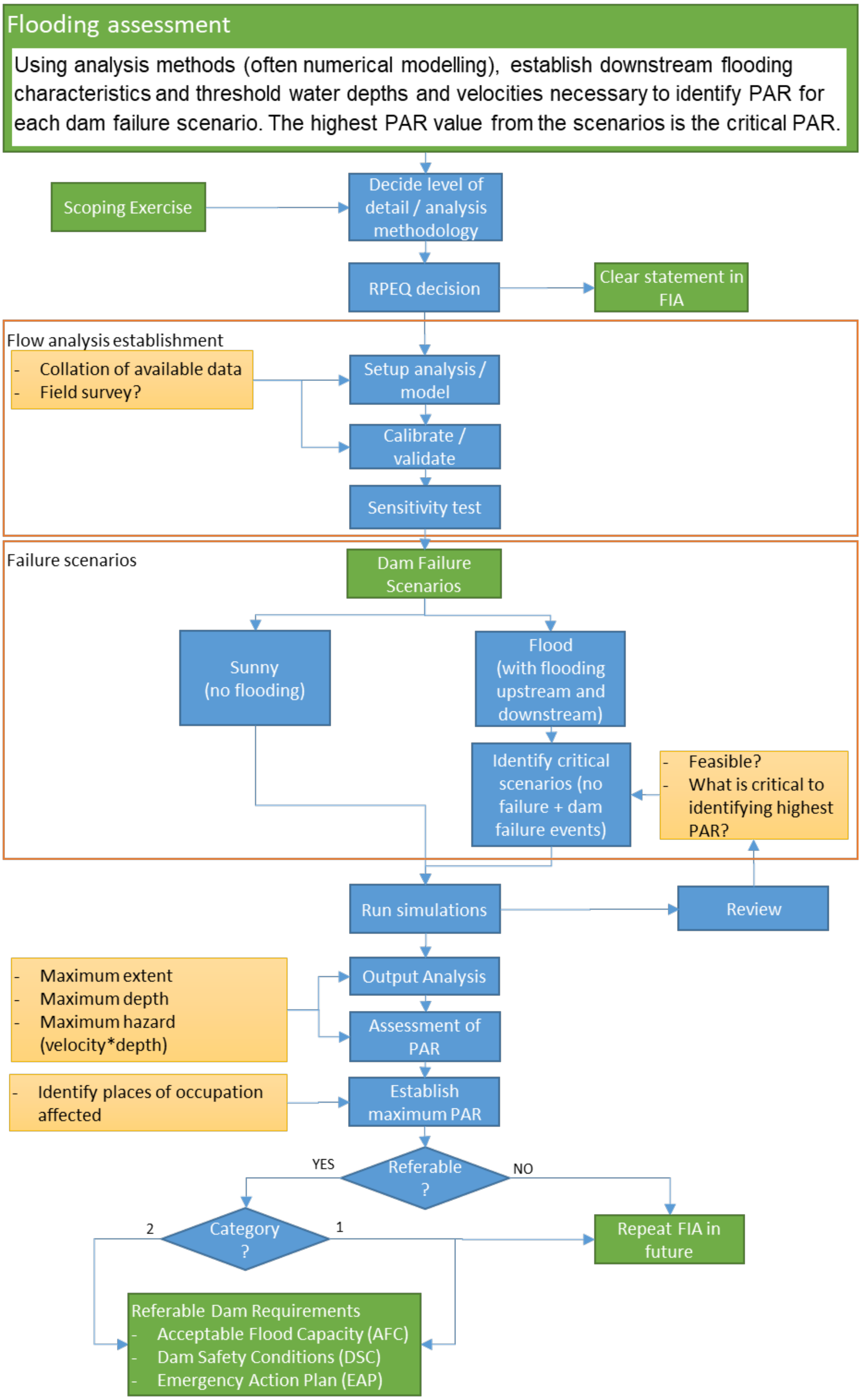
[4] Guidance on selection of hydrological analysis approach for flood studies and flood mapping is provided in DNRME, 2017. Visit www.dnrm.qld.gov.au and search for 'Guide for flood studies and mapping in Queensland'.

2.4 Flooding Assessment



2.4.1 Level of detail

The flooding assessment identifies the highest PAR from inundation generated from dam failure scenarios (Section 2.3), considering both sunny day failure (no flood event occurs at the time of failure) and dam failure during flood events (with the dam failure hydrograph superimposed on a flood event). This establishes the failure impact rating of a dam (Table 2).

Sections 1.11 and 2.2 discuss aspects to consider when scoping the FIA which are relevant for the flooding assessment, which include:

- Specific to flood assessment:
    - The number and locations of dam failure scenarios to be assessed
    - The complexity of the downstream catchments and floodplain
- Additional considerations:
    - Circumstances and available data
    - The certainty of the outcome
    - The value of concurrent studies

The level of detail and analysis methodology to be adopted must be clearly justified in the FIA submission.

2.4.2 Failure scenarios

A failure scenario is a specific feasible dam failure mode combined with a specific flood event. It is important to correctly identify the critical failure scenario that produces the highest PAR or, at least, a scenario that clearly identifies FIR.

- Dam failure mode
    - The feasible dam failure mode considers both the failure mechanism and location of the failure on the dam structure.
    - The location(s) of the failure reflects the location(s) of potential PAR.
    - Figure 1 in Section 2.3 provides examples of how to identify feasible dam failure modes.
- Flood event
    - The specific flood event upon which the dam failure event hydrograph will be superimposed considers the locations and levels (plinths) of potential PAR.
    - The temporal and spatial distribution of rainfall and runoff, including influences from both upstream and downstream, are considered when assessing the flood event.
    - As described in Section 2.4.3, the critical flood event for a given dwelling will cause peak flood levels that just reach the plinth level.

Section 2.4.5 provides further discussion on how to identify PAR from the flood assessment outputs.

A sufficient number of failure scenarios need to be assessed to demonstrate that the critical scenario with the highest PAR has been identified.

As a guide to scoping the number of failure scenarios it is recommended that potential PAR locations in the failure impact zone are initially identified. This will then inform the identification of feasible dam failure modes and flood events that could inundate these locations. The influence of downstream tributaries and catchments upon the flood event should be considered.

For situations where a large PAR (well in excess of 100) and subsequent assignment of FIR is obvious from only one scenario it may not be necessary to analyse a large number of flood events or collect extensive plinth level data for the FIA.

2.4.3 Critical flood event

No-failure flooding is flooding that occurs without a dam failure event. It includes runoff from the catchment upstream of the dam (including spillway outflows and gate operations) as well as runoff from the downstream catchment and any tributaries.

The critical flood event is the no-failure flood which, when combined with the dam failure event, causes the highest consequence.

How the critical flood event is identified will depend upon the particulars of the FIA. The following steps are recommended as a rough guide to identifying the critical flood event.

Table 8 : Steps to identify critical flood event

ID	Step	Description
1	Estimate downstream impact area (failure impact zone)	This helps to identify the list of places of occupation that may be subject to consequence in the event of a dam failure. If available, the PMF extent is a reasonable first pass description of the maximum extents of the failure impact zone.
2	Assemble information on places of occupation	Key information includes the number of places of occupation, their location and the minimum and maximum plinth levels. If there are multiple places of occupation, assemble key information for identifiable clusters (for example, a particular township may be identifiable as being in a specific geographical location and relatively consistent plinth levels).
3	Consideration of downstream catchment and tributaries?	As illustrated in Figure 3, there are situations where flooding at a particular location can be caused by one or more inflows from upstream, tributaries and local catchments. Situations like this may need to be considered, especially if an event is identified that extends the failure impact zone further downstream. Note that the key feature of the critical flood event is flood level relative to plinth levels at places of occupation; subtleties such as timings of tributary inflows, likelihood of rainfall events between sub-catchments, etc may not be relevant.
4	Quick initial assessment	A simplified analysis method (see **Appendix 7** for example) can be considered to provide a quick initial assessment of candidate flood events. If the simplified analysis accuracy is considered acceptable, no further analyses may be necessary.

ID	Step	Description
5	Are there multiple places of occupation?	For multiple places of occupation, with a range of plinth levels, identifying the critical flood event requires a range of flood events to be analysed. Applicable no-failure flood events are those that produce flood levels between the lowest plinth level and the minimum of the highest plinth level and the PMF. The number of applicable flood events will depend upon the number of places of occupation, their geographic spread and the range between minimum and maximum plinth levels. For example, a series of design flood events could be the 'bank full', the 2%, 1%, 0.2%, 0.05% AEP and PMF events. However, as illustrated in Figure 4, if the lowest plinth level is close to the 1% AEP flood level then it is unlikely that the "bank full' event would need to be considered.
6	Are there only a few places of occupation?	For situations with only a few places of occupation a series of discrete flood events can be generated by scaling specific design events so that no-failure flood levels are at or just below the plinth.
7	Are there critical cases to be investigated more carefully?	Potential PAR that, if confirmed as PAR, would result in a dam becoming regulated or being assigned a specific consequence category, may justify more detailed analysis. Also, potential PAR in critical locations such as immediately downstream of the dam or close to the main river channel may justify a more detailed analysis. See step 6.
8	Validate analyses	In all cases, validation of analyses is recommended (see **Appendix 7**).

Figure 3: Example of a situation where significant flooding arises from downstream catchments including tributaries

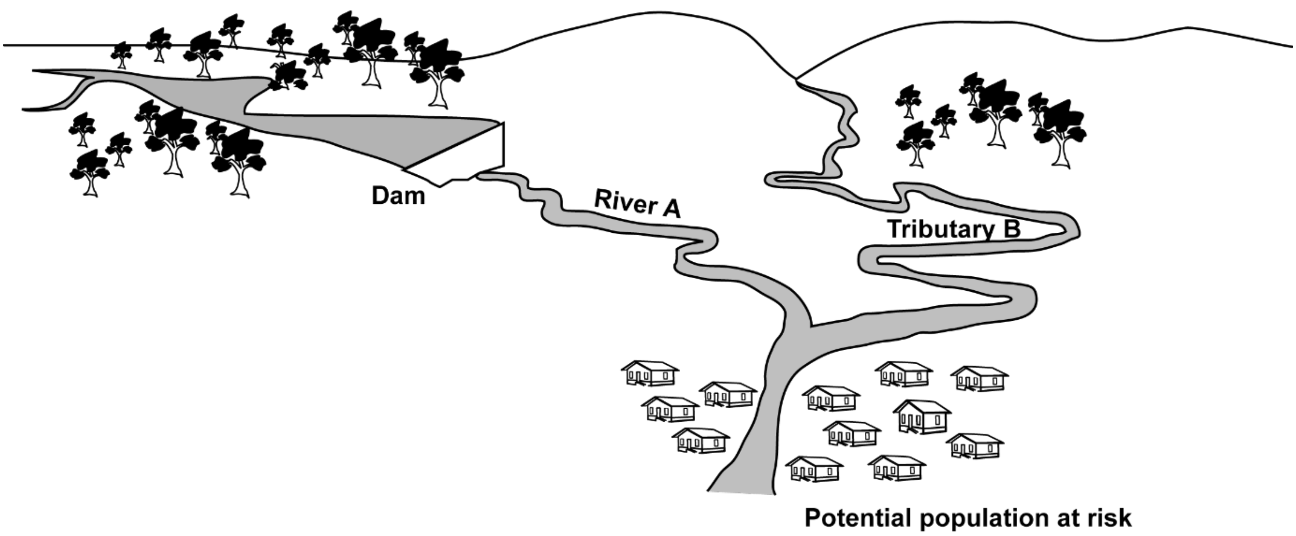
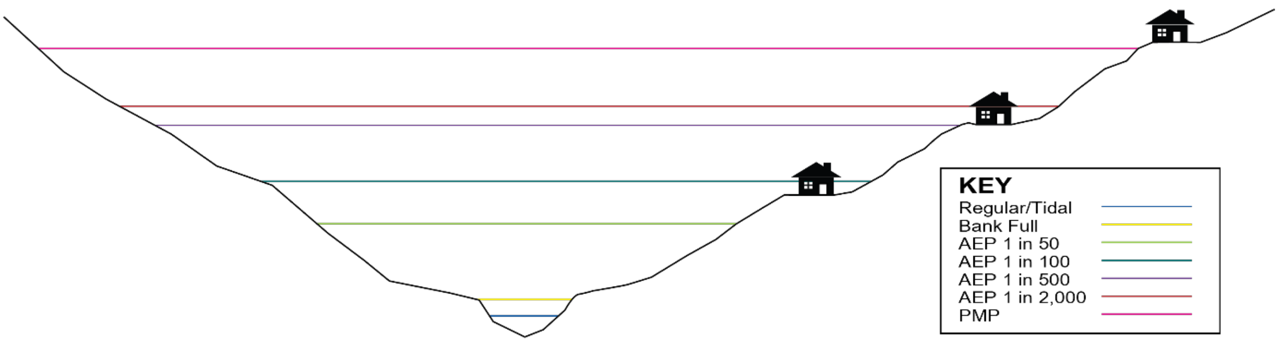


Figure 4: Example of a range of flood events to be considered for failure scenarios



2.4.4 Flow analysis

Flow analysis of both no failure and dam failure floods are required to assess consequence.

Appendix 7 provides background information relating to methods of hydraulic analysis, including a simplified analysis method and advice on more comprehensive analysis using hydraulic / hydrodynamic modelling.

2.4.5 Assessment of PAR

2.4.5.1 PAR analysis methodology

People are considered to be part of the dam failure PAR if they:

- Are not excluded under the legislative definitions of PAR (Section 2.4.5.4).
- Occupy buildings or other places of occupation that lie within the failure impact zone (Section 2.4.5.3).
- During a no-failure flood event they are not inundated by water exceeding the depth thresholds of 300mm.
- During the dam failure event, which is the no-failure flood event with the dam failure hydrograph superimposed, they are inundated by water exceeding 300mm and the difference in flood depths is greater than 300mm.
- For the comprehensive assessment there may be an additional exclusion for dam failure event depths between 300mm and 500mm and a flood hazard (depth x velocity) lower than $0.4m^2/s$.
- Road users can also be assessed as part of PAR (see **Appendix 11**), but this is not mandatory.

This methodology is captured in Table 9. A discussion on the assignment of threshold depths and velocities applied in this table is provided in **Appendix 10**.

The broader methodology, which takes the iterative nature of the assessment between dam failure scenarios and the identification of places of occupation into account, is summarised in Table 10. **Appendix 9** provides flowcharts illustrating the same methodology for both the simplified approach and the comprehensive approach. Also provided is the methodology logic and the corresponding Excel formula (which can be pasted into Excel and applied).

Table 9: Failure impact thresholds for determination of PAR

	Depth (D) over the building's plinth (mm)		Total depth (D) x velocity (V) of flow (m^2/s)	Population at risk
	No failure flood	Dam failure flood	Dam failure flood	(yes/no)
All assessments	D ≥ 300 mm			No
	Difference in depths < 300 mm		Irrespective of DV	No
Simplified assessment		D ≥ 300 mm	DV not considered	Yes
Comprehensive assessment		300 mm ≤ D < 500 mm	DV < 0.4 m^2/s	No
		300 mm ≤ D < 500 mm	DV ≥ 0.4 m^2/s	Yes
		D ≥ 500 mm	DV not considered	Yes

Table 10: Procedure for assessment of PAR

Step	Description
1	Identify relevant places of occupation in the failure impact zone, with plinth levels (d_{PLINTH}). • Flow analysis (**Appendix 7**) identifies the failure impact zone within which the number, location and nature of places of occupation are identified. • Plinth levels (d_{PLINTH}) of places of occupation are determined (or estimated if conducting a preliminary assessment). • Section 2.4.3 describes approaches when a densely populated failure impact zone is being investigated.
2	Allocate populations for each place of occupation (P_{OCC}). • Default populations for a variety of building types are provided in **Appendix 4.**[5] o This list is not exhaustive and some judgement maybe required for other building types. o The types of buildings in the failure impact zone can be determined initially through online searches. • In most cases, assumptions on building occupancy rates will need to be verified with a site inspection (see Section 2.2.3). • The written assessment must state the nature of the site and justify the populations used for those places of occupation not listed in the default populations.
3	From the flooding assessment, extract maximum flood depths at each place of occupation for each flood scenario. This assessment should incorporate flow analysis for a range of flood events with and without dam failure scenarios, including subsequent output analysis. The depth velocity product may also need to be considered for comprehensive analyses For each place of occupation and flood scenario with and without dam failure, extract the following: • the no-failure flood event which, at a given location, has a water depth d_{NF} • the dam failure flood event which, at a given location, has a water depth d_F • the dam failure flood event which, at a given location, has a velocity V and hazard dV (= d_F x V)
4	PAR is determined by stepping through each place of occupation and each flood scenario. • Table 9. • Alternatively, **Appendix 9** provides flowchart, logic diagram and Excel formula.
5	Repeat steps 3 and 4 for each place of occupation to accumulate PAR for a specific flooding event and dam failure scenario.

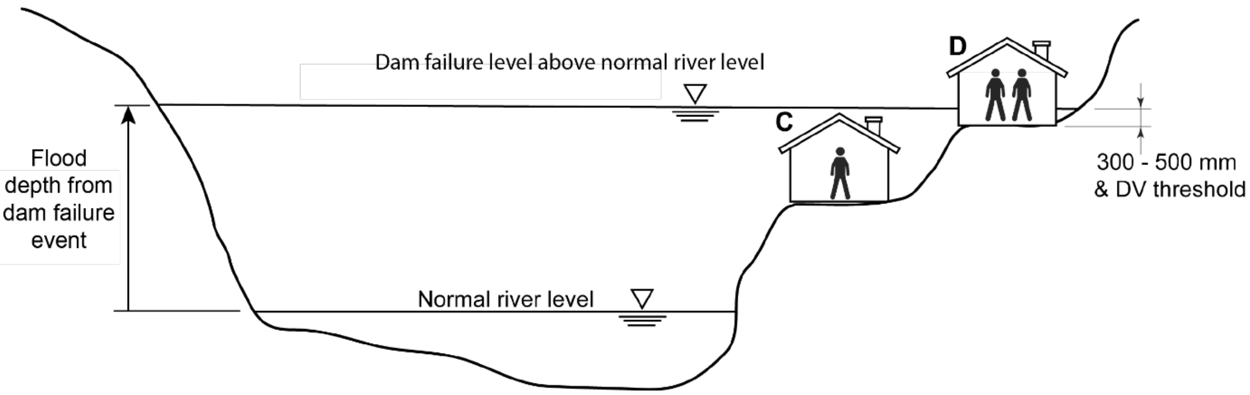
[5] It is recognised that PAR may vary according to the time of day, day of week and season. Under specific circumstances, such as for distinguishing between category 1 and category 2 FIR, the RPEQ may consider a more detailed investigation of default populations and exposure fractions. Otherwise, the values provided in Appendix 4 should be used.

Step	Description
6	Repeat steps 3 to 5 for all identified flooding events and dam failure scenarios. The highest PAR value from each iteration of event/scenario is then defined as the dam failure PAR.
7	Document the highest PAR (PAR_{MAX}) and identify the critical flood event and dam failure scenario that generates this PAR.

2.4.5.2 Examples of calculation of PAR

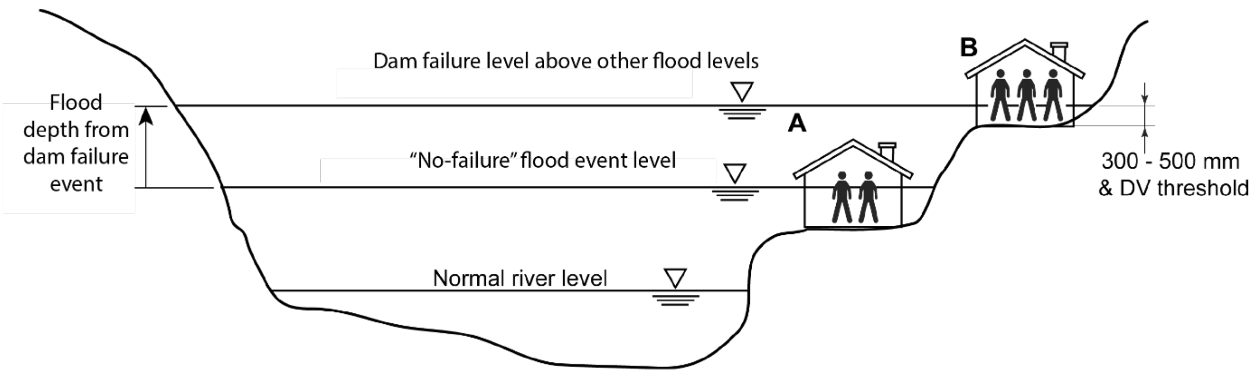
Scenario	Description
Sunny day dam failure	3 people residing in houses C and D are at risk from a dam failure for a sunny day failure event. This is an event where flooding is due to dam failure only. If modelling suggests the failure impact thresholds given in Table 9 are exceeded for both houses, the PAR is therefore 6 people. This is because there is nobody at risk from no-failure flooding (normal river level). **PAR = 3**

Figure 5: Example illustrating PAR for a sunny day dam failure



Scenario	Description
Flood failure scenario	5 people residing in houses A and B are at risk from flooding; the failure impact thresholds in Table 9 have been exceeded. For a specific no-failure flood event, House A is inundated by flooding over the 300mm threshold. For the same flood event with a dam failure, both House A and B are inundated. House A is not included in the PAR calculation and House B is. **PAR = 3.**

Figure 6: Example illustrating PAR for a dam failure during a flood event



2.4.5.3 Determining plinth level at a building/place of occupation

The failure impact threshold for a given flood event should be measured from the plinth level of a place of occupation. The plinth level is generally taken to be the level where the footing of the building meets the natural ground level. This definition has been adopted to account for people wishing to escape from buildings during flood events.

A different level may be applied if clarified and justified. Examples where a different level could be justified include:

- A house on sloping land.
- Where there is an excavated, habitable area below the natural ground level, for example, a basement.
- A house on stilts, with no habitable area below, where velocities will not affect the structural integrity of the house.
  - The Australian Emergency Management Handbook advises that the risk of failure for residential buildings increases above flood depths and velocities exceeding 1m and 1m/s (Australian Emergency Management Institute and Australian Government Attorney-General's Department 2014).
  - For velocities exceeding 2m/s, consideration should be given to the stability of foundations and poles of the buildings and if they can be affected by scour.

Similarly, floodwaters passing between and around buildings can produce zones of higher velocity that may exceed the average velocity. These areas should be critically examined, especially if the adoption of higher plinth elevations, for example to habitable floor levels, is being considered in the assessment.

Examples of plinth levels for common scenarios are shown in the following figures.

Figure 7: Flood depth taken from plinth level

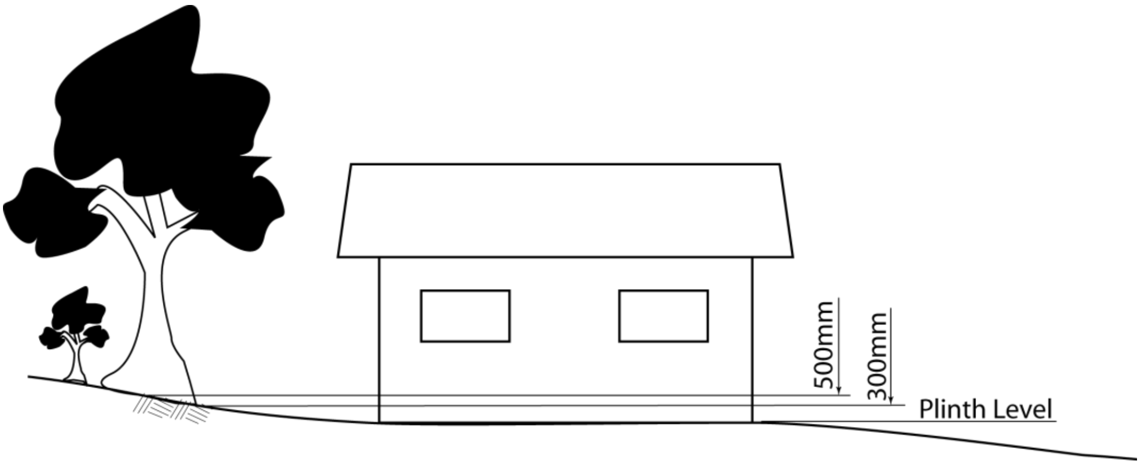


Figure 8: An example of plinth level for a place of occupation on sloping land

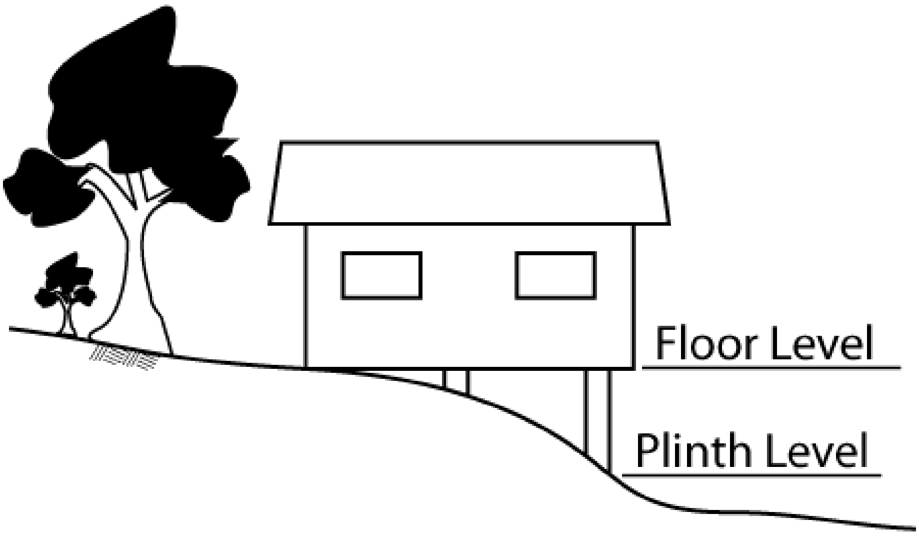
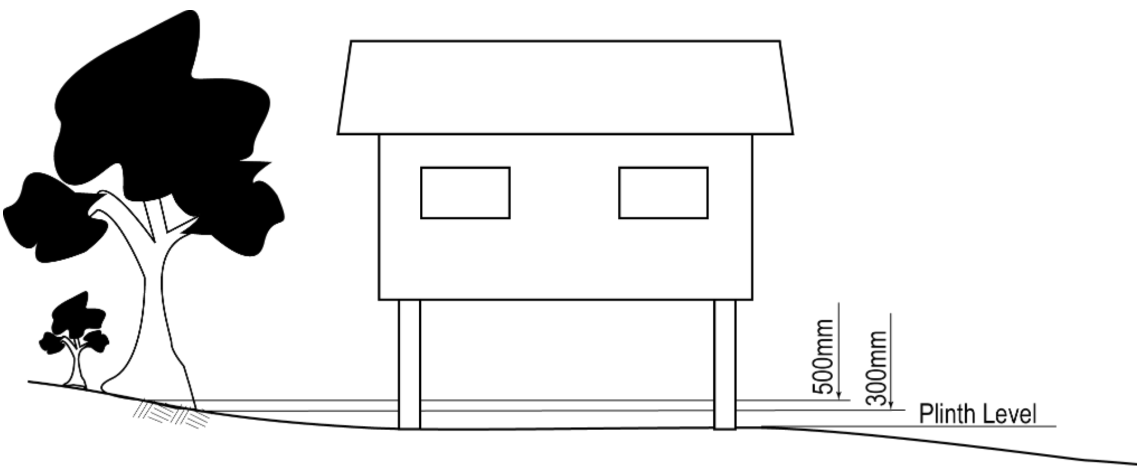


Figure 9: Example of plinth level for a place of occupation on stilts



2.4.5.4 Population excluded when determining PAR for failure impact rating

Table 11 lists exclusions to consider when calculating PAR for failure impact rating. Evidence and justification is required for any exclusions and, where unclear, a conservative approach is recommended.

RPEQ certification requirements (see **Appendix 3**) extend to the validity of any excluded PAR.

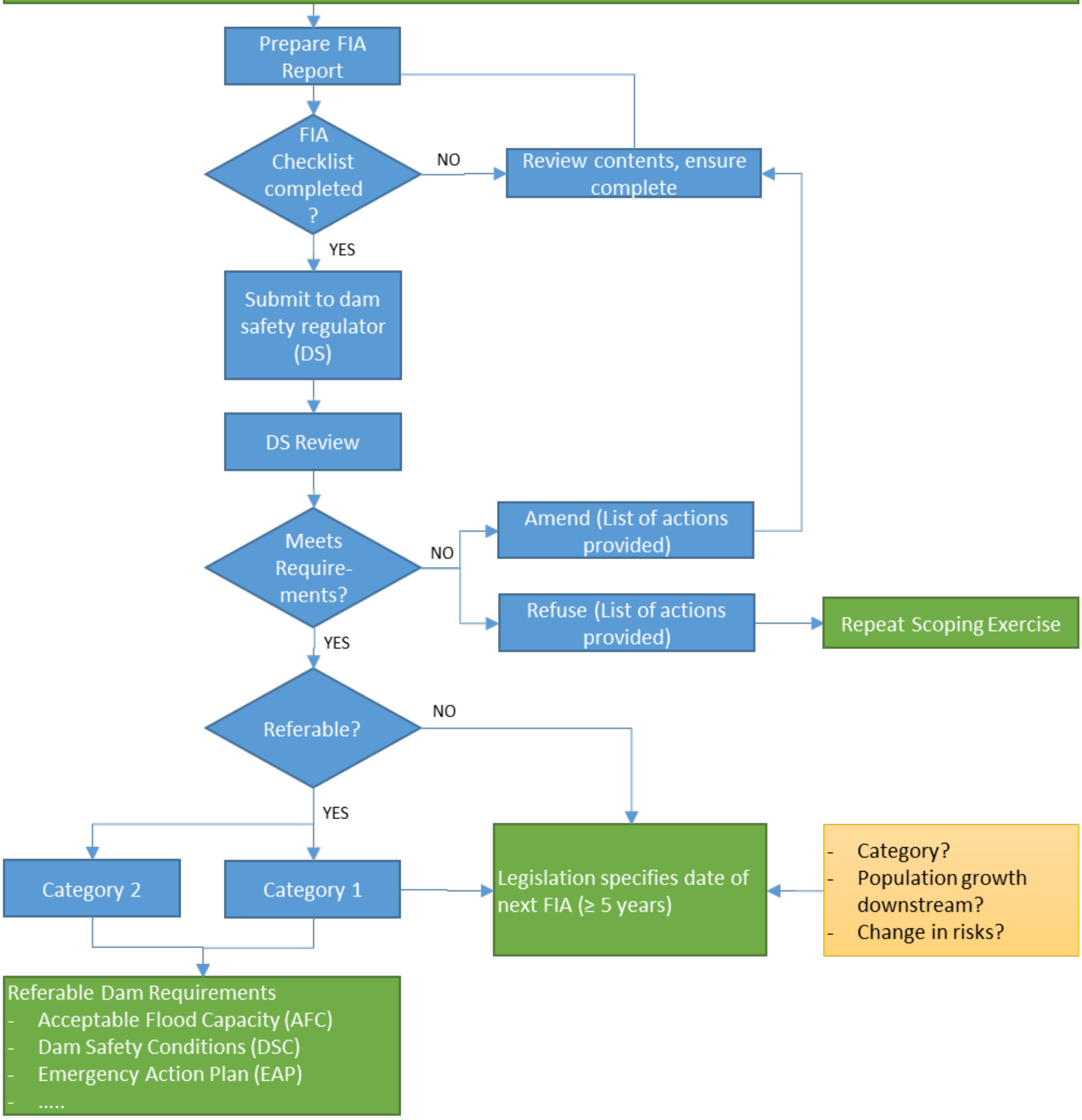
Table 11: Exclusions to PAR calculation

Exclusion	Description
A person at the workplace, if the dam is situated at a workplace under the *Work Health and Safety Act 2011*.	Populations are excluded from PAR calculation when they are situated on a workplace within a lot on which the dam is situated. The *Work Health and Safety Act* defines a workplace: • A workplace is a place where work is carried out for a business or undertaking and includes any place where a worker goes, or is likely to be, while at work.
A resident on the same parcel of land on which the dam is situated.	Although "parcel" is not defined in the Act for the purposes of the "resident" exclusion, the chief executive regards the following residents as excluded PAR: • Residents on one or more registered plan lots on which the dam is situated; that is, the dam is located on more than one lot. • Residents on a lot on which a dam is situated where the lot is split by a road, provided the lot is owned by the dam owner. Itinerant road users in this scenario may however be considered to be PAR in particular circumstances (see **Appendix 11**). The chief executive does not interpret this excluded PAR category as extending to residents on a lot or lots adjacent to the lot on which the dam is situated, regardless of ownership of those adjacent lots.
A person at a mine	The mining PAR exclusion calls up the definitions of *"mine"* and *"coal mine"* under the relevant mining legislation (the *Mining and Quarrying Safety and Health Act 1999)* if the dam is situated at a place that is a mine. Mining tenure information is available online. Visit www.business.qld.gov.au and search for 'online services for mining and resources'
A person at a coal mine	The coal mine PAR exclusion applies if the dam is situated at a place that is a coal mine under the *Coal Mining Safety and Health Act 1999.*

2.5 FIA Submission

FIA Submission

Submission to the regulator and, if criteria are satisfied, the dam becoming referable and regulated under the provisions of the Act. The failure impact rating assigned to a referable dam (none, category 1 or category 2) assists the chief executive in setting safety conditions appropriate for each dam and the timing for further FIAs.



2.5.1 FIA report

The final stage of the FIA process is to prepare the report. A suggested list of subheadings and inclusions for the assessment is provided in **Appendix 2**.

While it is not expected that the report will exhaustively cover every step of the analysis, it should provide enough information to allow the chief executive to assess the process critically along with any assumptions made. A clearly written assessment, incorporating an appropriate level of detail, will enable the chief executive to make an informed decision whether to accept, require a review of, or reject the assessment.

DNRME is willing to respond to any questions and provide clarification on the FIA process if required.

2.5.2 FIA Report Checklist

Appendix 1 provides a checklist to be completed prior to submission of an FIA. The FIA submission should consider attaching this checklist to the FIA Report.

Appendix 2 provides a heading structure and checklist of items that need to be included in the FIA report. The RPEQ should use their own engineering judgement to decide what to include in the report. However, the report should contain sufficient information for the chief executive to be able to thoroughly review the document and make a decision.

Note that the RPEQ must provide a statement of certification as per the template in **Appendix 3**.

2.5.3 Submission

An FIA must be submitted to the chief executive for acceptance. When accepted by the chief executive and a PAR of two or more people has been identified, this will then determine the failure impact rating for the dam (see Table 2).

The requirements of the Act for dams found to be referable include the application of dam safety conditions and the preparation of an emergency action plan (see Section 2.5.5).

2.5.4 Regulator Review

Once the FIA has been submitted, the chief executive will assess the document. The chief executive will either accept, require a review or reject the FIA:

Table 12: FIA review outcomes

<table>
<tr><th>Decision</th><th colspan="2">Outcome</th></tr>
<tr><td rowspan="5">Accept</td><td colspan="2">A notice accepting the FIA will be issued by the chief executive within 30 business days after acceptance of the FIA.

A failure impact rating is assigned according to dam failure PAR. The failure impact rating assigned to a referable dam assists the chief executive in setting safety conditions appropriate for each dam and the timing for further FIAs.

The failure impact ratings (determined from dam failure PAR) are:</td></tr>
<tr><td>• PAR < 2</td><td>No failure impact rating – Dam is not referable</td></tr>
<tr><td>• 2 ≤ PAR ≤ 100</td><td>Referable dam, Category 1 failure impact rating</td></tr>
<tr><td>• PAR > 100</td><td>Referable dam, Category 2 failure impact rating</td></tr>
<tr><td colspan="2">Unless the dam is accepted as Category 2 the notice will also state the date for the next FIA to be submitted (at least 5 years from day of acceptance).

If the dam is accepted as referable (Category 1 or 2) there will be a requirement to prepare an emergency action plan (EAP, see next section). Dam safety conditions may also be applied (see also next section).</td></tr>
<tr><td>Reject or review</td><td colspan="2">The chief executive may reject or require a review of a submitted FIA if the assessment is:

• Not completed in accordance with this guideline – the checklists in Appendix 1 and Appendix 2 have been compiled to help ensure the guidelines are followed.
• Not certified by an independent RPEQ in accordance with Appendix 3 of these Guidelines.
• Incomplete; for example, insufficient analysis was undertaken to adequately determine the PAR.
• Incorrect; for example, the type of assessment or the background data adopted was inappropriate or inconsistent in context.

Before requiring a review or rejecting an FIA, the chief executive may require the dam owner to provide additional information. This is to assist the chief executive in deciding if a review or rejection is necessary.

If a review or rejection notice is given, a list of actions will be provided to the dam owner and a resubmission of the FIA will be requested. The dam owner must amend the assessment in accordance with the guideline, addressing the reasons for the review or rejection and ensure it is recertified prior to submission.</td></tr>
</table>

2.5.4.1 Appealing the chief executive's decision

If the chief executive requires a review of, or rejects, an FIA, a dam owner may apply to the chief executive for an internal review of the decision. The dam owner will be notified of the outcome of the review. If the dam owner is still not satisfied, the provisions of the Act allow the dam owner to appeal against the review decision in the Planning and Environment Court (see Chapter 7 of the Act).

2.5.5 Consequences of a dam becoming referable

2.5.5.1 Dam safety conditions

Once an FIA is accepted for an existing dam, and the dam is referable, the chief executive may apply dam safety conditions.

Dam safety conditions require the dam owner to establish a dam safety management program and govern how the dam is to be managed. This includes requirements set for documentation, reporting and inspections. The purpose of this program is to manage the risk of dam failure by ensuring the dam is appropriately operated and maintained.

Conditions for dams may vary according to the type of dam and the specific circumstances of that dam. Safety conditions can also be applied or amended by the chief executive at any time after the dam has been built.

Once an FIA is accepted for a proposed dam, and the dam is referable, application must be made under the *Planning Act 2016* for a development permit to construct the dam. Safety conditions would normally be attached to any development permit issued for a referable dam.

The chief executive recognises that the consequences of a failure for some referable dams may be lower than others. Consequence categories are therefore an optional consideration to make a case for reducing the number of dam safety conditions in recognition of the lower risk. This may reduce the level of ongoing expense a dam owner incurs in satisfying the conditions. If it appears the dam may have a 'low' or 'very low' consequence category, the dam owner, in consultation with the certifying RPEQ, can collect additional information to justify the category.

Consequence categories can be determined using either population at risk (PAR) or probable loss of life (PLL). There are several recognised methods for assessing the potential risk to life of dam failures:

- Reclamation Consequence Estimating Methodology (RCEM) (supersedes Graham, 1999 DSO-99-06)
- UK RARS for small dams and retarding basins
- HEC-LifeSim – Utah State University and USACE
- HEC-FIA (simplified LifeSim) – USACE
- Life Safety Model (LSM) – BCHydro and HR Wallingford

Further information on consequence categories can be found in the Guidelines on acceptable flood capacity for water dams (DNRME, 2017b). The ANCOLD Guidelines on the Consequence Categories for Dams (October 2012) also provide information on this topic.

2.5.5.2 Emergency action plans (EAP)

An EAP is a practical document that outlines what actions to take in the event of an incident, including who to notify and where to evacuate. It incorporates potential dam hazards or emergency events and actions to take in response, including identified stakeholders and communications protocols. The EAP requires consideration of emergency events in the context of community disaster management process.

If a Category 1 or 2 dam is accepted by the chief executive, the dam owner will be required under the provisions of the Act to submit an emergency action plan (EAP) for their dam for approval by the chief executive.

If construction of the dam is not finished when the FIA is accepted, the EAP must be submitted to the chief executive for approval within 3 months after construction is completed or at such earlier time as notified to the owner by the chief executive (that earlier time must be at least 30 business days as stated in the notice). If construction has been completed when the FIA is accepted, the EAP must be submitted within 4 months after acceptance.

There may be some areas of overlap between EAPs and the FIAs, for example, modelling requirements and inundation maps. If it appears the dam may become referable it may be cost efficient to prepare the EAP at the same time as the FIA.

Note that flood inundation mapping generated for FIA assessment may not necessarily be appropriate for EAP dam failure inundation mapping. Total PAR, as opposed to dam failure PAR, is considered for EAPs.

The current EAP guideline (DNRME, 2017a) is available on the DNRME website.

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Appendix 1 FIA Submission Quality Statement

This appendix provides a quality statement checklist to be filled in prior to submission of an FIA. The below quality statement should be considered for attachment to the submitted FIA Report.

Quality Statement
☐ **The report has been finalised as per checklist in Appendix 2 of the FIA Guideline.**
☐ **A literature review has been performed to ensure that all relevant and available information has been considered in this FIA.**
☐ **Data used to conduct the FIA is appropriate.**
☐ **The report and analysis have been subject to quality assurance checks and evidence is attached.**
☐ **Any areas of uncertainty have been clarified with DNRME.**
☐ **The FIA report provides sufficient documentation of analyses and findings to enable the chief executive to reach a decision.**
☐ **A statement of certification submitted by the RPEQ as per the template in Appendix 3 is attached to the submission.**
☐ **A site inspection was conducted by an RPEQ (or a representative of the RPEQ).**

Appendix 2 FIA Report Contents Checklist

This appendix provides a checklist recommended for inclusion in an FIA for suggested structure for an FIA report and a checklist of key facts and analysis outputs recommended for inclusion.

The RPEQ should use their own engineering judgement to decide what to include in the report. However, the report should contain sufficient information for the chief executive to be able to thoroughly review the document and make a decision.

A statement of certification must be submitted by an RPEQ as per the template in **Appendix 3**.

Section	Checklist
Executive Summary	A summary of the FIA, with emphasis on key details and outcomes: ☐ Dam name, location and owner ☐ Dam features ☐ Overview of analyses ☐ PAR (for both sunny day failure and flood failure) ☐ Brief description of the critical failure scenario producing the highest PAR ☐ The recommended FIA category for the dam
Introduction	☐ Introduction to the document, considering purpose, legislative context, scope, report structure, QA processes adopted, etc
Characteristics	**General** ☐ Name of dam ☐ Referable Dam number (if known) ☐ Location (lat/long) of dam ☐ Owner of dam (individual or company) with contact details (including primary contact) ☐ Status of dam (existing or proposed) ☐ Property description of land on which the dam is located (include lot and plan number, etc) ☐ Date of construction ☐ Date of previous submissions and acceptances of FIAs to the chief executive ☐ Name of independent Registered Professional Engineer and RPEQ number **Geography** ☐ Catchment area (include subcatchments as appropriate) ☐ Catchment description considering terrain, land use, land cover, etc. ☐ Names of water features (rivers, creeks, lakes, etc) ☐ Definition of middle thread distance (AMTD, km) **Dam description** ☐ Type (homogenous earthfill dam, zoned earth and rockfill dam, concrete dam, etc)

Section	Checklist
	☐ Height (referenced to absolute datum and also to natural bed at the downstream toe or, if the dam is not across a watercourse, between the lowest elevation of the outside limit of the dam and the top of the dam) ☐ Length from end of left abutment to end of right abutment) ☐ Description of spillway ☐ Details and description of other dam components (saddle dams, etc) ☐ Purpose of storage (water supply for potable use, irrigation, etc) ☐ Dam storage capacity to full supply level (in megalitres) ☐ Dam surface area at full supply level ☐ Spillway rating curve ☐ Storage capacity curve
Data	**General** ☐ Summary of data ☐ Statement of accuracy and appropriateness **Literature Review** ☐ Summary of relevant documentation, research, information, observations etc **Site Inspection** ☐ Date of site inspection ☐ RPEQ attending site inspection ☐ Map showing places of occupation and features inspected
Dam failure scenarios	☐ Analysis techniques used, with justification ☐ Sunny day failure modes identified ☐ Flood failure modes identified ☐ Details of dam failure analyses (dimensions, volume removed, timing, etc) ☐ Sensitivity testing ☐ Details of dam failure hydrographs
Flooding Assessment	**Hydrology and Hydraulics** ☐ Hydrologic technique used and justification for use ☐ Hydraulic technique used and justification for use ☐ Description of model / analysis build ☐ Description of parameters and initial/boundary conditions ☐ Validation (calibration, verification, sensitivity testing) ☐ Appropriateness of data ☐ Statement of accuracy and sensitivity **Failure impact zone** ☐ Map of failure impact zone ☐ Identification and description of all potential PAR considered (including plinth levels) ☐ Demonstration that analysis approach / model extent is sufficient to capture all PAR within failure impact zone

Section	Checklist
	Failure scenarios ☐ Description of flood events considered ☐ Description of failure scenarios **Assessment of PAR** ☐ Description of any PAR exclusions ☐ Description of PAR assessment methodology ☐ Description of the critical failure scenario producing PAR (both sunny day failure and flood failure) ☐ Statement of PAR and recommended failure impact rating
Conclusions and recommendations	☐ PAR ☐ Recommendations for failure impact rating ☐ Justification of any assumptions, or the use of alternative methodologies to those presented in this guideline
Appendices	**FIA Quality Statement Checklist** ☐ Attach FIA Submission Quality Statement Checklist (**Appendix 1**) **RPEQ Statement** ☐ Signed RPEQ certification, see **Appendix 3** for template **Quality Statement** ☐ Details demonstrating compliance to relevant quality assurance requirements adopted to prepare the FIA **Flood maps** ☐ Failure impact zone maps for critical failure events, showing inundation extent, PAR, nearby places of occupation / key infrastructure and (where appropriate) peak water depth, velocity, DV and time to peak ☐ Maps to include map number, scale, map date and height accuracy ☐ Maps to include topographic and/or aerial or satellite imagery ☐ Consider submitting digital copies of flood map layers for example, shape or kml files **Hydrology and Hydraulic Analysis (supporting contents of main report)** ☐ Time series of hyetographs, hydrographs, water levels, etc (boundary conditions) ☐ Maps of model features, computational grids, roughness parameters, catchment definitions, etc ☐ Details of any structures ☐ Detailed validation outputs **Other (supporting contents of main report)** ☐ Any other information to support the findings in the main report

Appendix 3 Template for RPEQ certification of the FIA

This dam failure impact assessment was prepared by ***<u>Company</u>*** Pty Ltd and certified by ***<u>Name</u>***

As at the <insert day of month, year> the certifier states the following:

- That the failure impact assessment (FIA) has been prepared in accordance with the Guideline for failure impact assessment of water dams (DNRME, 2018) and that it is not based on information that I know is false or misleading;
- That I am not the owner, an employee of the owner, the operator, or an employee of the operator of the dam being assessed;
- That I am satisfied that the inspection of the site has accounted for sufficient points of impact, covering the failure impact zone as a minimum, to justify the failure impact rating.
- That the information and analyses included in the assessment are appropriate and sufficiently accurate, and that the assessment has been made from these;
- That the FIA is a reasonable estimate of the population at risk for the purpose of the FIA and that the estimate is consistent with:
    - The detail and accuracy of the modelling used; and
    - The extent of the failure impact zone.

Signature

Name (RPEQ registration number)
on behalf of *Company* Pty Ltd
Postal address
Contact number(s)
Email address

Appendix 4 Default populations

Nature of building or other place of occupation	Equivalent population
Detached housing [1, 2]	2.8 per house
Semi-detached, row or terrace housing, townhouse [1]	2.0 per house
Flat, unit or apartment [1]	1.8 per unit or flat
House or flat attached to a shop, office, etc. [1, 2]	2.5 per house or flat
Approved caravan parks [1, 2, 21, 22]	1.6 per caravan site
Approved camping grounds [3, 21]	0.73 per camping site
Hotel/motel accommodation [4]	1.0 per bedroom
Child care centres [5]	0.4 per child and staff member
Kindergartens, pre-schools [6]	0.3 per student and staff member
Primary schools (day) [6]	0.3 per student and staff member
High schools (day) [6]	0.3 per student and staff member
Tertiary education centres [7]	
Lectures—day	0.35 per student and staff member attending during the day
Lectures—evening	0.15 per student and staff member attending during the night
Medical centres [8]	1.7 per member of staff
Hospitals [9]	1.0 per bed plus 0.33 times the total number of staff
Institutional accommodation [10]	1.0 per bed plus 0.33 times the total number of staff
Sport/community centres [11]	5.25 times the total number of staff
Aged care [12]	1.0 per bed plus 0.33 times the total number of staff
Places of worship [13]	0.075 per member of staff and patron
Entertainment centres [14]	0.06 times total number of seats plus 1 for the permanent onsite staff.
Restaurants [15]	0.3 per member of staff and diners' places
Tavern/hotel bars [16]	0.17 per m^2 of patrons' area
Offices [17]	0.4 per employee

Nature of building or other place of occupation	Equivalent population
Shops, shopping centres [18]	2.0 per 100 m^2 of gross area
Service stations [19]	0.4 times the total number of staff
Airport [20]	0.06 per passenger plus 0.33 times the total number of staff
Mines	Total of all personnel working in inundated area where the path to escape the inundation will be cutoff by the incoming flows.
Industrial buildings and other non-residential sites	0.4 times the total number of staff
Department of Transport and Main Roads moorings	2.0 per mooring

Notes:

1. The occupancies for these dwellings are derived from the overall Queensland figures for persons, by dwelling structure and occupied dwelling structures, by tenure type (private dwellings) in the 2016 census.
2. These values have decreased from the 1996 estimate based on the 2016 census.
3. This occupancy comes from an analysis of figures from January 2011 to June 2014 for the number of permits issued, the numbers of campers per permit and the duration of each permit from Queensland Government's data website. The average number of campers per permit was 3.0 and the average duration of each permit was 3 days. The average number of permit per site per year was 203. The previous average site occupancy rate of 14.5% was adopted again. Therefore an average occupancy value of 0.73 campers per site has been adopted.

   Calculation: 3 x 203 x 3 / 365 x 0.145 = 0.73
4. This occupancy assumes that a hotel/motel bedroom will typically accommodate two people, who will be present for half of any one day, and that number of staff will compensate for the fact that generally not all rooms will be (fully) occupied.
5. This occupancy is based on a typical 9.5 hour day (8:00-5:30).
6. These occupancies are based on a typical 7 hour day (8:30-3:30).
7. These occupancies are based on a typical 8 hour day (9:00-5:00) for day lectures and a typical 3 hour day (6:00-9:00) for evening lectures.
8. This occupancy is based on a 10 hour day (8:00-6:00) and assumes 3 patients at the location for each doctor and other staff member.
9. The occupancy rate of 1.0 per bed assumes that the number of visitors will compensate for the fact that generally not all beds will be occupied. The staff factor applies to the sum of the numbers of staff on different shifts, assuming all shifts are 8 hours.
10. These occupancies are identical to those for hospitals. It has been assumed that lower visitor numbers will offset the higher bed occupancy ratio for institutions.

11. This occupancy is based on a typical 12 hour day (7:00 am-7:00 pm), 6 hour shift and assuming 20 patrons at the location for each staff member.

    Calculation: 21 x 6 / 24 = 5.25

12. These occupancies are identical to those for hospitals. It has been assumed that lower visitor numbers will offset the higher bed occupancy ratio for aged care.

13. This occupancy is based on the following assumed patronage:

    a. full 9:00am—noon; 1:00 pm—4:00 pm (6 hours per day, 2 days per week)

    b. staff numbers are 5% of number of patrons

    Calculation: 6 x 2 x 1.05 / 24 / 7 = 0.075

14. This occupancy is based on the following assumed patronage:

    a. these venues will be predominately used only 3 times a week, 4 hours each time

    b. each performance will reach 80% of capacity

    c. staff numbers are 2% of number of patrons during performance hours (excluding the permanent staff onsite)

    d. 1 permanent staff member onsite 24/7.

    Calculation: (3 x 4) x 0.8 x 1.02 / (24 x 7) = 0.06

15. This occupancy is based on the following assumed patronage:

    a. 10% full—9:00 am—noon, 2:00 pm—6:30 pm

    b. full-noon—2:00 pm, 6:30 pm—10:30 pm

    c. staff numbers are 10% of number of places

    Calculation: (7.5 x 0.1 / 24 + 6 / 24) x 1.1 = 0.3

16. This occupancy is based on the following assumed breakdown of daily patronage with weekdays (5 days) and weekends (2 days) calculated differently:

    a. 10% of daily peak—4:00 pm—6:00 pm

    b. 30% of daily peak—4:00 pm—6:00 pm (weekend)

    c. 100% of daily peak—6:00 pm—10:00 pm

    d. 80% of daily peak—6:00 pm—10:00 pm (weekend)

    e. 30% of daily peak—10:00 pm—1:00 am

    f. 100% of daily peak—10:00 pm—1:00 am (weekend)

    The Bar Licences Guideline of the Liquor Act 1992 cited maximum density of patrons as 1.5/m^2 per person. The occupancy rate is therefore based on an assumed annual average for the daily peak patronage of 0.7/m^2 including a 10% allowance to cover staff.

17. This occupancy is based on a typical 9 hour day (8:30-5:30).

18. This occupancy rate is an estimate based on information from the former Appendix B of Volume 1 of the Guidelines for Planning and Design of Sewerage schemes (issued by Department of Natural Resources) which has now been superseded by the DNRME Planning Guidelines for Water Supply and Sewerage.

19. This occupancy rate applies to the sum of the numbers of staff on different shifts, assuming all shifts are 8 hours. It contains a 20% allowance to cover customers.

20. This occupancy rate of 0.06 per passenger assumes that each passenger will stay at the airport for 1.5 hours. The staff factor applies to the numbers of staff on different shifts,

assuming all shifts are 8 hours. The 2012 data from 93 regional airports in Australia indicated an average of 711 passengers per airport per day.

Calculation: 1.5 / 24 = 0.06; 8 / 24 = 0.33

21. Only camping areas and caravan parks approved by government agencies (local, state or federal) or included in local authority planning schemes should be included. Because of the difficulties associated with determining the number of sites, of non-approved camping grounds and caravan parks (and their permanence), they are excluded from assessment.
22. The 1996 census indicated 1.8 per caravan, so the previous version of the guideline used 1.8 per caravan site. The 2016 census indicated 1.6 per caravan, so assuming there is one caravan per site, 1.6 per caravan site has been adopted.

Appendix 5 Simplified breach analysis (Q_{BREACH} formula) for embankment dams

A simplified assessment is generally based on the calculation of dam breach flows from an empirical formula against the capacity of cross-sections at critical downstream locations. As this approach is deliberately conservative and quick it is useful as an initial indication of potential dam failure consequences before proceeding with a more comprehensive assessment.

This assessment is valid for embankment dams only.

For the simplified methodology the dam breach for a given dam water level can be determined with the following formula:

$$Q_{BREACH} = 0.53FV^{0.87}H^{0.38}$$

- F = 1.3; a factor to account for the simplified nature of the assessment
- V = total volume of water released (in megalitres), measured from the water level to the lowest likely failure level
- H = maximum depth of water in the storage (in metres), taken from the top of the embankment to the lowest likely failure level

The following advice applies to the simplified dam breach analysis:

- This empirical discharge relationship is based on the failure of a typical homogeneous earthfill embankment up to a certain size limit. Care should be taken when applying this relationship to:
  - other dam types (not earthfill)
  - embankments exceeding 12 m in height
  - embankments made up of non-cohesive materials, such as gravels or ash
- Any other discharges from the dam under normal operating arrangements need to be added to provide the total discharge that could impact downstream populations.
- The maximum spillway discharge does not always result in the highest PAR. It may be necessary to check dam failure PAR for a range of dam levels (i.e. dam inflows).

An example of the application of the Q_{BREACH} formula is provided in **Appendix 8**.

Appendix 6 Comprehensive dam failure analysis

Embankment dams

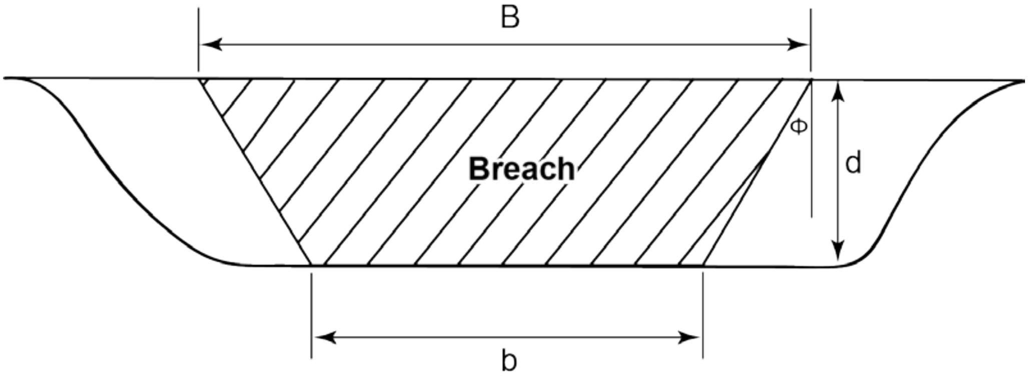
Table 13 describes a procedure (from Allen 1994) for determining breach flows from overtopping failures and sunny day failures of embankment dams. For piping failures it should be assumed that the breach is initiated at the level that produces the maximum discharge from the breach. Unless special provisions are made, overtopping failures should be assumed as soon as the embankment is overtopped.

In certain circumstances, it may be difficult to achieve realistic values for V_m, breach dimensions and breach ratios due to the nature of the empirical data behind this methodology. Examples of this include small dams or large volume dams with small embankment cross-section such as ring tanks. The RPEQ should use their engineering judgement to ensure that any breach dimensions and timings adopted are realistic and tested for sensitivity. The simplified breach formula in **Appendix 5** may be useful to provide an upper limit for these checks.

Several hydraulic modelling packages allow the modeller to input the breach properties calculated with this methodology. Alternatively, DNRME have an Excel based breaching spreadsheet which can be made available on request. It remains the responsibility of the certifying RPEQ to use their engineering judgement and ensure that any tools they adopt are performing as expected.

Table 13: Procedure for breach development for embankment dams

Step	Description
1	Calculate the Breach Formation Factor (BFF) for the assumed failure scenario: $BFF = V_w * h$ where: • V_w = Total volume of water to flow through the breach (megalitres) • h = Height differential between headwater and tailwater levels (metres)
2	Use Figure 11 to determine the volume of material expected to be removed during the formation of the breach, V_m (m^3).
3	Determine the size of the breach iteratively to correspond to the volume of material removed (V_m). The shape of the breach section removed is assumed to be trapezoidal (refer to figure below), with a top breach width (B), bottom breach width (b), breach depth (d) and side slopes (Φ). **Figure 10: Diagram showing key breach parameters**

Step	Description
	 If V_m is more than the volume of material available in the embankment, then it should be assumed that all the embankment is effectively removed and to replace V_m with this volume. The maximum extent of the breach should be assumed to extend to the maximum base width of the section. It is important to consider the channel geometry when calculating the breach size to ensure that the breach realistically fits within the cross-section.
4	Check to see that the breach size is within the following range of parameters[7] (dimensions in Figure 10): • breach side slope, ø, in the range 10˚ to 50˚ off vertical • 1.06 < B/b < 1.74 with a mean of 1.29 and a standard deviation of 0.18 • 0.84 < B/d < 10.93 with a mean of 3 and a standard deviation of 2.62
5	Use Figure 12 to determine the breach development time.
6	Simulate the dam breach event (in a model or analysis method, see Section 2.4) and examine the hydraulic conditions occurring in the breach throughout the discharge and qualitatively modify the parameters accordingly. For example, if the breach outflow is heavily affected by tailwater, increase the breach development time or reduce the size of the breach to reflect the reduced erosive capacity of the flow.
7	Conduct further sensitivity analysis on the adopted parameters as required with due regard to the composition of the embankment.

[7] Unless special circumstances prevail, such as a very high embankment being required to store a relatively small volume of water.

Figure 11: Outflow characteristics as a function of breach size

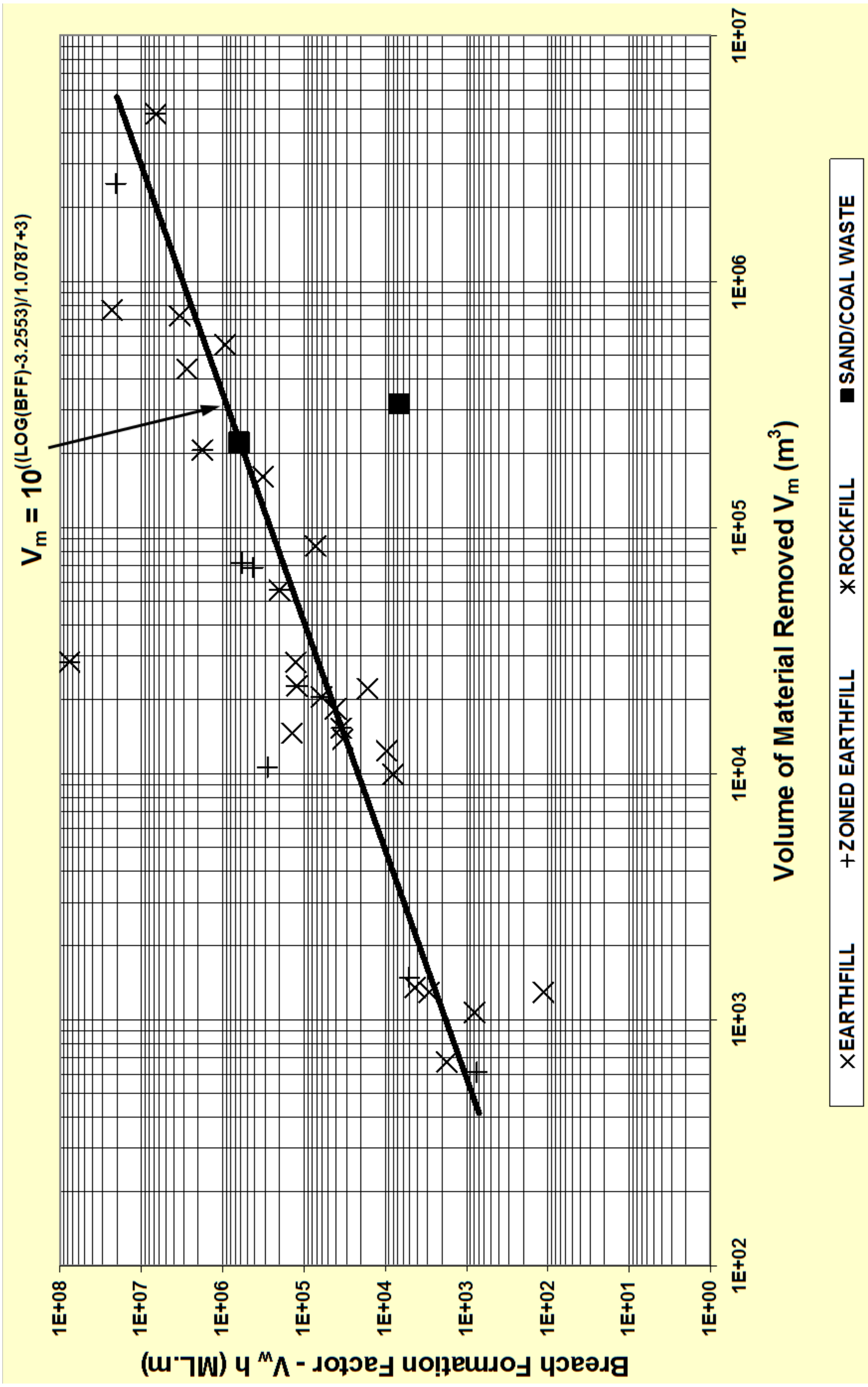
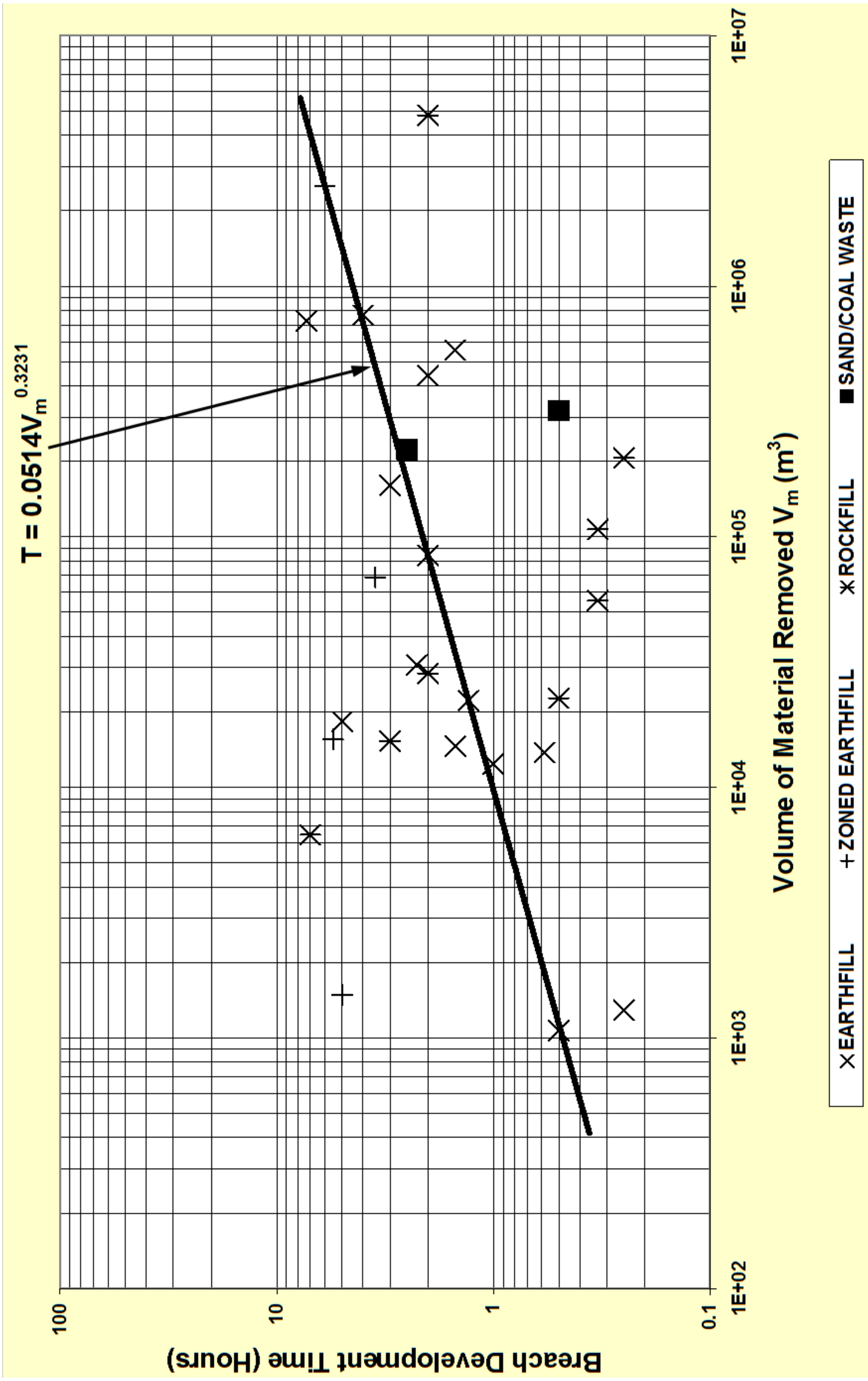


Figure 12: Breach development time as a function of material removed



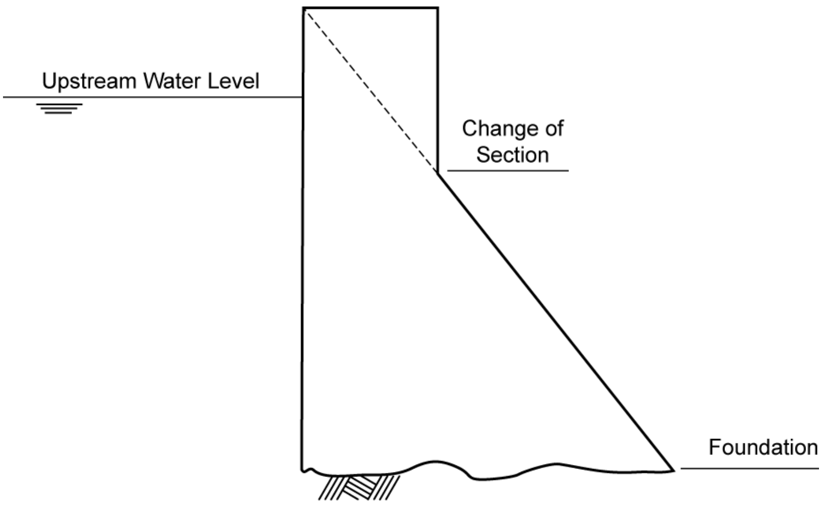
Concrete dams

Failure of concrete dams normally occurs with the sudden removal of a portion of the dam, or even all of it, from either a failure through the foundation of the dam, a structural failure through the concrete body of the dam, or toppling following toe erosion.

Concrete dams are typically designed to withstand overtopping from inflows, so there may be considerable uncertainty regarding which reservoir level will trigger a failure and how much of the dam will be removed from this failure. Mass gravity concrete structures are normally assumed to fail through either sliding in their foundations or along lift joint surfaces. Once a section of a monolith is removed it is generally assumed that the loss of lateral support will lead to similar losses of the adjacent monoliths.

Ideally a full analysis of a mass gravity structure would be performed to establish the most likely plane of failure. If unavailable, or for preliminary assessment, the procedure described in the following table can be applied.

Table 14: Procedure for break development of concrete dams

Step	Description
1	Determine the storage level at which failure is likely to occur.
2	If no design information is available, consider the removal of the: • top of the non-overflow section above the change of section and the dam foundation • entire concrete section
3	In the absence of better information, assume that at least 20% to 30% of the monoliths in the main section of a mass gravity structure are instantaneously removed at either the dam foundation or change of section. **Figure 13: Typical mass concrete dam cross-section** 
4	The quantity of water through the break is calculated assuming vertical side slopes.

Step	Description
	Assume monolith removal outside of this suggested range if there is a reason to do so.
5	Assumptions should be checked against the results of the hydraulic model. If a failure case is identified that has a greater impact on downstream water levels, this should then be adopted.
6	Rigorous sensitivity testing should be undertaken for all adopted parameters.

Arch dams

One of the most common causes of arch dam failure is foundation movement and the consequent loss of support to the arch. Loss of support at the abutments and resulting destruction of the arch action usually leads to very rapid almost complete failure of the dam. Similar rapid failures could be expected of multiple arch and barrel vaulted buttress dams.

To analyse these types of dams, the modeller should initially assume complete removal of the dam as quickly as the model will allow (i.e. instant failure).

Buttress dams

Buttress dams should be assumed to fail in a similar manner to mass concrete structures with at least 20% to 30% of the buttress bays lost instantaneously.

Consideration should also be given to the additional sudden loss of adjacent bays if they would then become unstable.

Concrete faced rock fill dams

Generally speaking, a concrete faced rock fill dam will have feasible failure modes that are a combination of features of a mass concrete dam and an embankment (earth) dam. This is particularly the case for the speed of formation of wall failure.

It may be possible in certain cases for one or more segments of the concrete facing dislodge from the underlying rock and a section of rock be washed out. In this case, any breach that forms in the rock fill is likely to be smaller than for a similar height clay core.

Unless an earth embankment core structure forms a substantial part of the wall structure, the dam may not be structurally compromised by loss of fines (piping) of a core.

Short of actual wall failure, the most likely outcome is a loss of contents of the dam. Of itself, this could produce quite large flow rates, but not of the same order as a dam failure flood.

Gated spillways

Flood waves caused by the failure or collapse of spillway gates generally do not result in major additional flooding. However, each case should be considered on its merits and spillways with several gates may need to be examined more carefully.

The gates do not need to collapse to produce a flood wave. Depending on the gate operating mechanisms, gates could completely open almost instantaneously to produce a sunny day failure.

A spillway gate failure scenario would normally not produce the highest dam failure PAR during major floods. This is because the gates are generally designed to lift clear under these conditions, which represents the upper discharge limit for the spillway for a given headwater condition.

Saddle dams

Saddle dams can fail relatively faster and more completely than the main embankment because they often store more water for a given embankment volume than the main embankment.

Consideration should be given to the effect of each embankment failure on the failure impact zone. The scenario that produces the highest PAR is then used to determine the failure impact rating. Figure 1 shows an example of this scenario.

Ring tanks with multiple cells

In the case of ring tanks with multiple cells, it is usually assumed that only the critical cell fails and it is not necessary to consider the simultaneous failure of two isolated cells.

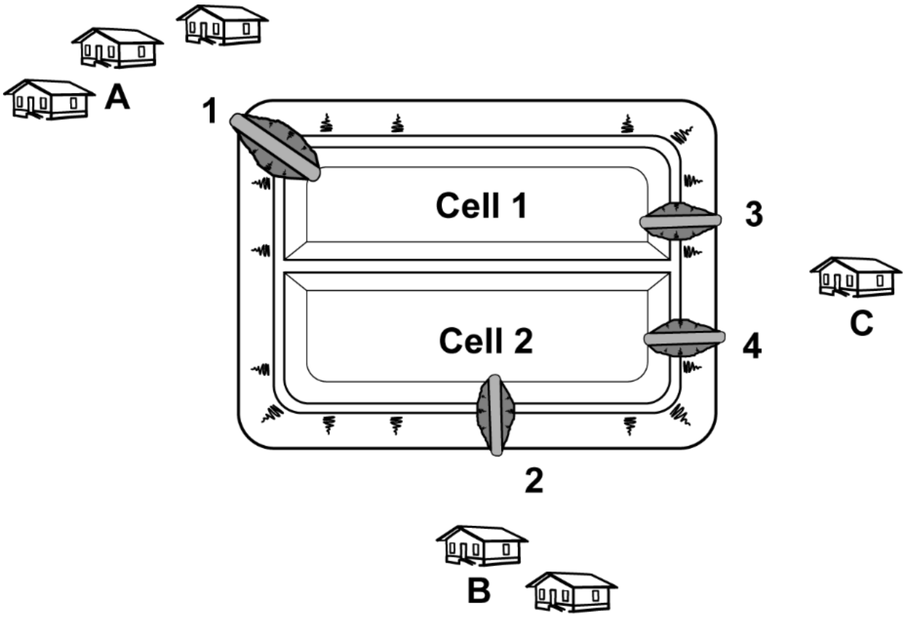
The consideration of simultaneous ring tank cell failure may be necessary if the headwater of one cell is higher than the other cells, or there is already a breach in one of the internal cell walls. The standard of design and construction of the internal wall should also be considered and whether there is potential for sudden drawdown failure.

Figure 14 shows a situation where multiple buildings are surrounding a two-cell ring tank. To assess this situation it may be necessary to consider the following scenarios:

- failure of cell 1, at location 1, causing flooding at building A
- failure of cell 2, at location 2, causing flooding at building B
- failure of cell 1 or 2, at location 3 or 4, causing flooding at building C

The cell that produces the highest PAR is the critical cell for this dam. For each of these cases it may be necessary to adjust the breach calculations depending on the height of the embankment at the breach location selected and the volume of water contained in the cell. Note that all potential breaks need to be considered and addressed in the FIA.

Figure 14: Analysis of multiple properties surrounding a two cell ring tank



Detention basins

Detention basins are a special class of dam that are designed to temporarily store water passing down a watercourse to attenuate flooding. They are usually dry in the absence of wet weather events and may have both a spillway and low flow outlet to pass smaller events and to drain the main storage following events.

Detention basins protect downstream populated areas from flooding, or reduce flooding risks to a degree that enables urban development. The primary design purpose is typically to mitigate flood peaks for more frequent events (1% AEP and more frequent) compared to other water storage dams. The design should accommodate larger flood events without failure or by failing in a safe manner.

Detention basins can have PAR and, in some cases, PAR close to the dam.

For FIA of detention basins, more frequent design flood events may need to be investigated compared to other water storage dams. Sensitivity testing may be required to consider blockages (of low flow outlets and any other flow conveyance structures); guidance on this aspect may be obtained from AR&R, QUDM and relevant publications by ANCOLD.

Other dam types

Assignment of failure modes and timings for dam types not specifically described in this guideline should be sourced from reputable engineering literature. It is recommended that any adopted failure parameters be benchmarked against the closest provisions provided in this guideline.

Alternative dam failure methodologies

There are numerous alternative dam failure methodologies available, including regression equations and physically based process models. It is also possible to predict failure properties for a given dam by comparing it to a historical failure of a dam of similar size and properties.

Examples of dam failure methodologies are provided in the references.

For consistency it is expected that the dam failure methodologies outlined in this guideline be adopted in most cases. If alternative methodologies are used the FIA must provide justification, supported by recognised literature and site-specific data, as well as a comparison to the methodology detailed in this guideline.

The FIA must document key parameters such as breach dimensions and development times.

Appendix 7 Flow analysis

Simplified flow analysis

The simplified downstream flow analysis methodology described in the following table (Table 15) follows from the simplified dam failure analysis (**Appendix 5**).

- The approach applies normal depth calculations to estimate maximum flood levels at a section for a given dam failure peak discharge.
- Limitations of the simplified flow analysis are summarised in Table 16. These limitations may drive the need to proceed to more comprehensive analyses (see next section).

The worst failure case (i.e. that which causes highest PAR) can often be estimated by assuming that the flood level without dam failure (d_{NF}) occurs at the plinth level of the place of occupation (d_{PLINTH}).

To assess the worst failure case, see Step 8 in Table 15. If performed at the outset of the analysis, the worst case assessment may assist in deciding upon the degree of effort:

- If the worst case produces PAR, some additional effort can then be invested in determining whether the no-failure flood level can be reached and, where multiple residences are involved, what the critical level is cause the highest PAR.
- If the worst case does not produce PAR, the analysis can be stopped (subject to sensitivity checks).

Examples of application of the simplified flow analysis are provided in **Appendix 8**.

Note that the analysis methodology in Table 15 follows a similar logic to that described in Table 10, Section 2.4.5.1.

Table 15: Procedure for simplified downstream flow analysis (note limitations in Table 16)

<table>
<tr><th>Step</th><th>Description</th></tr>
<tr><td>1</td><td>Identify critical cross-sections, at buildings or other places of occupation, where an estimate of discharge capacity and peak flood water level is required.

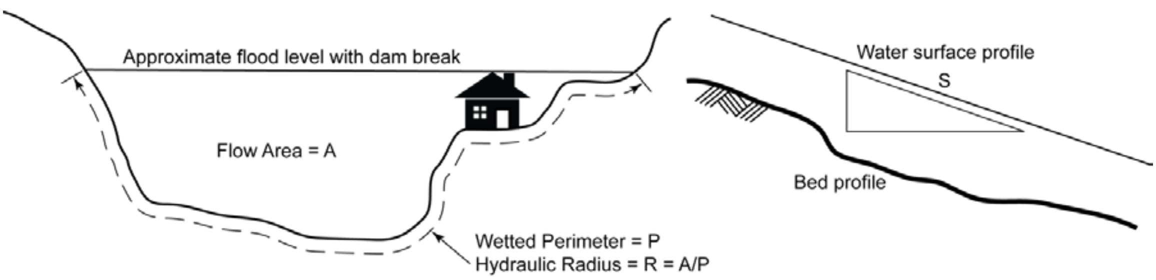
For each cross-section measure or estimate the following:
• Cross-section geometry (area, wetted perimeter, etc), see next step
• Plinth level of places of occupation, d_{PLINTH}

Population within the dwelling (see Appendix 4), P_{OCC}</td></tr>
<tr><td>2</td><td>For a specific flooding event and dam failure scenario (Section 2.3 and 2.4.2) establish peak discharges with and without dam failure:
• Q_{NF}
o The no-failure discharge caused by flooding without dam failure, which is spillway discharge plus any other flows from catchments below the dam
o At a given cross-section the corresponding water depth is d_{NF}
• Q_F
o $Q_F = Q_{BREACH} + Q_{NF}$
o The failure discharge caused by dam failure as well as no-failure flooding
o At a given cross-section the corresponding water depth is d_F</td></tr>
<tr><td>3</td><td>For each cross-section estimate flood depths (d_{NF} and d_F) associated with peak discharges (Q_{NF} and Q_F) using Manning's formula:

$$Q = \frac{R^{2/3}\,S^{1/2}}{n}A$$

Where (see also depiction of parameters in following figure):
• Q = the discharge at a cross-section
• R = hydraulic radius of cross-section = A/P (metres)
• S = slope of water surface profile (metres/metre)
• A = flow cross-sectional area (square metres)
• P = wetted perimeter of cross-section (metres)
• n = Manning's number

Figure 15: Parameters for simplified downstream flow analysis (Manning's formula)


</td></tr>
<tr><td>4</td><td>As defined in Section 2.4.5 (Table 9), PAR is assigned when the dam failure flood depth over the plinth of a place of occupation exceeds a defined threshold of 300mm (for the simplified assessment).</td></tr>
</table>

Step	Description

	Thus, PAR is determined using the following for each place of occupation:
	• IF $d_{NF} \geq d_{PLINTH}$ + 300mm THEN
	  o PAR = PAR + 0
	• ELSEIF $d_F \geq d_{PLINTH}$ + 300mm THEN
	  o PAR = PAR + P_{OCC}
	• ELSE
	  o PAR = PAR + 0

5	Repeat steps 3 and 4 for each place of occupation (potentially at more than one cross-section) to accumulate PAR for a specific flood event and dam failure scenario.
6	Repeat steps 2 to 5 for all identified flood events and dam failure scenarios. The highest PAR value from each iteration of event/scenario is then defined as the dam failure PAR.
7	If preferred, flood depths from multiple cross-sections (calculated in step 3) can be mapped onto a topographic map, or GIS, to illustrate the failure impact zone for the scenario. Considering the prevailing topography and contours, interpolation between the calculated points can then be made to create a failure impact surface.
8	A worst failure case can be estimated by assuming that the flood level (d_{NF}) occurs at the plinth level of the place of occupation (d_{PLINTH}). To assess the worst failure case, use the following procedure: A. Repeat Step 1 with the following adjustments: • Assume $d_{NF} = d_{PLINTH}$ • Back-calculate Q_{NF} using Manning's formula and d_{NF} • Check that Q_{NF} does not exceed PMF • Calculate $Q_F = Q_{BREACH} + Q_{NF}$ B. Repeat steps 2 to 6

Table 16: Limitations of the simplified downstream flow analysis

Limitation	Comments
Does not take into account flood peak attenuation or backwater effects downstream of the dam.	Flood peak at the location of potential PAR may be lower than that applied. Time dependent (hydrodynamic) analyses may be required in this instance.
Accuracy of cross-sections and the locations and levels of the impacted buildings.	The level of accuracy of baseline information is a key aspect of the scoping exercise (Section 2.2).
Accuracy of the stream slopes adopted.	Stream slope can be predicted from the overall bed slope, however this can be difficult to estimate when topographic data is limited. Testing can establish sensitivity of predictions to parameter estimates.
Assessment of cross-sections at river bends.	Cross-channel variations in water level can occur around river bends. Care should be taken, particularly when the place of occupation is situated on the outer bank.
In general the approach may not be applicable for dams that fail onto floodplains or more complex land formations.	Floodplain analysis typically requires a comprehensive 2D analysis to determine dam failure impacts (see next section). However, a well-placed cross-section may still be useful to obtain indicative results.
Manning's equation can sometimes be difficult to solve by hand for complex channel geometries.	There are several online calculators available for this. Alternatively, DNRME have an Excel based calculation tool that can be made available on request. It is the responsibility of the certifying RPEQ to ensure that any tools they adopt are functioning as expected.
Not suitable for subsequent requirements of referable dams.	Comprehensive flow analysis is required to generate flood maps, inundation extents etc that would be applied to EAPs, etc.

Comprehensive flow analysis

A comprehensive flow analysis should be adopted in situations where the accuracy of the simplified process is not considered adequate to calculate PAR.

As discussed in Section 2.2, the type of comprehensive flow analysis is an important consideration and should be based on what is necessary and cost effective to allow the certifying RPEQ to make a valid assessment of PAR.

Selection of types of hydraulic models to be used

Comprehensive dam failure analyses should be undertaken using suitably documented and validated numerical models (or other justifiable analysis approach). This should be done as per current hydraulic, and preferably hydrodynamic, modelling practices. An assessment of the resolution and accuracy of each model must also be made, taking into account that greater model resolution and accuracy may be required in more densely populated areas.

The available options will probably include whether to conduct the analysis using a 1D model, a 2D model or a combined 1D / 2D coupled model.

It is likely that time-dependence will influence hydraulic behaviour (flood attenuation, storage effects etc as well as, for future applications, time to peak of flood wave); a time-dependent (or hydrodynamic model) is recommended. The discussions provided in this section assume that all modelling is hydrodynamic.

Issues that should be considered include:

- whether the flow path for a dam failure flood wave is along a well-defined and confined watercourse, predominately moving in one direction
- whether the flow is capable of moving in two directions, for instance, wider floodplains, braiding of the watercourse or alternative flow paths are present
- whether there are structures that may affect the flow, for instance, bridges, culverts, weirs or levees
- data availability and accuracy of survey or existing models
- If the dam is likely to become referable, increased accuracy may be required for flood inundation mapping included in an Emergency Action Plan (EAP)

One-dimensional (1D) flow modelling

Typically, 1D models are spatially defined as a branch (or series of branches) along which discharge (in a direction either upstream or downstream) and water level is calculated at predefined calculation points along the branch. Cross-channel influences, such as superelevation around bends and interactions between main channel and floodplains, can be more difficult to simulate. Also, a reasonable understanding of the dominant flowpaths is required as part of the model setup.

1D modelling can be used to assess dam failure impacts in situations where there is a well-defined and confined watercourse and the water is predominately moving in a single direction. This approach may apply to the assessment of dams that are likely to fail into rivers, creeks or drainage channels with the PAR situated along the banks of these watercourses.

Due to the preference to apply more empirically based equations, complex hydraulic structures such as weirs (which include elevated roads, railways and levees), bridges and culverts are often modelled in 1D. These empirical equations are overlaid into the numerical scheme, replacing the standard momentum equation, to represent structure flows. Note that most modelling packages provide options to embed the 1D structure equations into more complex 2D (and 3D) numerical schemes.

Simulation times for 1D models are generally faster than for 2D models.

1D modelling of floodplains and dam failure events is a mature branch of engineering. There are numerous commercial and public domain modelling packages available and a wide range of resources available that provide guidance for best-practice modelling techniques.

The following figure shows the layout of a typical 1D model. Table 17 provides a guide to minimum spatial resolution and downstream extent of a 1D model applied to dam failure analysis.

Note that 1D models can be designed to be "quasi-2D", where multiple flowpaths can be defined. For example, a river and floodplain can be discretised into three separate flowpaths (the left-bank floodplain, the main channel and the right-bank floodplain) with interconnecting branches representing levee overtopping. While application of 1D models in this manner are less frequently applied (2D modelling is typically applied instead), this "multi-channel" approach can provide a more accurate representation of velocities and water levels on floodplains.

Figure 16: 1D flow analysis

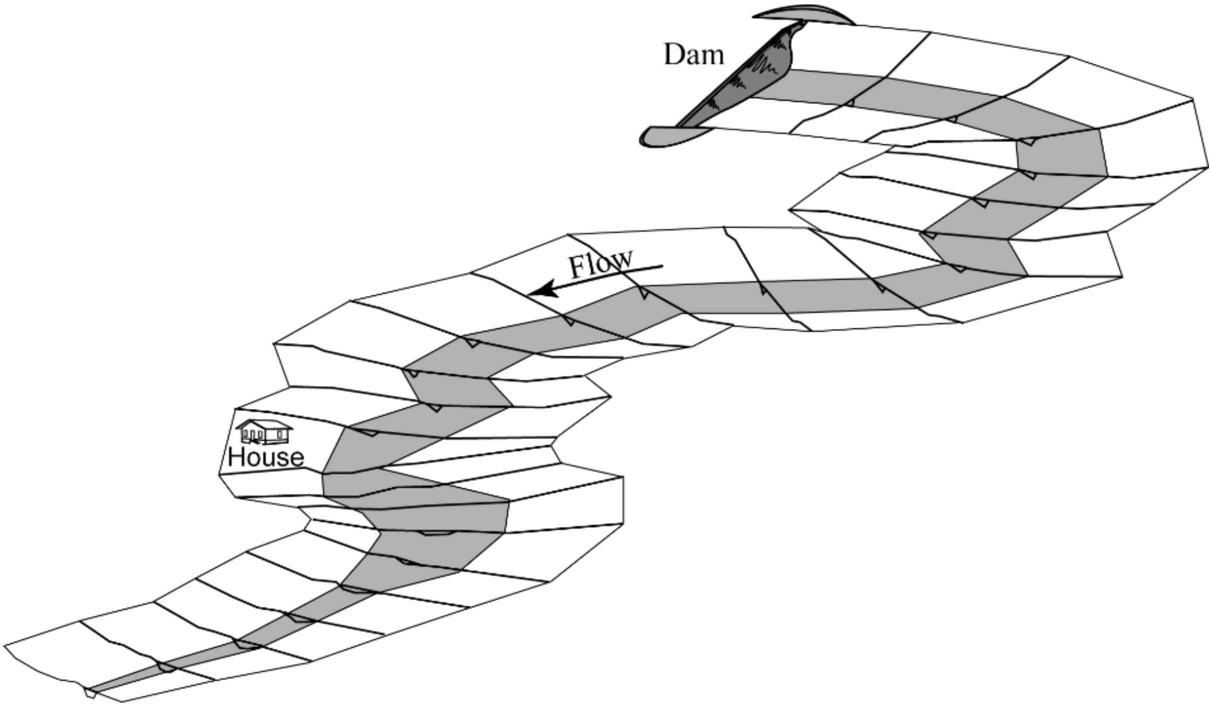


Table 17: Maximum recommended cross-section intervals and indicative downstream distances for 1D model applications[8]

Storage (megalitres)	Indicative intervals between cross-sections	Indicative total distance downstream (preliminary assessment)
20,000	1 km	Up to 60 km

[8] Recommended distances reflect the requirements to ensure that the model extends sufficiently far downstream so that there are negligible incremental effects to downstream populations and that cross-sections intervals are sufficient to reasonably resolve the flood wave propagation.

Storage (megalitres)	Indicative intervals between cross-sections	Indicative total distance downstream (preliminary assessment)
2,000	0.5 to 1 km	Up to 20 km
200	Not greater than 0.5 km	Up to 5 km

Two-dimensional (2D) flow modelling

Typically, 2D models are spatially defined as a grid (or irregular mesh) across which velocity (components in both EW and NS directions) and water level is calculated at each grid point. Cross-channel influences, such as superelevation around bends and interactions between main channel and floodplains, are more accurately simulated compared to 1D. Also, flow patterns tends to reflect the topography defined on the 2D grid, rather than according to pre-defined flowpaths.

2D models are used to assess dam failure impacts in situations where flow moves in multiple directions or where there are no clearly defined dominant flowpaths (which is often the case during extensive overland inundation of floodplains). Example applications of 2D modelling include ring tanks that fail directly onto a floodplain, or where a dam impacts on a dwelling before the flow channelises.

As mentioned in in the previous section, complex hydraulic structures such as bridges and culverts are often modelled in 1D due to the preference to apply more empirically based equations. Most modelling packages provide options to embed structure equations.

Simulation times for 2D models are generally slower than for 1D models. That said, 2D models are presently widely used and, if topographic information is readily available, their setup and application to a study can be faster.

2D modelling of floodplains and dam failure events is a mature branch of engineering. There are numerous commercial and public domain modelling packages available and a wide range of resources available that provide guidance for best-practice modelling techniques. Specific to dam failure analysis, the following points are made:

- The topography in 2D models is represented by gridded or meshed terrain data. This data may be obtained through either survey or LiDAR.
- Downstream model extents should consider recommendations provided in Table 17.

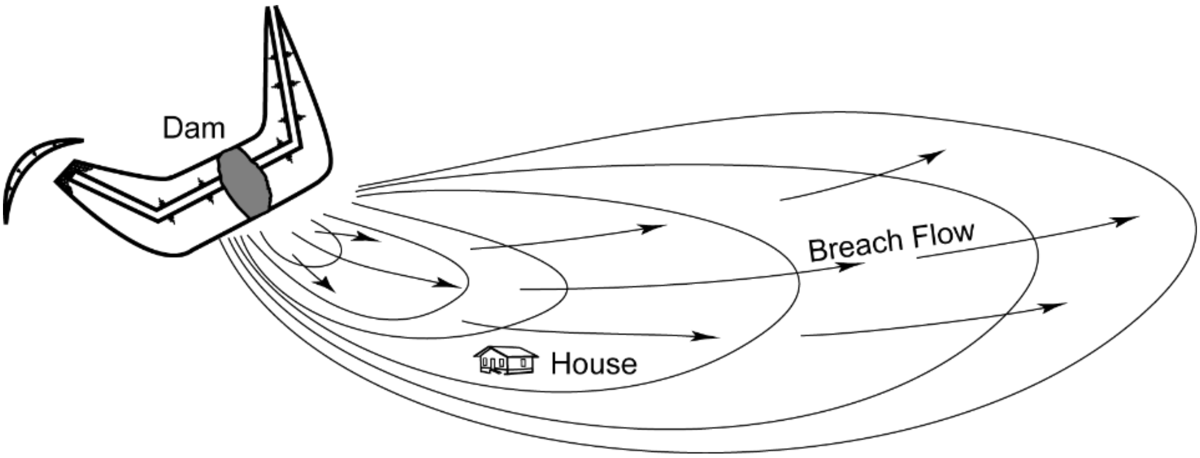
Additional cross-sections may be required at locations where there are buildings or other places of occupation, particularly in areas where there may be PAR or in areas with sudden changes of grade, channel widening or contracting. Additional cross-sections may also be required leading up to, and away from, hydraulic structures.

It is likely that the model application will be far more resolved, and conservatively much further downstream, than these recommended distances.

- Choice of spatial resolution (grid size) is often a trade-off between achieving higher resolution whilst maintaining reasonable computational performance (simulation times). This in turn is influenced by factors including model extent and duration of flood event (noting that computational effort in most models is strongly dependent upon how many and how often computational cells are wet). Most models are constrained by the Courant condition; this means that a halving of spatial resolution typically increases computational effort by a factor of 8 (i.e. 4 times more spatial cells requiring 2 times more timesteps).
- A flood wave from a dam failure event can be steep. Numerical models with higher order spatial and temporal schemes, or with an appropriately accurate description of the wave front, may provide more accurate predictions.
- To accurately represent a main river channel in a 2D model there should be more than 4 to 6 cells defining the channel width; this depends upon variability in the channel and model performance, especially relating to representation of turbulence. This level of resolution in the main river channel may not be necessary if a significant fraction of flood flows is overland.
- Care is required when modelling “hydraulically significant” topographic features such as elevated roads, levees or railways. In particular, ensuring that the crest elevation is preserved in the model grid or, if grid size is relatively coarse relative to width, considering the implementation of a weir flow equation.
- Modelling techniques are available to circumvent many of these constraints, including the application of flexible mesh models and 1D/2D modelling (see next section).
- The points above are valid for both fixed grid and flexible mesh modelling approaches.

The following figure shows the layout of a typical 2D model.

Figure 17: 2D flow analysis



Coupled (1D/2D) modelling analysis and other modelling options

Coupled analysis involving a link between 1D and 2D models may need to be applied in situations where the flow fluctuates between channels and floodplains. This approach is useful when:

- A high resolution is required in a specific place of interest within a larger model domain
- Suitable model boundaries are significantly distant from the key area of interest
- There are physical features within the model domain that are better modelled using a different modelling approach

The following figures show examples of scenarios where a coupled model may be required.

There may be other specific examples where alternative modelling options could be applied. In all cases the choice of model to be applied, and the manner in which it is applied, must be justified and subject to validation and sensitivity analyses.

Figure 18: Coupled 1D / 2D flow analysis (example scenario 1)

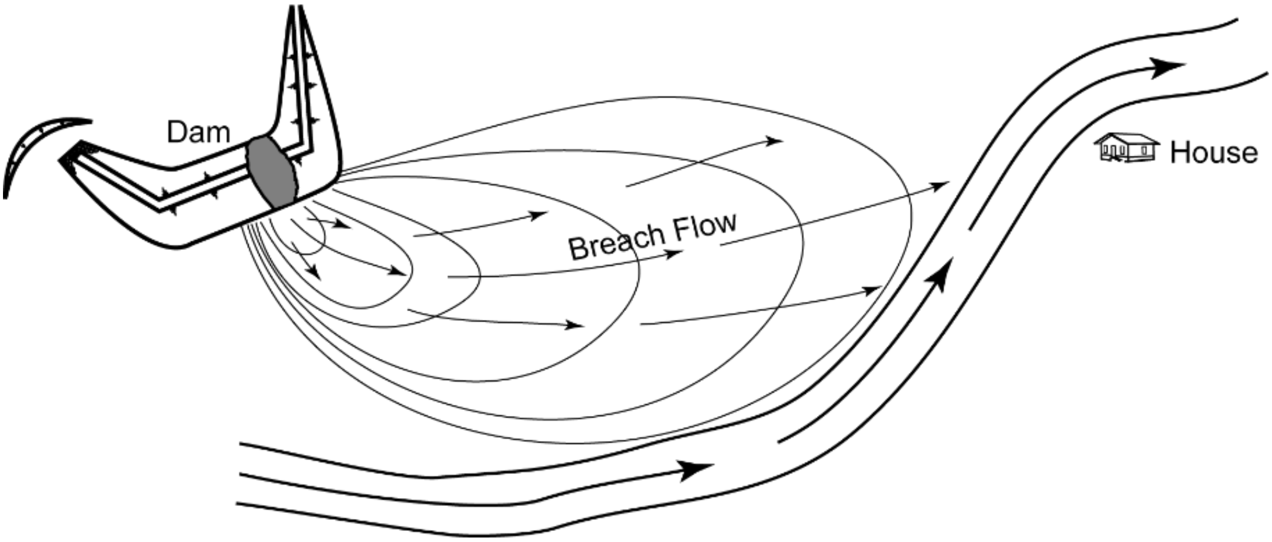


Figure 19: Coupled 1D / 2D flow analysis (example scenario 2)

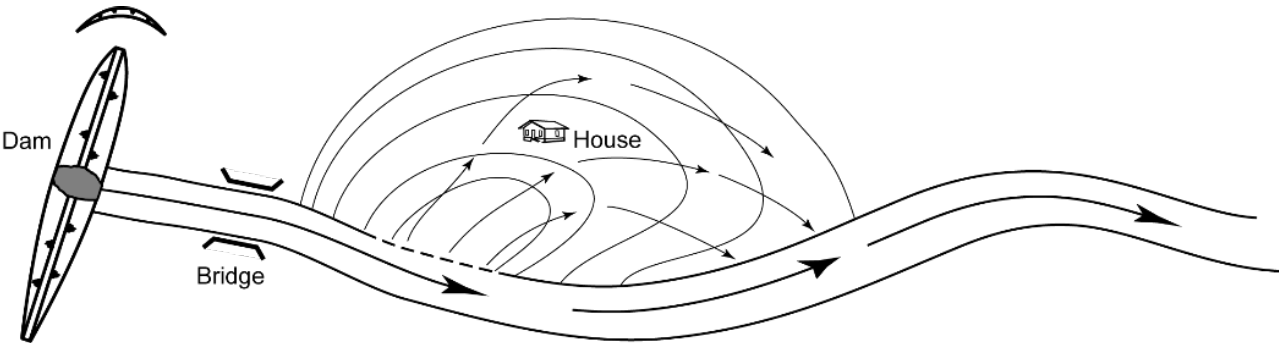
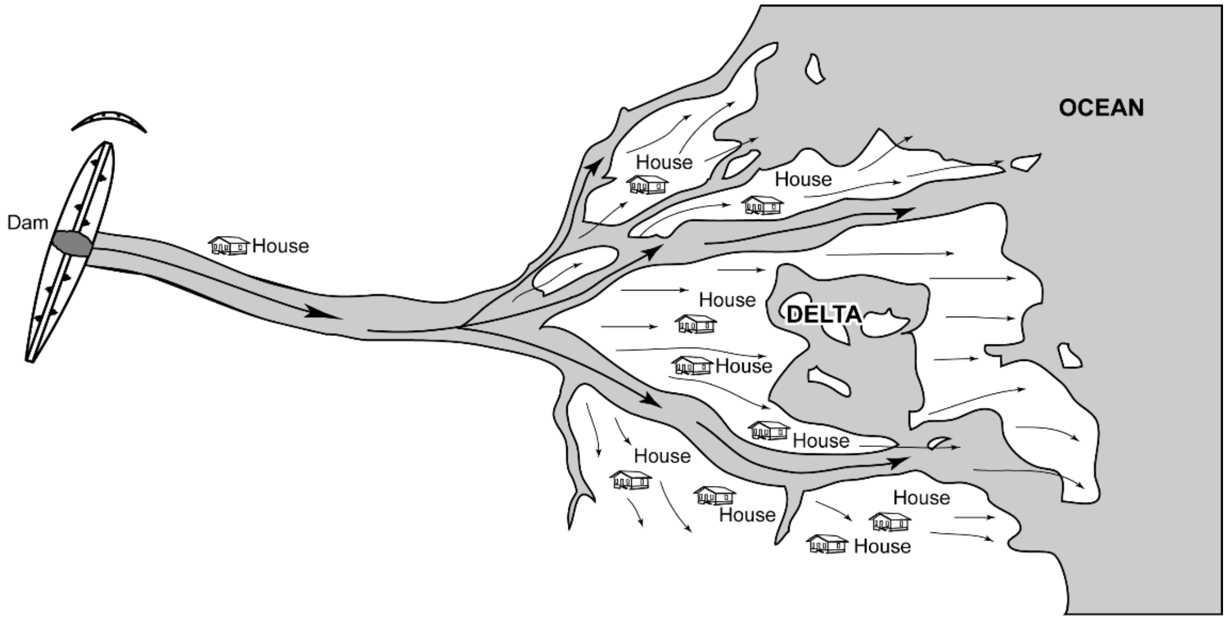


Figure 20: Coupled 1D / 2D flow analysis (example scenario 3)



Validation of analysis

Numerical models (or any similar analytical technique) require, where available, comparisons to measurements or observations in order to demonstrate accuracy and reliability.

Calibration (and Verification)	Calibration is the process where model parameters are adjusted, within scientifically justifiable ranges, to match measurements. Verification is the process where the calibrated model is then tested against another set of measurements or another period of time or event. It is recognised that calibration and verification to a reliable and comprehensive dataset is rarely possible, however the modeller should make use of any available event data or field observations to ground-truth their model. • As an example, observations on debris levels on vegetation, fences or property levels may provide valuable information to check a model's performance. • It may be necessary to adjust model parameters to reflect historical conditions (for example, calibration to a flood event from 50 years ago may require bed roughness adjustments to account for land use changes, or bed level adjustments to account for changing bed forms within a river channel). • Often the relative magnitudes of calibration events (for which data is available) are less than the design dam failure floods. This needs to be considered in the validation process and may be a key uncertainty to investigate as part of sensitivity testing. • Data for calibration needs to be fit-for-purpose; for example, calibration of a hydrological model to a minor runoff event

may not necessarily provide confidence in a model's capability to predict runoff from an extreme flood.

- Paleo-hydrology and paleo-flood assessments can provide insightful evidence of extreme historical flood events.
- Section 2.2.6 provides further advice relating to data collection.

Sensitivity Testing	If there is limited data with which to calibrate or validate, additional efforts should be applied to sensitivity testing. Sensitivity testing is the process where the model is tested to sensitivity of selection of model parameters (including boundary conditions and initial conditions where of relevance). This provides an indication of the variability of predictions and an understanding of what aspects of the model generate the most uncertainty in predictions. The following items should be considered as part of these checks: • channel and floodplain roughness • elevation of structures • break formation considerations including size, time, orientation and location • channel bed slope • boundary locations and types • accuracy of topographic information
Impact on FIA process	It is important that calibration, verification and sensitivity analyses is performed to any modelling used in the FIA process. Sensitivity testing becomes more important when suitable calibration data is lacking, which is often the case when considering extreme flood events that can cause dam failures.

Outputs

Outputs from the flow analysis for each scenario will specifically include:

- Maximum extent, water depth and velocity of flooding
- Maximum hazard (depth * velocity)

These outputs are then used to identify PAR.

Flood maps of the modelled dam failure scenarios are a useful tool to communicate the outcomes of the FIA to any audience.

While a map for every scenario modelled is not required, a sufficient number of maps should be provided to demonstrate that a representative range of failure scenarios and sensitivity tests were assessed and, more generally, to support the assessment.

Electronic copies of flood map layers, for example, shape files or kml should be included with the submission if possible.

As a minimum, the flood maps should:

- a map for the critical scenario that causes the dam failure PAR is required

- identify failure impact zones for any key scenarios modelled
- show properties affected within the failure impact zone
- identify pre-failure and total failure scenarios
- be produced at a resolution that is clear and easy to read, both electronically and printed
- be colour coded to show flood depths clearly and, if necessary, depth times velocity thresholds
- comply with general mapping styles with respect to the selection of colours, labelling, legends and titles
- include an appropriate number of layers, for example, roads and other land marks to provide context

Other outputs to consider:

- time series of rise, peak and fall of water levels at key locations downstream
- animations showing the propagation of the flood wave (useful to communicate outputs to non-technical stakeholders)

There are many modern mapping tools, which can produce detailed flood maps. These packages can consume high-quality imagery, which can be used as a base layer to overlay inundation data from the model. It is also possible to add other layers of interest such as roads, property boundaries or contours.

Appendix 8 Examples of breach flow and depth calculations

Application of the Q_{BREACH} formula

The following is an example application of the Q_{BREACH} formula. In this scenario, there is a small embankment dam on a gully, with a broad crested weir spillway. The dam has the following characteristics:

- height from toe to embankment crest: 5.4 m
- above ground volume to embankment crest: 200 ML
- height from toe to spillway crest: 4.4 m
- above ground volume to spillway crest: 150 ML
- spillway channel width: 10 m

For a sunny day failure scenario, only the impact on downstream places of occupation from the breach-only component is considered. That is, there are no associated wet weather events and the total discharge passing PAR locations (Q_{TOTAL}) is the breach flow (Q_{BREACH}).

$Q_{TOTAL} = Q_{BREACH}$
$Q_{BREACH} = 0.53FV^{0.87}H^{0.38}$
F=1.3, V=150ML, H=4.4m
$Q_{BREACH(SD)} = 0.53x1.3x150^{0.87}x4.4^{0.38} = 95m^3/s$

For a flood failure scenario, the effects of dam failure (Q_{BREACH}) must be considered in addition to spillway discharge ($Q_{SPILLWAY}$).

$Q_{TOTAL} = Q_{BREACH} + Q_{SPILLWAY}$
$Q_{BREACH} = 0.53FV^{0.87}H^{0.38}$
$Q_{SPILLWAY}$ can generally be approximated with the broad crested weir equation in this case -
$Q_{SPILLWAY} = CLH^{\wedge 3/2}$
F = 1.3, V = 200 ML, H = 5.4 m – 4.4 m = 1 m (spillway depth), C = 1.55 (weir coefficient)

$Q_{SPILLWAY} = 1.55 \times 10\ m \times 1\ m^{\wedge 3/2} = 15.5\ m^3/s$
$Q_{BREACH} = 0.53 \times 1.3 \times 150\ ML^{0.87} \times 4.4m^{0.38} = 131\ m^3/s$
$Q_{TOTAL} = 131\ m^3/s + 15.5\ m^3/s = 146.5\ m^3/s$

This example continues in the following section where these flows are translated into water depth in a cross-section.

Normal Flow Calculations (to estimate flood depths)

Scenario 1 – The flood level (without dam failure) is below the property plinth level

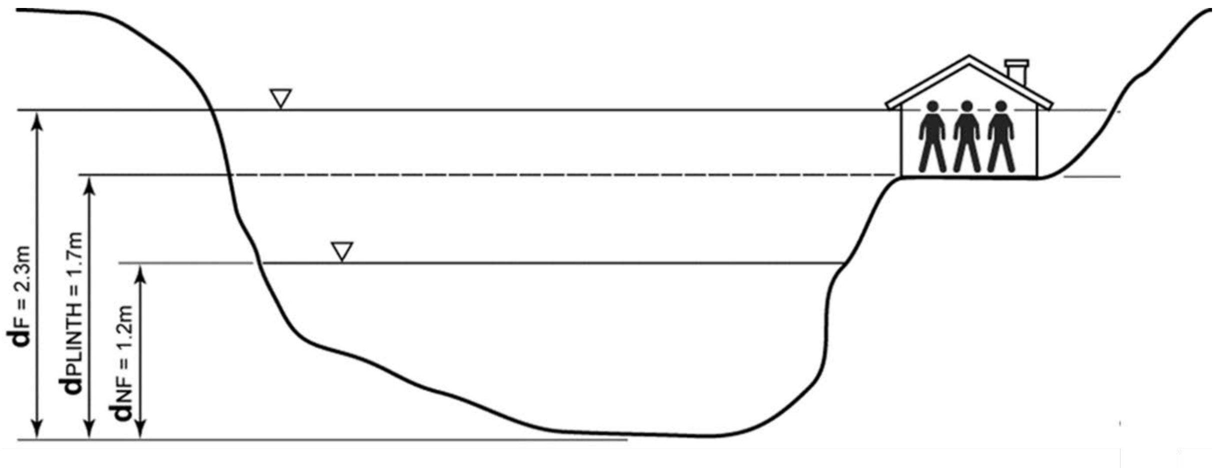
Continuing on from the simplified flood failure example presented in the previous section, the following flows were established:

$Q_{SPILLWAY}$ = 15.5 m^3/s
Q_{BREACH} = 131 m^3/s
Q_{TOTAL} = 146.5 m^3/s (i.e. $Q_{SPILLWAY} + Q_{BREACH}$)

It is assumed in this scenario that there are no additional no-failure flooding inflows.

These flows can then be used to solve for depth using Manning's formula and the example cross-section below.

Figure 21: Depths obtained for scenario 1



Where:

- d_{NF} = the non-failure case i.e. the flooding caused by flooding without dam failure (i.e. the depth obtained from solving $Q_{SPILLWAY}$ plus any other flows from catchments below the dam with Manning's formula)
- d_F = the failure case i.e. the same flood from d_{NF} with the dam failure flood (i.e. the depth obtained from solving Manning's formula with Q_{TOTAL})
- d_{PLINTH}= the level from the base of the channel bed to the footing of the occupied dwelling

For this example, assume the Manning's formula produces the following results:

d_{NF} = 1.2 m
d_F = 2.3 m
d_{PLINTH} = 1.7 m

Considering the failure impact thresholds for simplified assessment (Table 2, Section 6.9.1), d_{NF} is 0.5 m below the building's plinth level (i.e. $d_{NF} < d_{PLINTH}$ + 300mm) and d_F is 0.6 m above the plinth (i.e. $d_F \geq \text{MAX}(d_{PLINTH}, d_{NF})$ + 300mm).

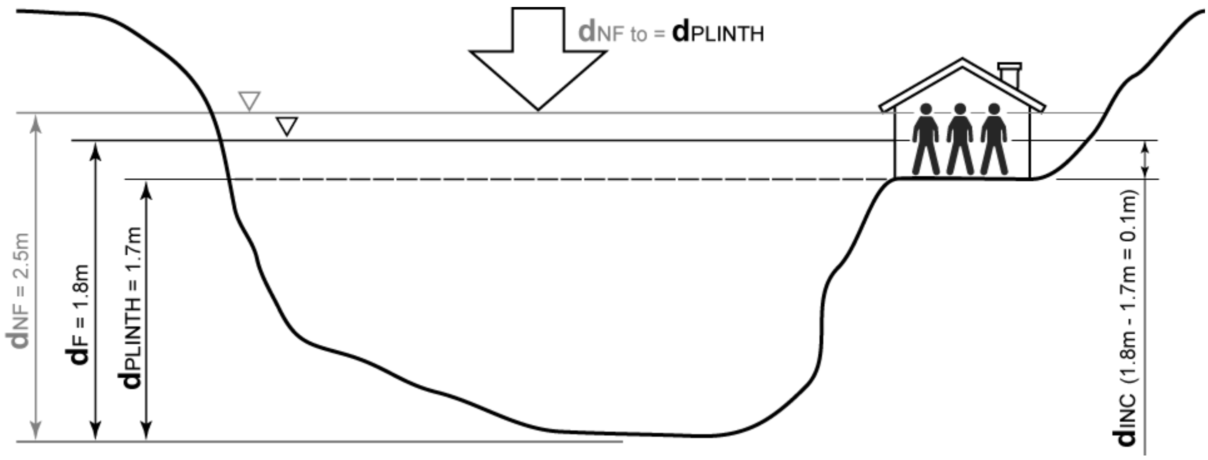
Therefore, this dwelling would be considered at risk.

Scenario 2 – The flood level (without dam failure) is above the property plinth level

This scenario demonstrates how no-failure flooding can be scaled to identify the critical flood event for predicting PAR for a single property.

Assume the no-failure flood level (d_{NF}) was solved with Manning's formula and found to be 2.5 m. This is 0.8 m above the property plinth level, so the property is already substantially inundated by flood water before a dam failure occurs.

Figure 22: Depths obtained for scenario 2



To identify the critical no-failure flood for this property for PAR determination, the suggested approach is to lower d_{NF} to equal d_{PLINTH} and assume that the dam failure occurs when no-failure flooding is at this level. By doing so, any subsequent inundation above this level is known to be caused entirely by the dam failure flood. Thus, a new no-failure flood event is determined so that $d_{NF} = d_{PLINTH} = 1.7$m.

Q_{BREACH} is then added to the no-failure flood flow d_{NF}. Using Manning's formula, the depth of these summated flows gives d_F which, in this example, is 1.8 m.

Considering the failure impact thresholds for simplified assessment (Table 2, Section 6.9.1), d_{NF} is at the building's plinth level and d_F is 0.1 m above the plinth (i.e. $d_F < MAX(d_{PLINTH}, d_{NF}) + 300mm$).

Therefore, this dwelling would not be considered at risk.

The concept of setting the non-failure case to the plinth level and determining the dam failure impacts above this level is useful for simplified analyses because it provides the worst failure case possible for a dwelling with minimal effort. It is also a way of addressing uncertainty with flooding calculations without undertaking further analysis or field work.

Appendix 9 PAR Assessment procedure flowcharts and logic

Flowcharts, illustrating the PAR assessment methodology, are presented in Figure 23 for the simplified approach and Figure 24 for the comprehensive approach.

Figure 25 provides the methodology logic and the corresponding Excel formula (which can be pasted into Excel and applied).

Figure 23: Procedure for assessment of PAR – flowchart for simplified assessment (no flood velocities considered)

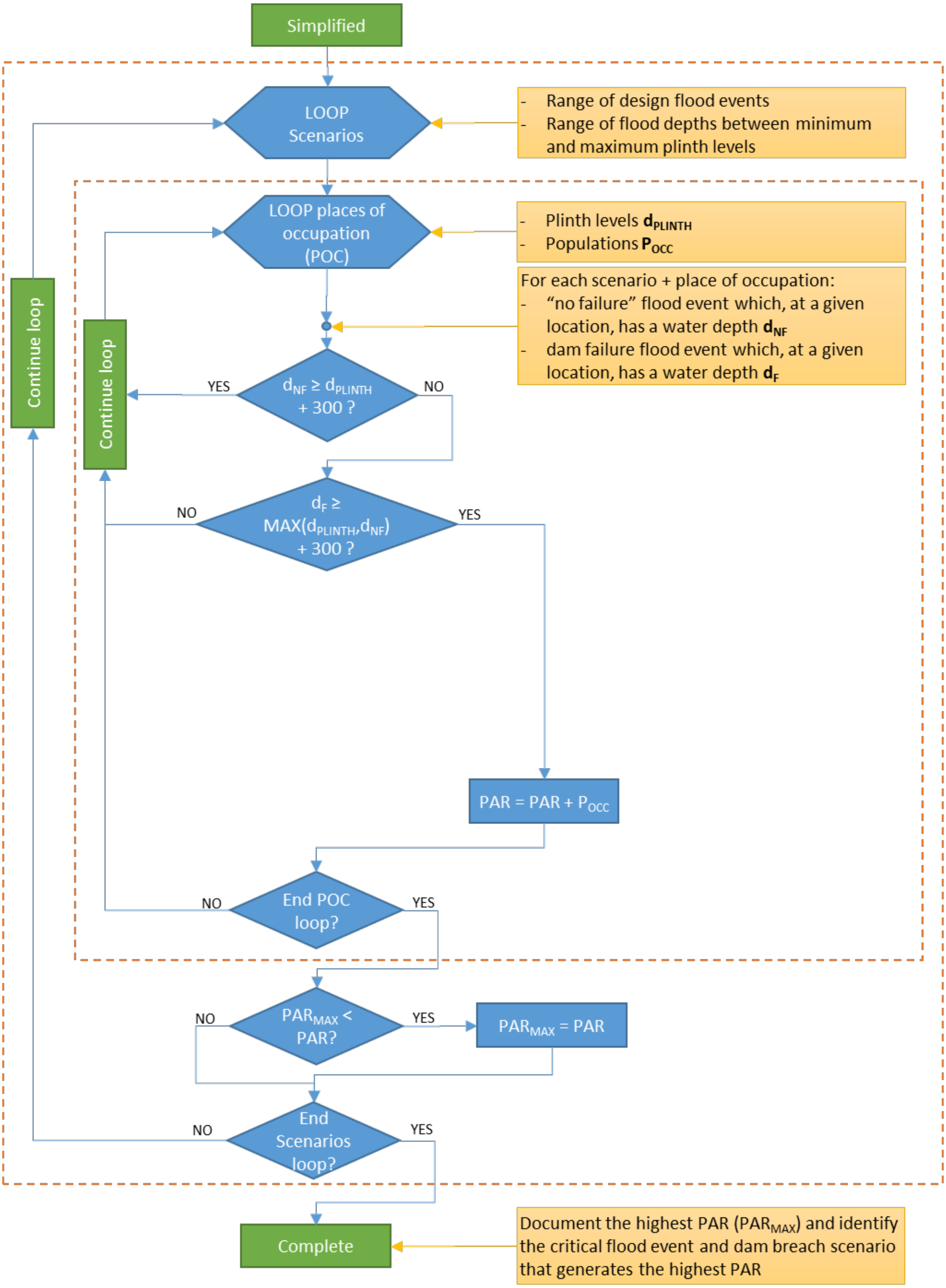


Figure 24: Procedure for assessment of PAR – flowchart for comprehensive assessment (flood velocities considered)

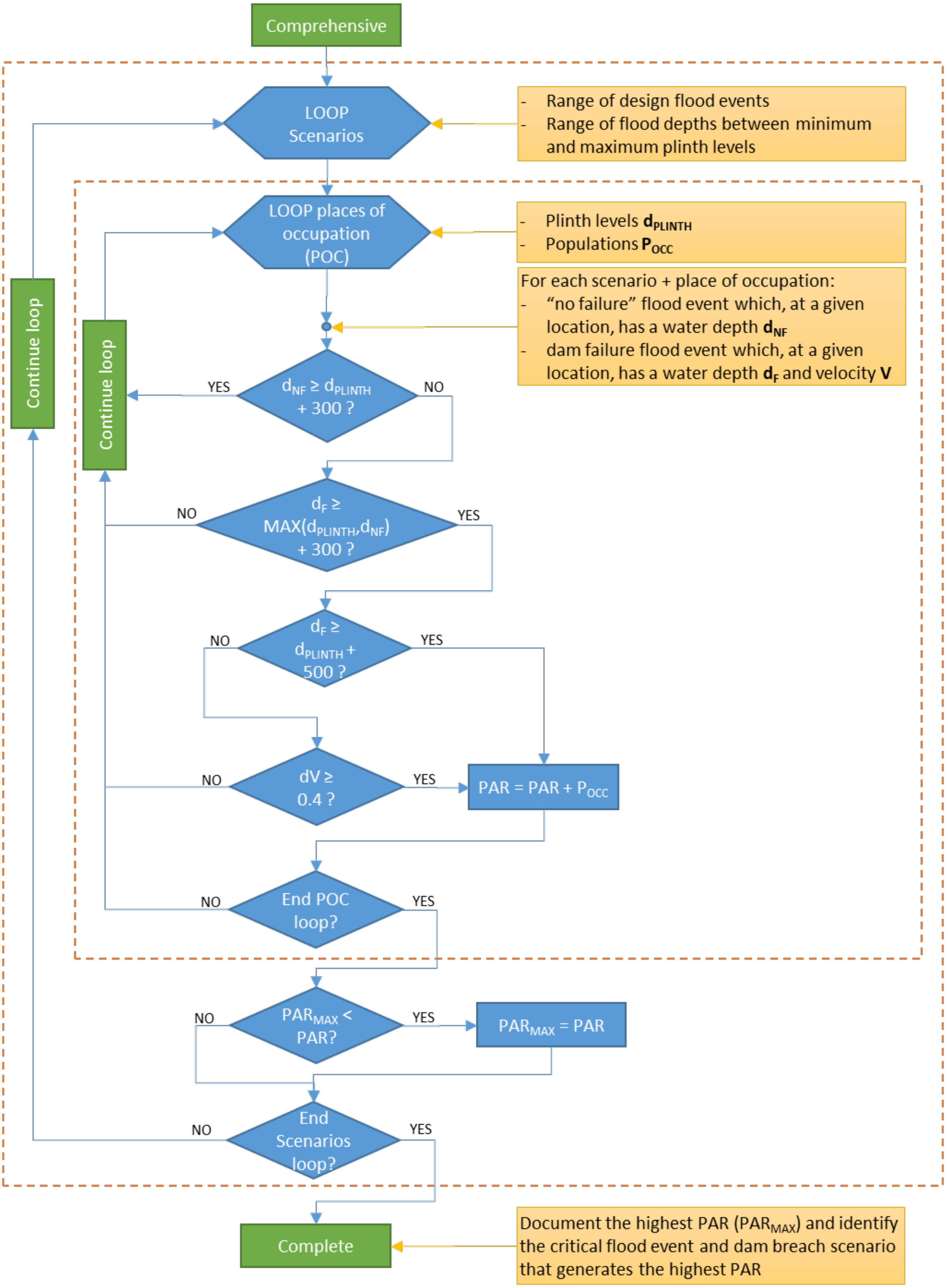


Figure 25: Procedure for assessment of PAR – methodology logic and Excel formula

Logic to identify dam failure PAR:

- Set $PAR_{MAX} = 0$
- LOOP through all identified flooding events and dam failure scenarios
    - Set PAR = 0
    - LOOP through all identified places of occupation
        - Test if PAR exists in the place of occupation, considering depth (d) and hazard (dV) thresholds and comparison between the "no failure" flood event (NF) and the dam failure flood event (F)
            - IF $d_{NF} \geq d_{PLINTH}$ + 300mm THEN
                - PAR = PAR + 0
            - ELSEIF $d_F \geq MAX(d_{PLINTH}, d_{NF})$ + 300mm THEN
                - IF simplified THEN
                    - PAR = PAR + P_{OCC}
                - ELSEIF comprehensive THEN
                    - IF $d_F \geq d_{PLINTH}$ + 500mm THEN
                        - PAR = PAR + P_{OCC}
                    - ELSEIF $dV \geq 0.4m^2/s$ THEN
                        - PAR = PAR + P_{OCC}
                    - ELSE
                        - PAR = PAR + 0
                    - ENDIF
                - ENDIF
            - ELSE
                - PAR = PAR + 0
            - ENDIF
    - Continue LOOP
    - IF PAR_{MAX} < PAR THEN
        - PAR_{MAX} = PAR
- Continue LOOP
- Reported PAR = PAR_{MAX}

Excel formula logic:

```
=IF(DNF>=DPLINTH+300/1000,0,
IF(DF>=MAX(DPLINTH,DNF)+300/1000,
IF(V=0,POCC,
IF(DF>=DPLINTH+500/1000,POCC,
IF(DF*V>=0.4,POCC,0)
)),0))
```

Appendix 10 Description of Depth (D) and depth x velocity (DV) thresholds for PAR

Thresholds

Places of occupation within the failure impact zone are identified as populations at risk if the thresholds in Table 18 exceed the plinth level of the structure.

The simplified and comprehensive assessment approaches (with and without velocities considered) are described in detail in Section 2.4.5 and **Appendix 9**.

Further clarification of the plinth level concept is provided in Section 2.4.5.

The following points apply to the criteria in the table:

- Maximum DV should be calculated by multiplying water depths at a given location with the corresponding velocity for the same location and timestep.
- The comprehensive assessment methodology is consistent with the simplified assessment except for failure event depths between 300 and 500mm.
- The simplified methodology should only be applied when DV cannot be reliably determined.
- The DV thresholds reflect a reasonably conservative view of flood hazard.
    - Figure 26, which is described in ARR (2016), provides detail on flood hazard criteria for people.
    - The 300 to 500 mm depth range has been adopted as there is a general agreement through experience and research that this is the limit where people of different ages and abilities can safely wade through low velocity floodwater.
    - Similarly, the 0.4 m^2/s DV criterion has also been recommended in Australian Rainfall & Runoff as a threshold for children and vulnerable people (Ball et al 2016).
    - The thresholds presented in the table are comparable to those in Figure 26, noting that the upper velocity threshold does not need to be explicitly specified because of the 300mm depth threshold.

Difference between PAR methodology and flood hazard assessment

The PAR assessment methodology is not simply a subtraction of flood hazard categorisations between two inundation events. Key differentiators:

The no-failure flood event only considers depth and not flood hazard.	As discussed in Section 2.4.3, the flood event most likely to be critical to estimating PAR has a flood depth at, or just below, the plinth. Establishing this critical flood depth would be challenging if a flood hazard categorisation was adopted rather than simply a depth threshold. A range of flood events can be applied for situations with densely populated failure impact zones (see Section 2.4.3); under such circumstances a flood hazard assessment approach could be considered valid for the flood event threshold. However, it is considered important that the assessment methodology allows for a relatively straightforward investigation of individual places of occupation.

The assessment methodology considers a threshold depth change between the no-failure flood event and the dam failure flood event.	Without this check, the assessment methodology would likely identify every place of occupation within the failure impact zone as PAR; there would be a flood event with a flood depth just below the depth threshold and then a dam failure event that is just above the depth threshold.

DV for 1D models

For 1D models with defined waterways, the average velocity for the cross-section at the place of occupation should be adopted. This velocity should then be multiplied by the maximum water depth, measured at the lowest point at the location of interest.

If velocity cannot be reliably calculated for a given section or the depth/width averaged value provided by the 1D model is not considered representative at the location of interest, it may be appropriate to apply a depth only analysis as per the simplified methodology presented in **Appendix 9.**

DV for 2D models

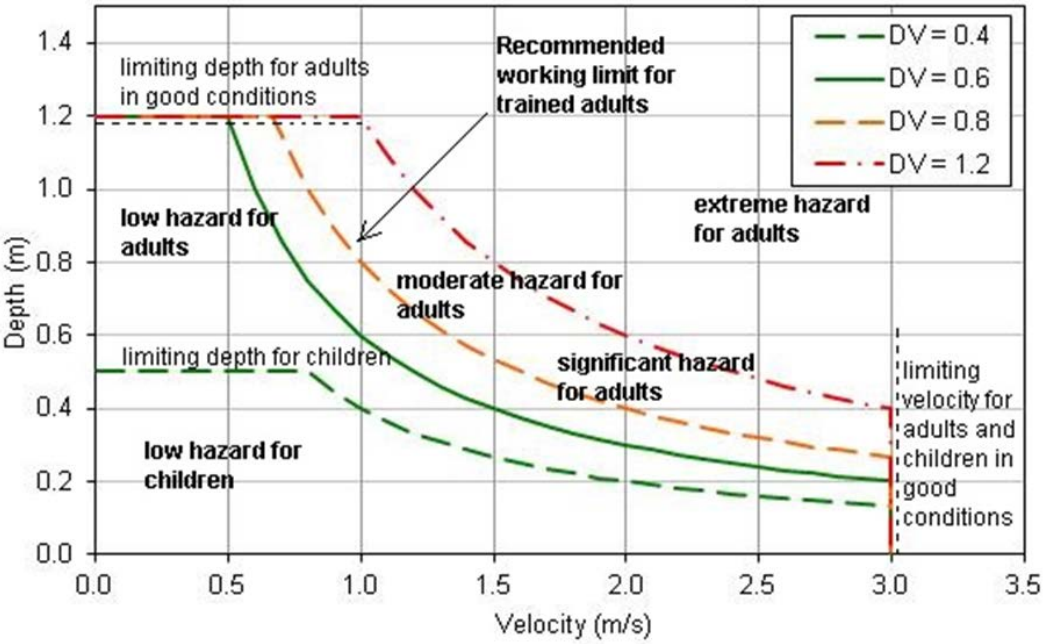
Modern 2D modelling packages generally include calculation tools to assist with the generation of DV profiles. Where possible, the highest DV value in the cells adjoining the footprint of the building should be adopted.

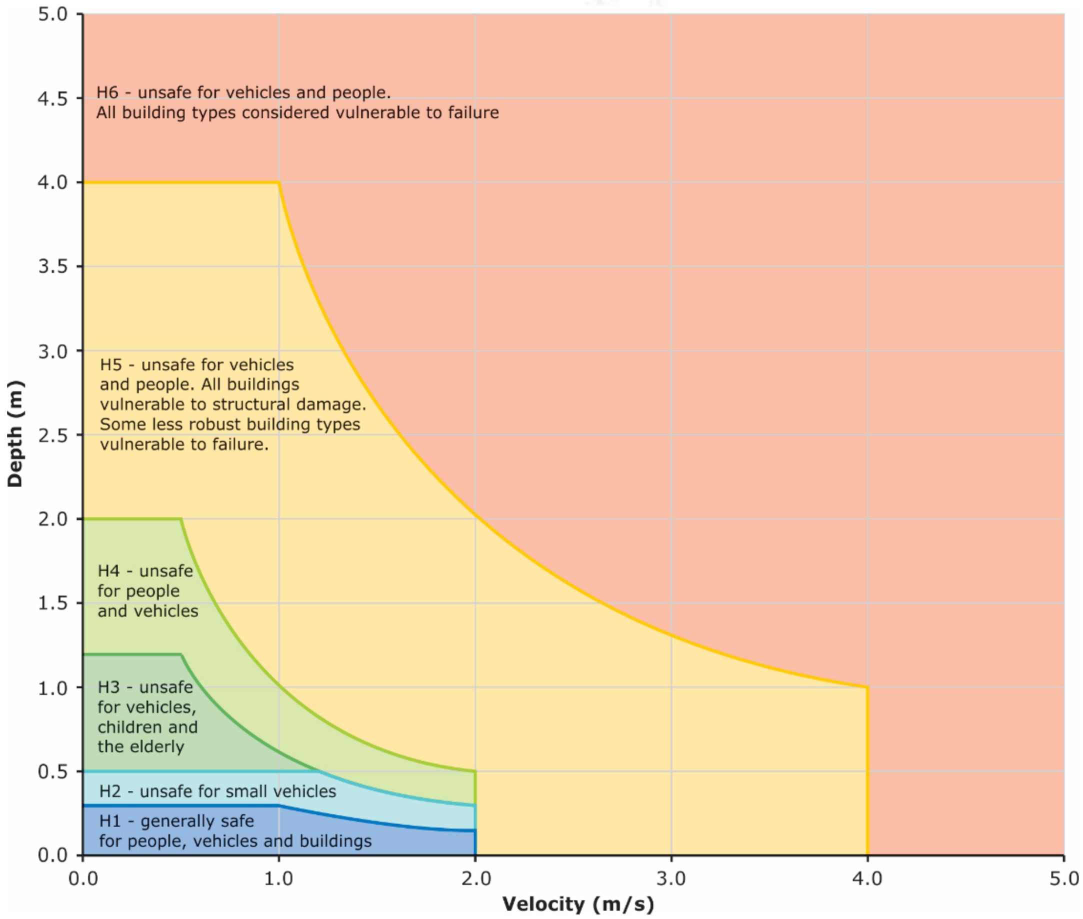
Table 18: Failure impact thresholds for determination of PAR[9]

	Depth (D) over the building's plinth (mm)		Total depth (D) x velocity (V) of flow (m^2/s)	Population at risk
	No failure flood	Dam failure flood	Dam failure flood	(yes/no)
All assessments	D ≥ 300 mm			No
	Difference in depths < 300 mm		Irrespective of DV	No
Simplified assessment		D ≥ 300 mm	DV not considered	Yes
Comprehensive assessment		300 mm ≤ D < 500 mm	DV < 0.4 m^2/s	No
		300 mm ≤ D < 500 mm	DV ≥ 0.4 m^2/s	Yes
		D ≥ 500 mm	DV not considered	Yes

[9] This table is identical to Table 9 in the main document.

Figure 26: Safety Criteria for People in Variable Flow Conditions (from Sections 7.2.3 and 7.2.7 of ARR 2016, http://book.arr.org.au.s3-website-ap-southeast-2.amazonaws.com/), which provides the basis for threshold values in Table 18. Top image describes people stability (Section 7.2.3 and bottom image describes general hazard (section 7.2.7)





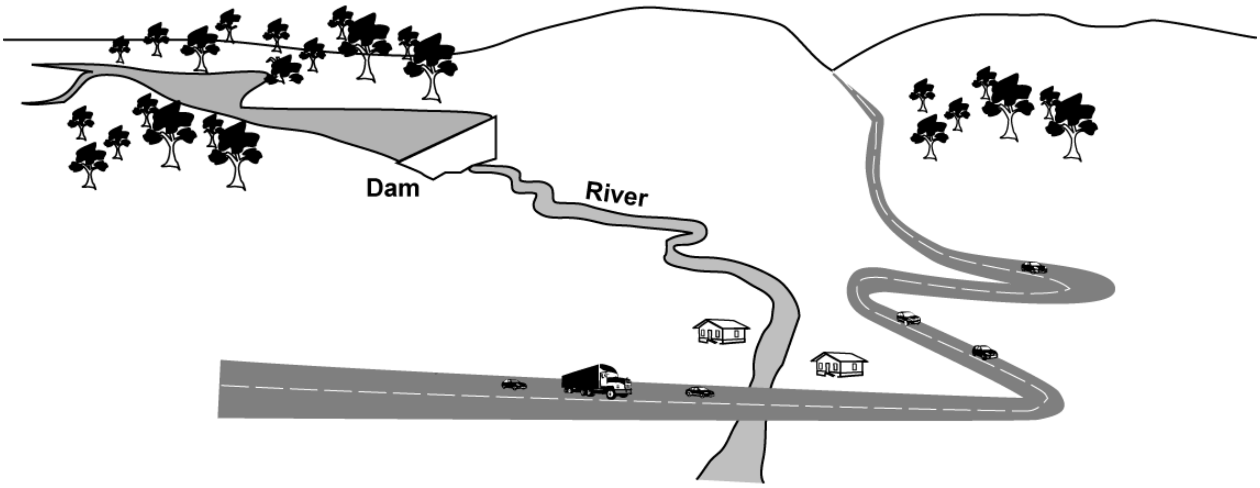
Appendix 11 Assessment of PAR on roads (if preferred)

Introduction

Consideration may be given to itinerants on roads in situations where there may be a sufficient number of potential PAR to change the failure impact rating for the dam. Road users may be at risk in the event of a dam failure if they are within or driving through the failure impact zone during a dam failure.

This section outlines methodologies for estimating the PAR on roads, noting that PAR on roads is an emerging consideration and there is currently limited formalised guidance available. The advantages and disadvantages of each method should be considered (including any not listed in this section), as well as the available data, before deciding the best method to adopt.

Figure 27: Illustration of PAR on a road



Issues to consider

There are numerous practical issues to consider:

- location specific traffic volume (based on published data or traffic survey)
- traffic patterns based on surrounding buildings (schools, shopping centres, church, sports centre, etc.) which might affect peak traffic times
- the presence of road crossings over rivers or tributaries, type of crossing and how this may affect the situation
- the topography of the road and surrounding region may influence if a driver chooses to stay on a ridge or attempt to cross the floodwater when the failure occurs
- depth and depth times velocity criteria for a road to be considered inundated and hazardous to vehicles
- driver behaviour during flood event with or without warning signage
- vehicle type and occupancy rates
- vehicle speeds when entering and crossing the flood waters
- if people are likely to abandon their vehicles
- the presence of real-time warning systems in the region
- road type e.g. one lane or multi-lane

- the effect of extreme weather situations on traffic volumes (i.e. it could be assumed that more people will stay at home during a weather event)
- effect of dam failure type e.g. sunny day failure versus flood failure

Lookup Table

The following table demonstrates a first pass relationship between average annual daily traffic (AADT) and PAR.

The table assumes a 15 minute hazard exposure time and one person per vehicle then applies the simplified method described in the next section. Assumptions and limitations also described in the next section should be considered when using this table.

Table 19: Indicative relationship between PAR per vehicle and AADT for a 15 minute hazard exposure time

Average PAR	AADT
1	100
2	200
5	500
10	1000
21	2000
52	5000
104	10000

Simplified method

This method is based on a simple calculation to determine the number of vehicles from the average annual daily traffic (AADT) data that will be impacted upon for a given hazard duration.

The method is easy to apply as it only requires data for AADT, hazard exposure time and an assumption of the number of people per vehicle. It may be useful in situations of limited complexity, or as an estimate to establish if further analysis is required.

The average PAR across a given section of road can be determined by:

$$PAR_{av} = \frac{AADT \times N_v}{24 \times \frac{60}{t_{haz}}}$$

Where:

PAR_{av} = Average population at risk	
AADT = Average annual daily traffic	Traffic data, measured as AADT for major roads and highways, is available from the Queensland Government Data website by visiting https://data.qld.gov.au and searching for 'roads'. For other roads, AADT data may also be obtained from some local governments, either through their website or by request. If AADT data is not available for a given road, it may be necessary to estimate road usage through traffic counters or extrapolated from a manual traffic survey.
N_v = Assumed number of people per vehicle	Car occupancy rates can be estimated this considering the predominant vehicle types and infrastructure in the area and testing assumptions for sensitivity. The Austroads website (www.austroads.com.au) also publishes vehicle occupancy statistics for some Queensland centres.
t_{haz} = The hazard exposure time (minutes)	The hazard exposure time (t_{haz}) should reflect the duration of the dam failure at the road site of interest. This can be extracted from the assessment outputs by analysing time series hydrographs at key points of interest and estimating how long vehicles may be exposed to the hazard. Alternatively, the break formation time can be adopted as an initial estimate. As a starting point, research has shown that still water depths over 300 mm may be unsafe for small vehicles and over 500 mm for larger vehicles. At velocities of 3.0 m/s, these depths decrease to 100 mm for a small vehicle and 200 mm for larger vehicles (Cox et al 2010).

The method does not consider driver behaviour, assumes that any vehicle within the hazard zone is potentially at risk regardless of its type and speed, and assumes there is an even distribution of vehicles across an entire day. Sensitivity testing is recommended to assess the impact of these assumptions, particularly for events which may affect the distribution of traffic cycles over the day (for example shopping centres, schools or roadworks).It may be necessary to undertake a more comprehensive investigation when considering roads with higher AADTs.

Example calculation

A 10 m high, 100 ML dam is situated upstream of a minor rural highway with an AADT of 1000 vehicles. Field observations suggest that large cars and utilities with an average of two people per vehicle predominantly use the road.

The FIA determined that there were also two houses in the impact zone, giving a PAR of 5.6. The hydraulic model used for the FIA suggests that a particular section of this road may be impacted by 500 mm of water for up to 15 minutes.

Based on this information:

AADT = 1000 vehicles
N_v = 2
t_{haz} = 15

$$PAR_{av} = \frac{AADT \ \times N_v}{24 \times \frac{60}{t_{haz}}}$$

$$PAR_{av} = \frac{1000 \ \times 2}{24 \times \frac{60}{15}}$$

Therefore PAR_{av} = 20.8 people

Given that the FIA has already established a PAR of 5.6 people, the total PAR is therefore approximately 26 people (i.e. 5.6 + 20.8).

Consequently, in this case, the road would have a category one failure impact rating regardless of whether the road was included in the analysis or not.

Other methodologies for assessing PAR on roads

There are several other established methods for assessing PAR on roads. These include the Graham Method, the Campbell Method and the GHD Method.

Graham Method (2008)	The Graham Method is based around a simple empirical relationship. It does not take account of actual hazard experienced at the road or traffic flow in a quantitative manner. Graham method should only be used in the absence of road specific hazard or traffic data.
Campbell Method (2013)	The Campbell Method calculates PAR on each section of inundated road as a whole. This calculation is based on a hazard type, traffic volume, vehicle speed, vehicle occupancy, the probability of a driver taking action to avoid the hazard, the probability of an accident given driver behaviour and the fatality rate following an accident. Although the Campbell method is simple to implement, some criteria may be subjective. There may also be sensitivity issues regarding road hazards vary across the length of a road.
GHD Method (2016)	The GHD Method (Woodman et al 2016) calculates the PAR on each section of inundated road and attempts to make considerations for driver behaviour, vehicle stability and flood severity along as they vary across a given section of road. It should be noted that the method requires access to traffic volume, average speed data as well as depth and depth time velocity information in the hazard area from a 2D hydraulic model.
LIFESIM	LIFESim is a modular, spatially-distributed, dynamic simulation system for estimating potential life loss from dam and levee failure floods. Development of LIFESim has been sponsored by the U.S. Army Corps of Engineers (USACE) and the Australian National Committee on Large Dams (ANCOLD).