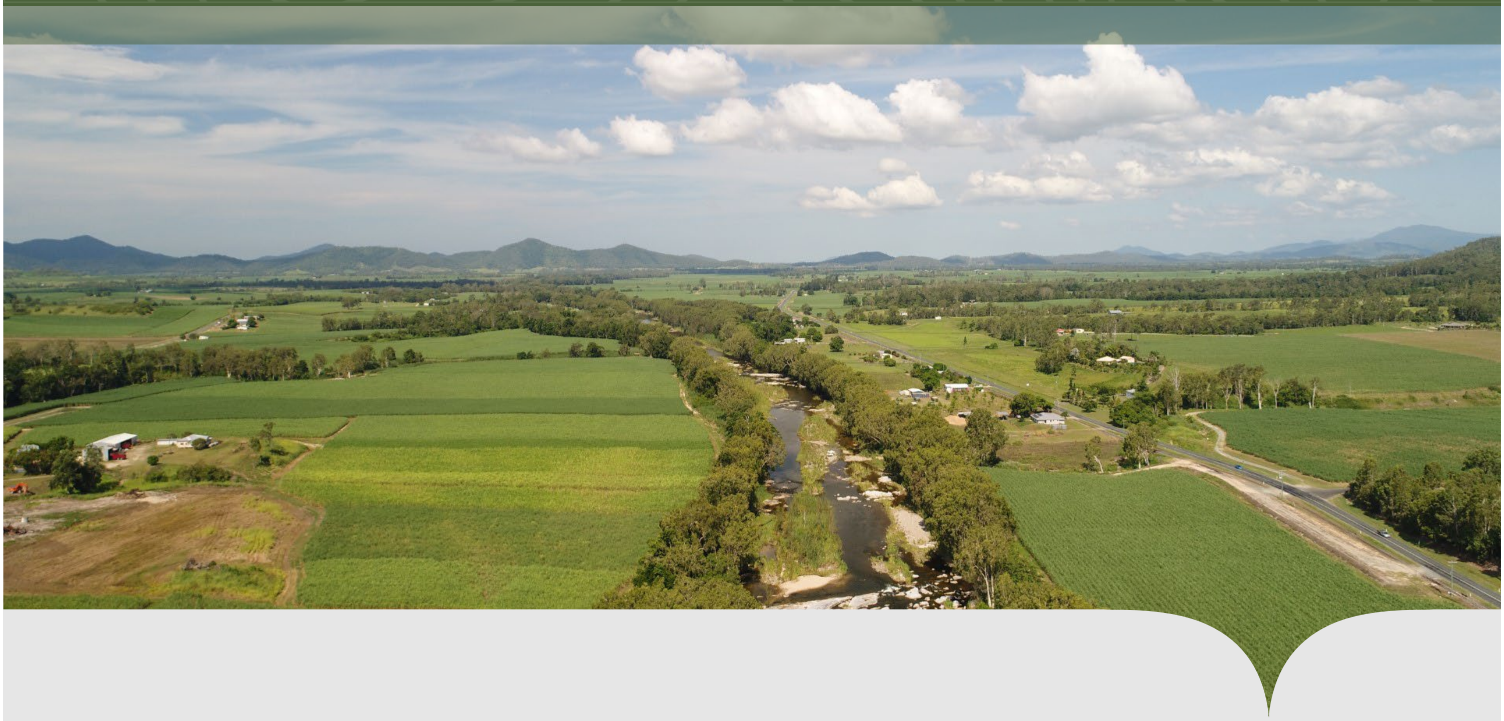
Queensland Government

Department of Regional Development, Manufacturing and Water



Guidelines on Safety Assessments for Referable Dams

November 2023

Version 8

rdmw.qld.gov.au

Acknowledgement of Traditional Owners

We respectfully acknowledge the Aboriginal and Torres Strait Islander peoples as the Traditional Owners and Custodians of this Country – the lands and seas on which we meet, live, learn, work and play. We acknowledge those of the past, the Ancestors whose strength has nurtured this land and its people, and we recognise their connection to land, sea and community. We pay our respects to them, their culture and to their Elders past and present.

This publication has been compiled by the Department of Regional Development Manufacturing and Water.

Interpreter statement:

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Summary

This guideline:

- Is an approved guideline under s572 of the *Water Supply (Safety and Reliability) Act 2008* (Act[1]).
  - It is to be used in the process of applying dam safety conditions (DSC) to a referable dam, that has been issued by a duly authorised delegate of the chief executive pursuant to s354(2) of the Act, to ensure suitable dam safety standards are applied under the Act.
  - Development permit conditions imposed under the provisions of the Act and the *Planning Act 2016* can 'call up' or reference relevant sections of these guidelines as a way of undertaking particular activities.
- Describes:
  - A risk assessment.
  - A standards-based assessment (acceptable flood capacity).
  - Other considerations described in Section 3.5.
- Describes circumstances and timings associated with addressing a dam safety risk:
  - Unacceptable risks requiring immediate action.
  - Short term risks requiring consideration of reducing full supply level at a dam.
  - Upgrade schedules to address long term risks.

While this guideline is intended for referable dams in Queensland, the principles described apply to all dams and similar infrastructure.

This guideline does not address aspects associated with failure impact assessments, emergency action plans and dam safety management programs; these are described in separate published guidelines.

Content is generally consistent with the Australian National Committee on Large Dams' (ANCOLD) Risk Assessment Guidelines (2022) but also considers developments in other Australian and international jurisdictions.

This guideline has been developed by the dam safety team of the Department of Regional Development Manufacturing and Water with input and review from dam owners and industry stakeholders in Queensland. It reflects their knowledge and experience.

While the primary audience for the guideline is dam owners and operators the contents are intended to be informative guidance for all stakeholders.

[1] https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2008-034

How to use this guideline

Section	Description	Intended readers
Introduction	The purpose of, and responsibilities associated with, dam safety in Queensland. A comparison between this guideline and the corresponding ANCOLD guideline is provided.	Primarily owners and operators of referable dams or their employees and consultants. Secondly, other dam owners, decision makers and those wishing to understand the context and justification of dam safety standards.
Background	The background information includes discourses on particular aspects of dam safety. Its content may not necessarily fully resolve an issue or provide full clarity of intent; rather it provides context to specific recommendations provided elsewhere.	
Safety assessment (incorporating standards and risk based methodologies)	Relevant information to support an assessment of safety of a referable dam in Queensland.	Primarily dam engineers, dam operators and supervisors responsible for the management of a referable dam.
Construction risks	Requirements for dam safety during construction.	
Timeliness of addressing intolerable risks	Description of categories of intolerable risks at dams and recommended responses. This includes descriptions of: • Circumstances where reduction of full supply level is applied for dam safety reasons. • Dam safety upgrade timeframes with specific upgrade schedules.	
References	References to scientific literature and industry guidelines are provided.	
Appendices	Appendices to support the guideline and provide background information.	

Version history

<table>
<tr><th>Version / Date</th><th>Comment</th></tr>
<tr><td>1. February 2007</td><td>Original approval; prior to this acceptable flood capacity was a component of the Queensland dam safety management guidelines.</td></tr>
<tr><td>2. May 2010</td><td rowspan="4">Modifications reflecting progressive legislative amendments and adjustments to upgrade schedule.</td></tr>
<tr><td>3. December 2012</td></tr>
<tr><td>4. August 2016</td></tr>
<tr><td>5. July 2017</td></tr>
<tr><td>6. December 2019</td><td>An interim and minor revision to address a specific requirement relating to definitions associated with reducing full supply level of a dam for safety reasons.
• A revision of Section 4.3: Situations requiring consideration of reducing the full supply level of dam for safety reasons. The revision includes clarification of the description of unacceptable risk and interim risk reduction measures and its application to section 399B of the Water Supply (Safety and Reliability) Act 2008.
• Replacement of Department of Energy and Water Supply (DEWS) with Department of Natural Resources, Mines and Energy (DNRME) throughout.
• Inclusion of a version history.</td></tr>
<tr><td>7. November 2021</td><td>Why a revision was considered necessary:
• Upgrade timings
– The previous version provided limited evidence to support the deadline dates of 2025 and 2035 for dam safety upgrades.
– The regulatory framework had no requirement for dam owners to report on progress of dam upgrade projects.
– The 2025 upgrade date applied to standards-based assessed dams with AFC < 65%. These dams could defer this upgrade date by conducting a risk assessment, which has a single date requirement of 2035.
• Need to contemporise
– The title of the guideline did not reflect progression towards risk-based methodologies.
– Some content was not considered relevant to the intent of this guideline or is better explained elsewhere.
– Indicators of Australian life expectancy and mortality rates have changed.
– Department names and other minor housekeeping adjustments were required.
– The previous version set out a number of processes and recommended parameters without accompanying explanation.
Significant changes include:
• Guideline title adjusted to reflect intent of guideline and risk-based assessment techniques (which don’t refer to an acceptable flood capacity).
• Adjustments to individual and societal risk requirements.
• Exclusion of the previous ALARP cost-benefit analysis methodology, replaced by a reference to CSSL as described in ANCOLD (2003).
• Revision of upgrade timings, including annual upgrade project plan reports.
• Removal of descriptions no longer considered relevant.
• Additional descriptions included where considered relevant.</td></tr>
<tr><td>8. November 2023</td><td>Changes include:
• Further discussion on addressing climate change.
• Further discussion on upgrade reporting requirements.
• Adjustment to Section 5.3.2: Determination of upgrade schedule.
• Update references to consider ANCOLD (2022) rather than ANCOLD (2003).
• Removal of references to October 2022 reporting requirements.</td></tr>
</table>

General information

The purpose of the Act is to provide for the safety and reliability of water supply. The purpose is achieved primarily by providing for:

- a regulatory framework for providing water and sewerage services in the State, including functions and powers of service providers and
- a regulatory framework for providing recycled water and drinking water quality, primarily for protecting public health and
- the regulation of referable dams and
- flood mitigation responsibilities and
- protecting the interests of customers of service providers.

This guideline has been prepared to inform the dam owner about dam safety conditions. In publishing this guideline the chief executive does not seek to supplant the responsibilities of the dam owner to ensure dam safety risks are tolerable, rather to establish the regulatory framework and process to support and encourage good practice.

Disclaimer

Dam owners can be liable for loss or damage caused by the failure of or escape of water from a dam. s364 of the Water Supply (Safety and Reliability) Act 2008 (Act) states:

'Nothing in this chapter affects the liability of a dam owner or operator for any loss or damage caused by the failure of a dam or the escape of water from the dam'.

The provisions of the Act will override this guideline in the event of any inconsistency between the Act and this guideline.

No responsibility is accepted for actions taken or any losses sustained based on reliance on an interpretation of this guideline to the exclusion of the relevant legislative provisions.

Dam owners and their agents are reminded that they must obtain their own legal and specialist technical and engineering advice about whether their actions will meet the requirements of the relevant legislation and are appropriate in their particular circumstances.

This guideline contains checklists and matters to consider. There is a risk that these checklists are incomplete as there may be other issues to consider that may be unique to a particular dam.

It is the responsibility of each dam owner to consider whether there are any matters beyond those contained in this guideline which may be of relevance to their dam.

The dam safety regulator is considered an informed source of knowledge in dam safety matters and is frequently asked to provide opinion or comment. This is provided within the constraints of the regulator's resource availability and time and is not intended to replace rigorous technical investigations to support or refute the opinion or comment.

No warranty is given to dam owners in relation to this guideline (including as to accuracy, reliability, completeness, currency or suitability) and no liability is accepted (including, without limitation, liability in negligence) for any loss, damage or costs (including consequential loss) relating to any use of this guideline.

Glossary

Term (abbreviation)	Description
Annual exceedance probability (AEP)	The probability that a given magnitude of event will be exceeded in any one year. Can be described as a probability (fraction of 1), percentage or a '1 in x year AEP', for example a 0.01 AEP, 1% AEP and 1 in 100-year AEP.
Acceptable Flood Capacity (AFC)	The flood event the dam spillway must have the capacity to pass without causing failure of the dam. AFC is derived from the PAR and failure consequence category using methods described in Section 3.3. AFC is often expressed as a flood with a specific annual exceedance probability (AEP). AFC has particular relevance to standards-based assessments when flooding as a cause of failure is considered in isolation. Flood capacity (or existing flood capacity) is the limiting flood event that can pass through a dam without failure. It is a proportion of the AFC flood event's inflow hydrograph which is determined as follows: 9. Discharge values of the AFC inflow hydrograph are scaled by a factor k to produce a trial flood event such that Q_{trial} = k Q_{cdse}, where: – Q_{trial} = Inflow hydrograph ordinate of the trial flood event – Q_{cdse} = Inflow hydrograph ordinate of AFC flood event – k = the proportion of AFC 10. The resultant flood is routed through the storage to determine the maximum headwater level in the reservoir. 11. Steps 1 and 2 are repeated with revised estimates of k until the maximum headwater level in the storage just reaches the dam crest or some other level at which failure of the dam would be a concern. 12. This proportion 'k' of the AFC, typically expressed as a percentage, is taken to be the flood capacity of the existing dam. Note that a risk-based assessment of a dam does not consider AFC nor flood capacity expressed as a percentage of AFC. A risk assessment will either consider a dam to have tolerable risks or not. If a dam has intolerable risks its performance is typically measured as the distance of the critical failure mode's F,N pair away from the societal limit of tolerability (measured in orders of magnitude of N and/or F) and a statement as to whether the dam meets ALARP or not.
Act	*Water Supply (Safety and Reliability) Act 2008*[2].
ALARP	As low as reasonably practicable principle, which states that risks, lower than the limit of tolerability, are tolerable only if risk reduction is impracticable or if its cost is grossly disproportionate (depending on the level of risk) to the improvement gained. See Section 2.3.
ANCOLD	The Australian National Committee on Large Dams Incorporated (ANCOLD Inc.) is an incorporated voluntary association of organisations and individual professionals with an interest in dams in Australia. ANCOLD was formed in 1937 as the Australian national committee of the International Commission on Large Dams (ICOLD), a non-government organisation established in 1928, and is one of 100 member countries. ANCOLD's mission is to be the industry body, representing its Members and Associates, disseminating knowledge, developing capability and providing guidance in achieving excellence for all aspects of dam engineering, management and associated issues. Amongst other things, this organisation publishes guidelines that are often adopted by states for dam engineering. Refer to www.ancold.org.au.
Catchment	A catchment is an area where water is collected by the natural landscape to a surface location or storage.

[2] https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2008-034.

Term (abbreviation)	Description
Certification	See RPEQ.
Chief executive	The chief executive of the department responsible for administering the provisions of the Act relating to referable dams. Sometimes referred to as the ‘dam safety regulator’ of Queensland. Reference to the chief executive includes reference to delegates under the Act.
Consequence category	Potential incremental losses and damages directly attributable to the failure of the dam. See also Section 3.3 and ANCOLD (2000).
CSSL	The cost to save a statistical life (CSSL, as described in ANCOLD, 2022).
Dam	Has the same meaning as in the Act. 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 above (these are often referred to as ‘associated works’ or appurtenant structures and can include features that influence dam safety). 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 the definition of ‘referable dam’ for further exclusions relevant to referable dams under the legislation and to FIA.
Dam owner	Has the same meaning as in the Act. An owner of a dam is the owner of land on which the dam is constructed or is to be constructed. Such an owner is any of the following, and includes the occupier of the land: • 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 licence 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.
Dam project	Works on an existing or new dam, including stages of specification, investigation (including safety review or safety assessment), design, construction, remedial works and decommissioning.
Dam safety management program	A dam safety management program is a systematic approach to managing dam safety including the required organisational structures, accountabilities, policies and procedures. It is the primary means of ensuring that dam failure risks are managed throughout the life cycle of the dam including design, construction, operation, maintenance and decommissioning. See DNRME (2020) for further information.
DSC	Dam Safety Conditions (DSC), the term generally used for safety conditions, applied by the chief executive to a referable dam. The conditions describe a set of conditions that the referable dam owner must comply with to ensure a suitable dam safety management program is applied. DSC are applied according to the consequences of dam failure, the characteristics of the dam and particular issues identified at the dam. See DNRME (2020) for further information.
Department (or DRDMW or RDMW)	Department of Regional Development Manufacturing and Water.

Term (abbreviation)	Description
	Previously responsible departments are: • Department of Natural Resources Mines and Energy (DNRME) • Department of Energy and Water Supply (DEWS) • Department of Environment and Resource Management (DERM) • Department of Natural Resources and Water (NRW) • Department of Natural Resources and Mines (NRM) • Department of Natural Resources, Mines and Water (NRMW)
Discount rate	Discount rate used in determining the net present value in CSSL calculations (refer to Section 3.4).
Emergency action plan (EAP)	Has the same meaning as in the Act. An EAP provides guidance for actions required as a result of any hazardous situations or emergency events occurring at a dam. There is a legislative requirement for all referable dams to have an approved EAP. See RDMW (2023).
Failure	Has the same meaning as in the Act. The physical collapse of all or part of a dam, or the uncontrolled release of any of its contents.
Failure event tree	A top-down, deductive failure analysis in which an undesired state of a system is analysed to combine a series of lower-level events.
Failure impact assessment (FIA)	Has the same meaning as in the Act. An assessment undertaken to determine the consequences of failure of a dam, for the purposes of deciding whether to categorise a dam as a referable dam under the Act. The assessment is described in DNRME (2018).
Failure mode	A way that failure can occur, described by a means by which element or component failures must occur to cause loss of the sub-system or system function.
Fall-back option	See standards-based assessment.
FN curve	As defined in ANCOLD (2022), '*curves that relate F (the estimated probability per year of causing N or more fatalities) to N. Such curves may be used to express societal risk to life criteria and to describe the safety levels of particular facilities (such as a dam)'.* *ANCOLD (2022)* states that FN curves are the *'preferred way of presenting societal* *risk is the use of F-N plots, where 'F' is the estimated annual probability of a failure expected to result in the loss of `N' or more lives'.*
Freeboard	Vertical distance between a stated water level and the top of the non-overflow section of a dam. The part of the freeboard that relates to the flood surcharge is sometimes referred to as the wet freeboard, and that above the flood surcharge, due to wind and other effects, is sometimes referred to as the dry freeboard.
FSL	Full supply level; level of the water surface when the water storage is at maximum operating level, when not affected by flood.
Good practice	A practice that has been proven to work well, produce good results and is therefore recommended. It is a successful experience, which has been tested and validated, in the broad sense, which has been repeated and deserves to be shared so that a greater number of people can adopt it. ANCOLD (2003a) describes good practice as '*...an authoritative consensus view across an industry*' and qualifies this statement that '*...owners should have in mind, primarily, recognised good practice in Australia.*' Further description is available in DELWP (2015).
Incremental PAR	Has the same meaning as PAR.

Term (abbreviation)	Description
Incremental PLL	Has the same meaning as PLL.
Individual risk	The increment of risk imposed on a particular individual by the existence of a hazardous facility. This increment of risk is an addition to the background risk to life, which the person would live with daily if the facility did not exist or, in the context of dam safety, if the dam did not fail (ICOLD 2005).
Intolerable risk	A referable dam has intolerable risks if: • When standards-based assessed, does not achieve 100% AFC, does not satisfy requirements for other potential failure modes (Section 3.3) or does not satisfy considerations in Section 3.5. • When risk assessed, does not satisfy individual risk tolerances, societal risk tolerances, CSSL (Section 3.4) or considerations in Section 3.5.
Loss of life	See PLL.
Notice	A written notice provided to the dam owner by the chief executive under the Act.
PAR	Population at risk. The number of persons calculated using methodologies described in a failure impact assessment (DNRME, 2018), whose safety will be at risk if the dam or the proposed dam after its construction fails. 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). DNRME (2018) provides the criteria and exclusions that define dam failure PAR. For the purposes of s346 of the Act, PAR has the meaning given to population at risk under s346(3) of the Act. See Section 2.5.
PPAR	Potential PAR. Persons initially identified as being potentially at risk if a dam or a proposed dam after its construction fails. A failure impact assessment is used to determine if PPAR are PAR (DNRME, 2018).
PLL	Probable loss of life (or Potential loss of life). The part of the population at risk (PAR) expected to lose their lives if a dam failure event occurred. PLL is calculated using methodologies described in industry literature including ANCOLD (2012 and 2022). See Section 2.5.
Probable maximum flood (PMF)	The flood resulting from probable maximum precipitation coupled with catchment conditions that are optimal for generating maximum runoff. It is a hypothetical flood estimate relevant to a specific catchment whose magnitude is such that there is negligible chance of it being exceeded. See **Appendix C**.
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. See **Appendix C**.
Probability of occurrence	Probability that the risk (event) could occur.
Referable dam	Has the same meaning as in the Act. A referable dam is one that would, in the event of failure, put a population of two or more people at risk. Referable dams are regulated under the Act for dam safety purposes. The Act defines a referable dam as a dam or proposed dam after its construction, for which: • a failure impact assessment is carried out under the Act and

Term (abbreviation)	Description
	• 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. A dam also becomes referable when: • the chief executive reasonably believes the dam has a category 1 or 2 failure impact rating and gives a referable dam notice (RDN) under the Act to the owner and • the owner does not submit a failure impact assessment disputing the RDN within the time specified in that RDN. The following cannot be considered 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 (noting that a weir typically will not have PAR, see weir definition)
RDN	Referable dam notice: described in s342A of the Act, a referable dam notice (RDN) is given to a 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.
Regulator	See chief executive.
Reservoir	An artificial lake, pond or basin for storage, regulation and control of water.
RFSL	Reduced full supply level, see Section 5.2.
Risk	Measure of the probability and severity of an adverse effect to life, health, property or the environment. In the general case, risk is estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequence. In the special case, average risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (that is, the product of the probability of occurrence and the consequence, combined over all scenarios) (ICOLD, 2005).
Risk assessment procedure	See safety assessment.
RPEQ	Registered Professional Engineer of Queensland under the Professional Engineers Act 2002[3]. See Section 1.5.
Safe	Safe, as used in this guideline, can be considered as meeting a risk that is acceptable to society. See Section 2.1.
Safety assessment (or safety evaluation, risk assessment, AFC assessment)	The method to assess whether a referable dam is of a deficient safety standard (see Sections 2.6 and 3.0).
Safety condition	Has the same meaning as in the Act. See DSC.
Safety standard	The safety standard is whether or not a dam has intolerable risks. See intolerable risk.
Safety review	An assessment of the integrity of a dam by assessing known and credible failure modes and mechanisms against safe acceptance criteria (engineering standards, dam safety guidelines) or risk management criteria. It considers all previous, as well as the need for further, engineering studies and investigations. A safety assessment is a component of a safety review. See DNRME (2020) for further information.
SFAIRP	So far as is reasonably practicable. See Section 2.3.

[3] https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2002-054.

Term (abbreviation)	Description
Small dam	See Section 3.3, Table 6.
Small dams approach	A standards-based assessment approach for small dams described in Section 3.3, Table 6.
Societal risk	Risk of widespread or large-scale detriment and multiple loss of life from the realisation of a defined hazard.
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. There can be more than one spillway at a dam (primary, secondary and auxiliary spillways). If the rate of flow is controlled by mechanical means (such as gates) it is considered a controlled spillway. If the geometry of the spillway is the only control, it is considered an uncontrolled spillway. Sometimes called bywash at small embankment dams.
Spillway adequacy	See acceptable flood capacity (AFC).
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.
Tolerability	Risk thresholds considered to be tolerable to secure certain net benefits. Risks that exceed the thresholds are intolerable.
Total PAR	See description in PAR.
USACE	United Stated Army Corps of Engineers. See https://www.usace.army.mil/.
Weir	Has the same meaning as in the Act. A barrier constructed across a watercourse below the banks of the watercourse that hinders or obstructs the flow of water in the watercourse. Weirs typically do not cause a substantial difference in water level (upstream to downstream) by the stage when the water is about to overflow the banks. A structure so described typically only generates in-bank afflux if it were to fail, so that habitable property is not incrementally impacted, there is no PAR and it is generally not referable. A structure that extends outside the banks of the watercourse, or stores water outside the banks of the watercourse, is unlikely to meet this definition of a weir. There may be circumstances where such a structure does have PAR and is referable. A weir with a variable flow control structure on its crest may require a failure impact assessment. See failure impact assessment for more information.

1.0 Introduction

1.1 Dam safety in Queensland

Dams in Queensland fulfil important roles including water supply, hydropower generation, flood and environmental management, and recreation. They provide valuable benefits to their owners and the wider community.

Dams need to be safe. Dam failure can release water in an uncontrolled manner that can result in loss of life, damage to property and environmental harm.

Dams whose failure would threaten personal safety are regulated by Queensland Government for dam safety purposes; these dams are called 'referable dams' (s341 of the Act and DNRME 2018).

Queensland's dam safety regulatory framework aims to achieve and maintain ongoing industry good practice in dam safety management through the full life of the state's referable dams so that risk to life, property and the environment is kept to within tolerable levels. The framework is guided by a set of general principles that seek to achieve full compliance to regulation and to ensure that actions and decision-making processes are justifiable, transparent and can withstand public scrutiny. The approach is risk-based, proportionate to the level of non-compliance and applies discretion where appropriate and relevant.

A key element of the framework is its adaptability and flexibility to respond to emerging requirements and changes in standards. This is underpinned by having in place relevant guidelines that inform and guide dam owners and relevant stakeholders on appropriate standards of practice. Those guidelines published by the department are described in Section 1.7.1.

1.2 Purpose

The purpose of this guideline is to support and supplement the dam safety management guidelines (DNRME 2020).

It should be used by referable dam owners in establishing the safety status of their dam and, if necessary, bringing it to an acceptable level of safety.

1.3 How to be compliant with this guideline

Queensland's referable dam safety regulatory framework operates under the Act and the Planning Act 2016[4] and captures both new water dam infrastructure development and upgrades to existing referable dams.

The chief executive has the power to impose or change dam safety conditions (DSC) on referable dams for dam safety purposes (s353 and s356 of the Act). DNRME (2020) describes the template DSC that typically are applied for safe management of referable dams.

Table 1 provides relevant discussion.

[4] https://www.legislation.qld.gov.au/view/pdf/inforce/current/act-2016-025.

Table 1 Safety assessment basis

DSC / Section in Act	Description	How to address
DSC 5	Template description in DNRME 2020: *Safety Assessment*[5] *(a) If a safety assessment using the Guidelines on Safety Assessments for Referable Dams 2023 results in an assessment that an upgrade is required to address an intolerable risk, an upgrade project plan in accordance with those Guidelines must be provided to the chief executive.* *Timing: By 1 October of each year*	Section 3.0 provides relevant information to support a safety assessment of a referable dam. A referable dam has intolerable risks if: • When standards-based assessed, does not achieve 100% AFC, does not satisfy requirements for other potential failure modes (Section 3.3) or does not satisfy considerations in Section 3.5. • When risk assessed, does not satisfy individual risk tolerances, societal risk tolerances, CSSL (Section 3.4) or considerations in Section 3.5. Evidence of intolerable risks emerge through dam safety management program activities such as safety reviews, comprehensive inspections, consequence assessments, failure impact assessments and other periodic or special inspections. As described in Section 5.0, a referable dam with intolerable risks can be compliant with this guideline so long as risk reduction actions, and the timeframes over which they are applied, are described and justified to the satisfaction of the regulator in an annually submitted upgrade project plan report.
DSC 6	Template description in DNRME 2020: *Design and construction* *(a) The dam must be designed and constructed, including any remedial works and decommissioning, by a suitably qualified and experienced professional engineer and described in a design report*	When a new referable dam is to be built, or when significant works are conducted for an existing referable dam, then the dam owner should consider Section 3.0 and 4.0 as well as relevant content in DNRME (2020).
DSC 9	Template description in DNRME 2020: *Safety review* *(a) A safety review of the dam must be conducted by a suitably qualified and experienced registered professional engineer, who is not an employee of the dam owner, in accordance with the Queensland Dam Safety Management Guidelines*	When a safety review is conducted for an existing referable dam, then the dam owner should consider Section 3.0 and 4.0 as well as relevant content in DNRME (2020).
S399B	Section 399B of the Act 'Dam owner may reduce full supply level in certain circumstances'	Section 5.2 provides supporting information regarding the application of section 399B of the Act.

[5] The template DSC in DNRME (2020) will be updated to refer to this revision of the guideline in the near future.

1.4 Responsibility for dam safety rests with the dam owner

Dam owners can be liable for loss or damage caused by the failure of, or escape of water from, a dam. Section 364 of the Act states:

'Nothing in this chapter affects the liability of a dam owner or operator for any loss or damage caused by the failure of a dam or the escape of water from the dam'.

Life safety risk is the primary concern associated with dam failure. Dam failure can also lead to disruption to community services, extensive economic losses and major environmental damage. A dam failure can have catastrophic consequences from which the owner, and others, may never be able to recover.

1.5 An RPEQ is required to conduct a safety assessment

A safety assessment is typically a component of broader studies including as part of the design and construction of a dam or a dam safety review. Such studies should be carried out by suitably qualified staff that meet the requirements of the *Professional Engineers Act 2002* and will typically require certification by a registered professional engineer of Queensland (RPEQ).

It is a requirement of the *Professional Engineers Act 2002* that professional engineering services in Queensland—or professional engineering services carried out interstate or overseas for a Queensland-based project—are carried out by a registered professional engineer of Queensland (RPEQ).

The only exceptions are if an unregistered person carries out a professional engineering service under the direct supervision of a RPEQ who takes full professional responsibility for the service, or the service is carried out only in accordance with a prescriptive standard.

Certification of dam safety works in Queensland typically requires engineering services to be undertaken and, therefore, requires RPEQ sign-off.

See DNRME (2020) and BPEQ (2019) for further information.

1.6 Contents not included in this guideline

This guideline only addresses matters relating to dam safety of water dams in Queensland.

This guideline does not provide detailed methodologies for assessment of dam safety; the coverage is high level and highlights specific considerations for referable dams in Queensland. Further details on the methodology should be obtained from relevant industry guidelines, including ANCOLD (see Section 1.7.2, Table 2).

This guideline does not address aspects associated with failure impact assessments, emergency action plans and dam safety management programs.

The description, development and approvals associated with a flood mitigation manual are not included in this guideline.

1.7 Other relevant guidelines

1.7.1 Queensland State regulatory guidelines

The following are guidelines and requirements applicable to water dams developed by the department:

- Guidelines on Safety Assessments for Referable Dams (this guideline).
- Guidelines for Failure Impact Assessment of Water Dams[6] (DNRME, 2018), for establishing if a dam is referable.

[6] https://www.resources.qld.gov.au/__data/assets/pdf_file/0005/78836/guidelines-failure-impact-assessment.pdf.

- Emergency Action Plan for Referable Dam Guideline[7] (RDMW, 2023), for the development of an Emergency Action Plan (EAP) for a referable dam.
- Dam Safety Management Guideline[8] (DNRME, 2020), for the development of a dam safety management program for a referable dam that complies with dam safety conditions.

Referable dams are to meet the requirements outlined in the guidelines issued by the chief executive. The guidelines are subject to review to strive to reflect contemporary good practice.

1.7.2 Use of ANCOLD guidelines

ANCOLD[9] is an Australian voluntary association of organisations and individual professionals with a common technical interest in dams. ANCOLD focuses on disseminating knowledge, developing capability, and providing guidance in achieving excellence for all aspects of dam engineering, dam management, and associated issues.

ANCOLD prepares and issues guidelines that represent good engineering practice. They are widely applied across Australia for large and small water and tailings dams. The department is a member organisation of ANCOLD and actively contributes to the development of many of these practice guidelines.

Queensland's regulatory requirements often reference ANCOLD guidelines as sources for information on suitable practices to achieve dam safety standards. Concepts developed by ANCOLD are adopted in the guidelines, providing a degree of consistency in dam safety management across Australia.

The contents and intent of this guideline generally reflects that of the corresponding ANCOLD guideline: Risk Assessment Guidelines (ANCOLD, 2022). While the concepts, principles, contents layout and definitions of this guideline seek to be consistent with ANCOLD (2022) there are differences due to the need to be consistent with specific state legislative purposes and decisions.

A summary of key differences is provided in Table 2.

[7] https://www.resources.qld.gov.au/__data/assets/pdf_file/0018/84015/eap-guideline.pdf.
[8] https://www.resources.qld.gov.au/__data/assets/pdf_file/0007/78838/dam-safety-management.pdf.
[9] https://www.ancold.org.au/.

Table 2 **Comparison with ANCOLD guidelines**

Aspect	This guideline	ANCOLD guidelines (ANCOLD, 2022)
Level of detail	High level, highlights specific considerations for referable dams in Queensland.	More detailed descriptions of assessment methodologies and discourses on their use.
Applicability	Only applicable to water dams in Queensland.	Applicable to all dams and similar structures.
Individual risks	The guideline does not specify a required threshold value but provides aspects to consider in its determination.	Separate minimum individual risk thresholds for existing dams (10^{-4}) and new dams (10^{-5}), subject to site specific considerations of PAR.
Societal risks	Societal risk curve is a single line with anchor point at annual probability of 10^{-3} and a risk neutral gradient, consistent with that applied by USACE (Snorteland, 2019).	Separate societal risk thresholds for existing dams and new dams, horizontal truncation at PLL = 100.
ALARP	Consistent with ANCOLD, CSSL with recommended parameters and a specific disproportionality. Reference made to ALARP considerations provided in ANCOLD. Additional considerations are included.	CSSL test, reference discussion on ALARP considerations.
Upgrade schedule	Consideration of timing of upgrades.	Limited description.
Application of reduced full supply level	Consideration of when to apply.	Limited description.

2.0 Background

2.1 How safe should a dam be

Dams, like any constructed infrastructure, have inherent uncertainties and as such there is always an element of risk to the community. No matter how well designed and constructed a dam cannot be 100 per cent safe; there is a very small yet finite probability of failure.

Risks associated with a dam are tolerated because the dam provides benefits, however our tolerance is limited by personal (or individual) safety concerns and safety concerns for society. These in turn reflect society's expectations of equity and fairness (i.e. a person living downstream of a dam should not be exposed to significantly greater risk than any other person), which manifest in legal obligations (both statute and common law).

A dam is considered 'safe' when it satisfies these individual, societal and legal principles (see **Appendix A** and **Appendix B**).

Any significant adjustment of standards should consider these principles. This implies a community-based decision, preferably by a community of people who are fully informed, aware of their risks and the benefits they derive by living with those risks.

The standards and their underlying principles are distinct to the engineering, science and economics of how dams are built. This means that compliance is not always economically justifiable, especially when intangible risks are difficult to quantify.

Dam safety standards increase as life safety risks increase. This presents opportunities to consider both the likelihood of the risk (i.e. a stronger dam is less likely to fail) and the consequence of the risk (i.e. numbers of people downstream).

The guiding principles and standards are recognised good practice from multiple industries and authorities globally who address community safety obligations associated with tolerable risks, as well as society's historical reactions to incidents causing multiple deaths. The principles have not fundamentally changed in the past 30 to 50 years and the standards applied to dams have not significantly changed in the past 20 years.

2.2 Factors that drive dam safety upgrades

The dam safety standards themselves have not changed significantly since the majority of Queensland's referable dams were initially constructed. The transition from standards-based to risk-based methodologies may have refined upgrade requirements for some referable dams.

The science and understanding of extreme rainfall and runoff, which has developed significantly in the past decades, has demonstrated that in some instances the magnitude and frequency of extreme floods were underestimated in the past. This is a major driver of referable dam upgrades in Queensland (see **Appendix C**).

Engineering practices and methods have improved which better identifies the need for structural improvements to dams. Typically, improvements are driven by lessons from failures and near-misses that are then collated and shared by industry.

Ageing infrastructure requires repairs and upgrades. Dams are long life assets and require periodic maintenance and repair. Damage during major floods requires repairs and can also point to a previously unknown deficiency that requires further consideration.

Dam safety standards are primarily driven by risk to life, so population growth downstream drives a need to upgrade dams. Many dams are situated on the outskirts of population centres which, through consistent population growth, can result in significant changes to the required dam safety standards.

The impacts of climate change upon safety standards of referable dams in Queensland are unclear and the subject of deep uncertainty (see Section 2.9).

2.3 Standard of care, ALARP, SFAIRP

As described in Robinson et al (2020), '*it is now essential to have positively demonstrated safety due diligence in a way that can withstand post-event judicial scrutiny*'.

As low as reasonably practicable (ALARP) or so far as is reasonably practicable (SFAIRP)?

ALARP is a test of risk acceptability, where risks are reduced to be 'as low as reasonably practicable'. A similar test is SFAIRP, where risks are reduced 'so far as is reasonably practicable'. There is confusion regarding the ALARP and SFAIRP approaches which has been exacerbated by the interpretation of ALARP adopted in ANCOLD (2003). Several references (Robinson et al 2020, Abelson 2018) consider that the ANCOLD (2003) interpretation of ALARP is indistinguishable from SFAIRP.

Irrespective of terminologies the methodologies and considerations described in this guideline are intended to address safety assessment. Key aspects to consider in this regard:

- Risks are reduced to levels that meet justifiable tolerability thresholds (i.e. individual and societal risks).
- Risks are reduced to a level '*that is tolerable and cannot be reduced further without the expenditure of costs that are grossly disproportionate to the benefit gained or where the solution is impractical to implement*'.
  - The cost to save a statistical life (CSSL) test (Section 3.4.4) is a quantifiable demonstration of risk tolerability that applies a modified cost benefit analysis. Note that this cost benefit analysis is a test of risk acceptability and not necessarily a means to economically justify a risk reduction.
- ANCOLD (2022) provides further reflections on its interpretation of ALARP and expands beyond the CSSL test to consider the level of residual risk, societal concerns, good practice and an informed community (Section 3.5.1).
- Additional aspects are proposed for dam owners to consider (Section 3.5.2).

2.4 Affordability

Affordability is not a consideration when deciding safety standards for dams, nor should it be a consideration when deciding upgrade schedules.

SWA (2013) describes how capacity to pay is not relevant, stating that '*The question of what is reasonably practicable is to be determined objectively, and not by reference to the particular PCBU*[10]*'s capacity to pay or other individual circumstances. A PCBU cannot expose people to a lower level of protection simply because it is in a lesser financial position than another PCBU facing the same hazard or risk in similar circumstances.*'

Balmforth (2021) cites ICOLD (2005) by stating that for high hazard dams '*a lack of resources cannot be used as a justification of inaction due to unaffordability*'.

2.5 Population at Risk (PAR) and Probable Loss of Life (PLL)

There are recognised methods for assessing the potential life safety consequences of dam failures described in scientific literature and applied in industry. Two distinct parameters are considered:

- Population at risk (PAR) is the number of persons whose safety will be at risk if a dam was to fail. See DNRME (2018) for a specific description as it applies to referable dams in Queensland.
  - PAR is typically more straightforward to estimate and can be directly applied from a failure impact assessment.
  - PAR can be considered as the upper limit of life safety risk associated with a dam.
  - PAR is applied to the standards-based assessment approach.
- Probable loss of life (PLL, or potential loss of life) is the expected loss of life if a dam was to fail.
  - PLL is a subset of PAR.

[10] Person conducting a business or undertaking (PCBU).

- PLL considers likelihood of life loss but assumes that a particular failure mode has occurred; in other words, PLL considers the exposure and vulnerability of impacted individuals to the hazard.
- PLL typically requires more rigorous analyses to quantify and, due to the need to predict behavioural responses, is subject to greater uncertainty.
- PLL is applied to the risk-based assessment approach.

Both parameters are:

- Consequential, meaning that dam failure is assumed (and the likelihood of the failure is not considered).
- Incremental, meaning that only persons at risk of a dam failure flood, but not the same flood without a dam failure, are considered[11].

2.6 Selection of standards and risk-based assessment approaches

There are two valid methods of assessment, standards-based (or fall-back) (Section 3.3) and risk (Section 3.4). A dam owner may choose either.

The standards-based assessment to identify the annual exceedance probability (AEP) of the acceptable flood capacity of a dam is a relatively straightforward methodology based upon PAR and consequence category. Considering that extreme floods are often the primary driver of dam safety concerns in Queensland, this focus on flood capacity to establish dam safety standards is reasonable. Note that consideration of other non-flood failure modes is also required.

Over the past 20 years philosophies of risk assessment and management have been progressively influencing the design, management and operation of water dams throughout Australia. The risk assessment methodology has matured over time, its application is more widespread and is producing more consistent results. The process encompasses all potential failure mechanisms including those unrelated to flooding. Often a standards-based assessment is applied as the basis to inform a risk-based assessment.

While comparisons vary there is some evidence to suggest that risk-based assessments lead to more thorough and informed assessments that are less conservative for flood capacity requirements compared to a standards-based approach, but with a correspondingly broader consideration and appreciation of all risks.

For small sized, small consequence dams a standards-based approach may be preferred for economic and practical reasons. A small dams approach is also available for such dams.

Beyond the limitations of application of the small dams approach, there is no requirement in this guideline to adopt one approach over the other.

2.7 Practicalities of consequence avoidance

Dam safety standards provide opportunities to manage dam safety by event avoidance (i.e. make a dam safer) or consequence avoidance (i.e. make downstream communities safer).

The predominant dam safety improvement measure is to make a dam safer. This is a reasonable approach because it improves the resilience of the dam's benefits (e.g. water supply security, etc) and there is more certainty in the reliability and longevity of the measures.

Consequence avoidance measures may be economical but are arguably more difficult to implement:

- Dam failure risk is widely understood to be the responsibility of a dam owner who may be challenged to rely on third parties to implement consequence avoidance measures.

[11] When considering emergency response; incremental PAR or PLL should not be used to assess effectiveness of emergency response measures such as distribution of alerts, coordination of evacuations, etc. Total number impacted is used, with Total PAR preferred as it represents the upper limit of life safety consequence associated with a dam.

- Planning controls downstream of dams such as land acquisition and land zoning are challenged by uncertainties that the measures will be permanent. If appropriately enabled and enforced, future dam upgrades could be avoided or accounted for as part of future development plans.
- Effective emergency response procedures can reduce life safety consequences during a dam failure event but are less likely to mitigate damage to infrastructure, the environment, economic ventures or ancillary health issues that could arise following a failure event. Quantifying the effectiveness of such procedures is challenged by the need to understand, conceptualise and simulate human behaviour accurately and consistently during disasters. This is difficult to assign reliable parameters to and prove accuracy for.
- Active protection works downstream that provide secondary community benefits, such as levees to protect population centres or elevated evacuation routes that provide roadways for traffic, could be preferred consequence mitigation measures.
- Consequence avoidance measures typically require community awareness of the risks to which they are subject to.
- Consequence avoidance can be considered as a supplemental measure to reduce risks in some situations.

Despite the challenges to implement and quantify it is recommended that consequence avoidance measures be considered where practical as a risk reduction measure.

2.8 Community awareness of dam safety risk

IGEM (2019) and Snorteland (2019) highlight the obligation to inform the community of their risks, especially if those risks change.

As a published document this guideline seeks to succinctly describe risk tolerability in a manner that is understood by the community. Emergency action plans, also published, provide information on risks associated with each referable dam and recommended response measures should there be a dam safety emergency.

It is recommended that dam owners be transparent with their knowledge of dam safety risks and seek to educate and inform the community when opportunities become available.

2.9 Climate change

DES (2019) among others highlight the need to consider the impacts of climate change in infrastructure planning. It is no longer a question of if climate change should be considered (although the severity of the impact is uncertain), it is a question of how significant the impact will be and when it will occur.

Climate change will impact all major factors that influence flood risk on dams, in particular the frequency and seasonality of rainfalls, their spatio-temporal distribution, antecedent conditions and operational conditions. It impacts analyses that assume non-stationarity of climatic conditions. There is considerable uncertainty surrounding these impacts, however recent studies are providing better quantification of the impacts and the uncertainties; Visser et al (2022) has provided a quantification of how climate change influences extreme rainfall events, and an expectation of influence upon flooding up to the probable maximum flood, which is often critical for dam design.

Irrespective of the uncertainties, when applying a prudent and good practice approach it is expected that plans and designs for a dam project should include a robust and fit-for-purpose consideration of the risks linked to climate change impacts over the design life of the dam. A dam owner should be asking whether “identified risks are manageable over the design life” as part of their questioning as to whether risks can be reduced to as low as reasonably practicable within the relevant timeframe.

Further research is needed to better understand the risks and potential impacts of such extreme weather events and, for the present, it is necessary to recognise that any projections of changes in extreme flood risk are subject to deep uncertainty (Wasko et al, 2021). Dam owners should consider the risks and potential consequences of extreme weather events linked to climate change and reflect upon the most recent, recognised good practice literature of the day.

Industry guidance is still evolving on this topic[12]. In the absence of more comprehensive guidance and advice an optional, high level, decision making process outlined in Table 3 may be useful when considering how progressive improvements in understanding over time may impact the ‘robustness of design’ of a dam.

[12] Other references noted include DTMR (2020) and ARR (2019).

Table 3 An optional, high level decision making process for addressing climate change risks for referable dams

Option	Criteria	Examples
1. No resilience or redundancy	• If the activity has low consequence if it failed, or • can easily be repaired or upgraded in future, or • has a short design life	• Interim works associated with construction
2. Build for end of design life scenario – Adopt a design standard that incorporates uncertainties	• If the activity has an unacceptably high consequence if it failed, or • the uncertainties surrounding projected future climate change impacts cannot be tolerated, or • if the resources/effort required for building a design that incorporates uncertainties at an earlier stage is cost effective, or • it is impractical to upgrade the asset(s) at a future date, or • if option 3 cannot be safely applied	• Critical infrastructure for which the uncertainties surrounding selection of an upgrade trigger make a staged upgrade unacceptably risky • The additional project costs for a design to meet worst case climate future conditions are not prohibitive • Cost benefits analysis shows a net benefit in up front expenditure which can be funded
3. Progressive modification – Build resilience now into design, and identify future stages to meet changing design requirements (which may differ from that projected today)	• If options 1 and 2 cannot be applied, then consider: – implementing any "easy wins" earlier to make future upgrades easier, and – identifying triggers for when future upgrades need to occur, and associated probabilities and timings, to guide planning for future investment decisions	• Easy wins for resilient design: – A relatively inexpensive enhanced foundation design approach to accommodate a future raise – When upgrading a dam, opting for a buttress design over a post-tension anchor design to provide more future flexibility in design • Future triggers – After performing a climate sensitivity analysis, decide to upgrade a dam only after (say) the mean 1.5^{0}C future climate state is reached. At that time a more accurate projection of extreme rainfall and runoff should be available[13]
Irrespective of the option selected, consider if steps taken are reasonably practicable to avoid future harms and damage	• Is the adopted design life reasonable? • Are decisions adequately justified and documented? • Is the dam owner fully aware of the risks? • Industry good practice is understood, and has been considered? • How does performance compare with other organisations with similar dams and/or similar risks?	• A climate sensitive dam policy has been adopted that is consistent with other dam owners with similar consequence dams. • Emerging and competent scientific research reveals a higher and more consequential risk of climate change than previously thought, is incorporated into your dam upgrade program. • Your consideration of the risk of climate change impacts as part of a dam project is too little and the dam fails due to a foreseeable flood event of a magnitude consistent with advice contained in best practice literature.

[13] Choice of baseline date may influence assessment of future triggers that consider global temperature rise. For example, IPCC (2023) highlights that 2011-2020 was around 1.1°C warmer than 1850-1900, however rates of rise have varied.

3.0 Safety assessment (incorporating standards and risk-based methodologies)

3.1 Overview

The following section provides relevant information to support an assessment of safety of a referable dam in Queensland.

Steps to consider are shown in Figure 1 and described in subsequent sub-sections.

It is expected that other relevant industry sources would also be required; for example, the relevant ANCOLD guidelines.

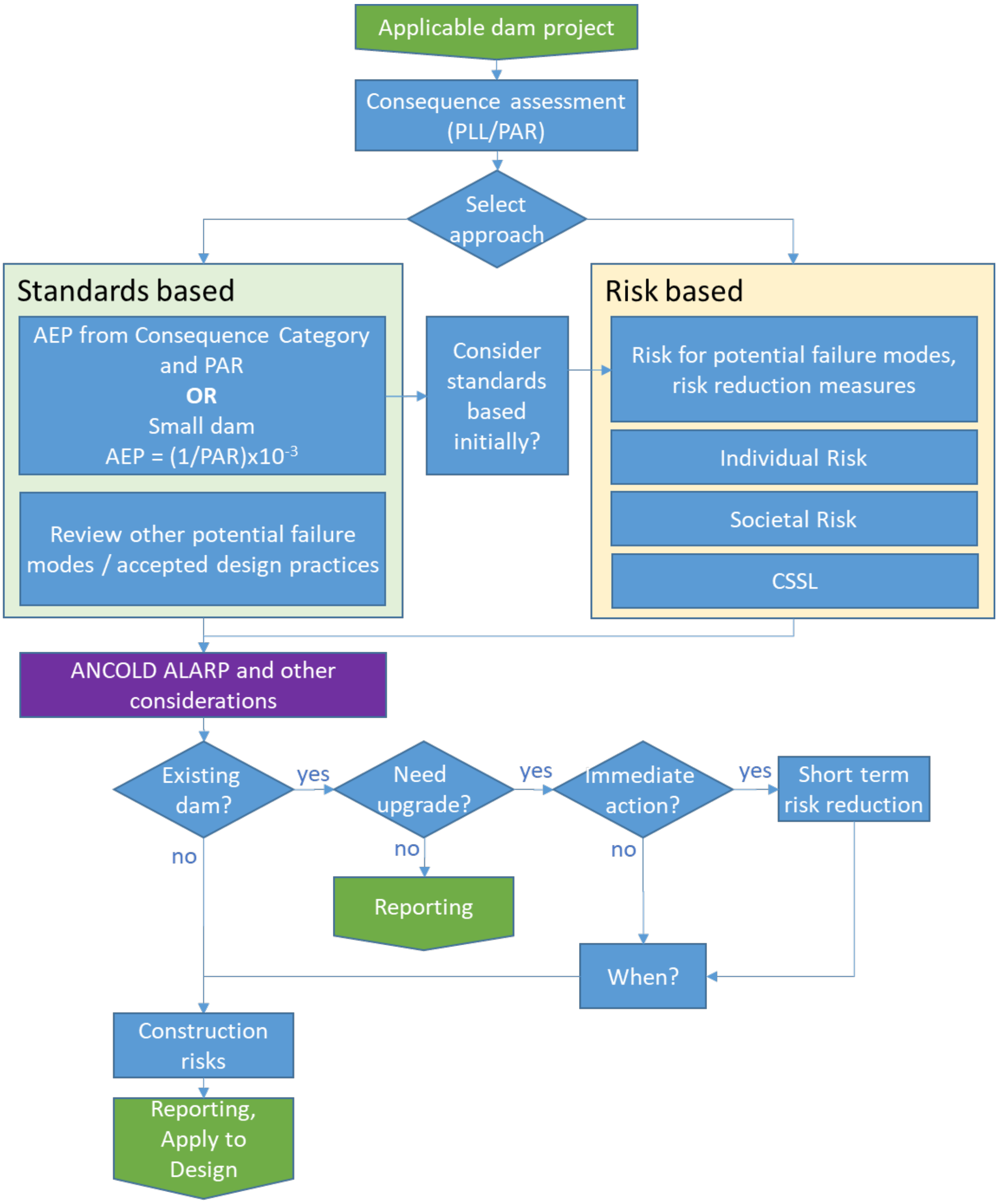

Figure 1 **Flowchart describing safety assessment of a referable dam project**

3.2 Consequence assessment

A consequence assessment predicts PAR and/or PLL for a range of potential failure modes which will then inform dam safety standards.

DNRME (2018) provides guidance on specific requirements for establishing PAR for referable dams in Queensland.

ANCOLD (2012) provides guidance on consequence assessment.

See Section 2.7 for further discussion on consequence avoidance measures.

3.3 Standards-based (or fall-back) assessment

A standards-based assessment requires consideration of all potential failure modes. Acceptable flood capacity (AFC), which is often the most important aspect of the assessment, is described here. Other aspects, such as structural stability, freeboard, operational failure or earthquake activity must also be considered. These matters are dealt with in separate industry guidelines (e.g., ANCOLD) and scientific and engineering literature.

The AFC is the flood event the dam spillway must have the capacity to pass without causing failure of the dam.

Standards-based assessment requires the identification of flood failure consequence category (Table 4) which, in combination with PAR, is used to identify the annual exceedance probability of the AFC (Table 5).

Alternatively, a small dams approach can be considered under specific circumstances (Table 6).

Subsequent hydrologic and hydraulic analyses of dam performance to the AFC event should assume wet antecedent catchment conditions and an initial full supply level in the dam reservoir.

Section 3.5 should be considered.

Table 4 Standards-based assessment: consequence category for referable dams[14]

PAR	Severity of damage and loss			
	Negligible	Minor	Medium	Major
$2 \le PAR \le 10$	Low[1]	Significant[4]	Significant[4]	High C[5]
$10 < PAR \le 100$	N/A[1]	Significant[2,4]	High C[5]	High B[5]
$100 < PAR \le 1{,}000$		N/A[2]	High A[5]	High A[5]
$PAR > 1{,}000$			N/A[3]	Extreme[5]

Notes:

1. It is unlikely that the severity of damage and loss will be ‘negligible’ where one or more houses are damaged.
2. Minor damage and loss would be unlikely when PAR > 10.
3. Medium damage and loss would be unlikely when the PAR > 1,000.
4. Change to High C where there is the potential for one or more lives being lost.
5. See ANCOLD (2012) for an explanation of the range of high consequence categories.

[14] Table developed from Table 3 in ANCOLD (2000b).

Table 5 Standards-based assessment: acceptable flood capacities for a range of PAR and severity of damage and loss

PAR	Severity of damage and loss: Negligible		Minor		Medium		Major	
$2 \le PAR \le 10$	Low	5.0×10^{-4} 5.0×10^{-4}	Significant	5.0×10^{-4} 1.0×10^{-4}	Significant	1.0×10^{-4} 1.0×10^{-4}	High C	1.0×10^{-5} C
$10 < PAR \le 100$		5.0×10^{-4} 1.0×10^{-4}	Significant	1.0×10^{-4} 1.0×10^{-4} C	High C	1.0×10^{-4} C B	High B	1.0×10^{-5} B
$100 < PAR \le 1000$	If in this region, go to the next highest severity of damage and loss category for the same PAR			A A	High A	A A	High A	A A
$PAR > 1000$						PMF PMF	Extreme	PMF PMF

Note:

Acceptable flood capacities are annual exceedance probabilities (AEP). Several capacities consider the flood associated with the probable maximum precipitation (PMP):

- A = PMP design flood
- B = PMP design flood or 10^{-6}, whichever is the smaller flood event
- C = PMP design flood or 10^{-5}, whichever is the smaller flood event

In the absence of any other methods recommended in scientific literature, the adjacent graph provides a simple method to estimate AEP of the PMP using catchment area (from Laurenson and Kuczera, 1999).

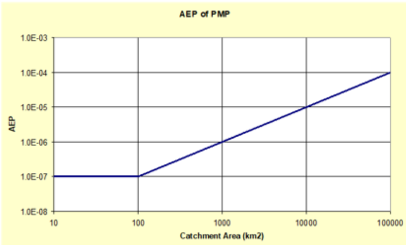

Table 6 Standards-based assessment: small dams approach

PAR	AEP of acceptable flood capacity
$2 \le PAR \le 15$	$\mathbf{AEP} = \left({}^{\mathbf{1}}/_{\mathbf{PAR}} \right) \mathbf{x\ 10^{-3}}$

Note:

The small dams approach is applicable to:

- a zoned or relatively homogeneous earthen embankment less than 12m high
- PAR ≤ 15
- uncontrolled spillways
- situations where PAR is located outside high depth/flow zones where depths of flooding of PAR < 3m and depth x velocity product < 4.6 m^2/s

The approach is not applicable to dams relying on spillways controlled by gates or other mechanical discharge control structures to pass the acceptable flood capacity.

3.4 Risk assessment

3.4.1 Methodology

The risk assessment methodology described in this guideline only covers the broad steps applied and highlights specific considerations for referable dams in Queensland (Table 7). Further detailed descriptions of the methodology should be obtained from relevant industry guidelines, including ANCOLD (2022).

Table 7 Overview of risk assessment methodology and specific considerations for referable dams in Queensland

Step
1. Identify potential failure modes
2. Estimate risk (likelihood and consequence) for each failure mode • Identify the steps to failure and the probability of occurrence of each step (often using a failure event tree). • Assess PLL associated with the failure mode (Section 3.2). • Consider risk reduction measures to address.
3. Estimate individual risk • Identify the most vulnerable person (or selection of people). • Calculate total risk to the individual by accumulating risks from each potential failure mode and considering exposure periods (Maslin et al, 2012 is a suggested reference for further guidance). • Compare total risk to the individual risk tolerability threshold (Section 3.4.2).
4. Estimate societal risk • Construct an FN curve. – Each discrete coordinate (f, N pair) is a potential failure mode's probability of failure and PLL. – f is aggregated from lowest to highest N to create F, N pairs. • Compare the FN curve to the societal limit of tolerability. – Risks satisfy societal tolerability if the FN curve is to the left or below the limit of tolerability (Figure 2, Section 3.4.3).
5. Consider CSSL • Test ALARP for risk reduction measures for each potential failure mode[15]. • Calculate a cost to save a statistical life (CSSL, Section 3.4.4). • Compare CSSL to the recommended Australian dollar value range (Section 3.4.4).
6. Assess the criteria in Section 3.5 • Review considerations in Section 3.5 (including ANCOLD ALARP).
7. Determine whether the risks are tolerable • If any of the individual, societal or other considerations (steps 3 to 6) are not met then reconsider the dam project and/or consider steps to address. – Review risk reduction measures to achieve a tolerable risk level through reducing likelihood and/or consequence of the potential failure mode (step 2). – If intolerability is significant, consider escalation of risk reduction measures (Section 5.0).
8. Prepare documentation to justify the risk position • Once tolerable risks have been achieved, reconstruct the FN curve to demonstrate the risk.

[15] As discussed in ANCOLD 2022, this is a disaggregated approach that considers an ALARP test for each potential failure mechanism. This can consider demonstration that prevention, control and mitigation measures have been addressed. These disaggregated tests may need to be aggregated to include in the CSSL test.

3.4.2 Individual risk

This guideline does not specify a required threshold individual risk tolerance but provides aspects to consider in its determination in **Appendix A**.

3.4.3 Societal risk

Selection of the threshold societal risk tolerance considers aspects described in **Appendix B**. Based on these considerations the threshold societal risk curve shown in Figure 2 applies.

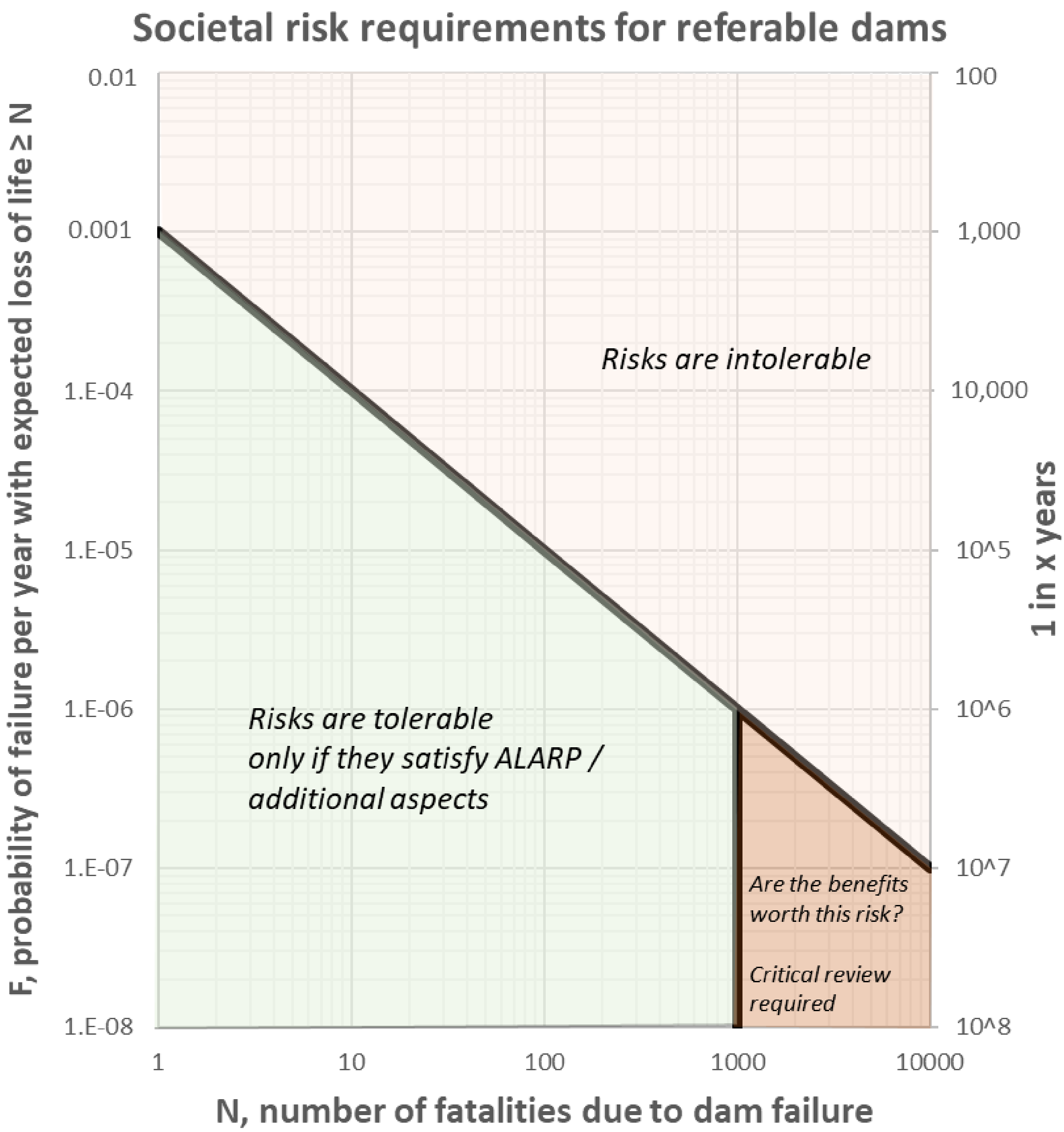

Figure 2 **Societal risk (F-N) plot**[16]

[16] As described in Section 3.5, ANCOLD (2022) considers a tolerability threshold that is one order of magnitude lower for new dams and major augmentations compared to existing dams.

3.4.4 Cost to save a statistical life (CSSL)

Cost to save a statistical life (CSSL, as described in ANCOLD 2022) is a cost-benefit metric which can help to inform a judgment for public health and safety risks.

CSSL is calculated using a cost benefit analysis where project costs and benefits are equal (i.e. a neutral cost-benefit-ratio). CSSL is then tested to assess the balance between equity (the right of individuals to be fairly and reasonably protected from life safety risks) and efficiency (the benefits of the dam to society), with the balance deliberately skewed in favour of equity (a gross disproportion).

ANCOLD (2022) provides the CSSL formula.

To annualise costs a discount rate of 7% and project life of 150 years is recommended.

Regarding disproportionality, a moderate / strong threshold is considered the minimum requirement to demonstrate ALARP (CSSL).

3.5 Other considerations

3.5.1 ANCOLD ALARP

ANCOLD (2022) provides appropriate discussion on '*considerations which contribute to a judgement that risks are ALARP*'.

3.5.2 Additional aspects

Other aspects to consider include documented demonstration of an effective dam safety management program (see DNRME 2020), defensible documentation describing and justifying appropriate assessment of harms and mitigation measures applied (see Section 3.8) and comparison to good practice and precedent.

The series of questions in Table 8 raise matters that a dam owner may also wish to consider. The questions relate both to consideration of dam failure risk as well as broader aspects of dam safety management that can contribute to risk reduction.

Table 8 Additional aspects

<table>
<tr><th>ID</th><th>Questions</th><th>Discussion / context</th></tr>
<tr><td>1</td><td>Are you achieving good practice?
• Are there industry guidelines that suggest a safer dam is needed?
• Explain why you are/are not considering these.</td><td rowspan="2">HSE (2003) defines good practice as 'those standards for controlling risk […] judged and recognised as satisfying the law, when applied to a particular relevant case, in an appropriate manner'. One measure of identifying good practice is that 'it is either written down or is a well-defined and established practice adopted by an industrial / occupational sector'.
ANCOLD (2022) highlights that good practice changes over time.
ANCOLD (2022) adopts a separate societal risk threshold for new dams and major augmentations that should be considered.</td></tr>
<tr><td>2</td><td>How do you compare to established industry practice?
• Is your dam safety management program consistent with or better than other organisations with similar dams and/or similar risks?
• Can you justify these differences?</td></tr>
<tr><td>3</td><td>Do the benefits outweigh the risks?
• What value does society derive from the dam?
• How does the value compare to the hazards?</td><td>This question relates to whether the risks posed by the dam are tolerable, noting that HSE (2001) defines a tolerable risk as 'a risk within a range that society can live with so as to secure certain net benefits'.</td></tr>
<tr><td>4</td><td>Will a dam safety upgrade increase flooding risk?</td><td>Consider whether it is reasonable that a dam upgrade, which strives to make a safer dam, may result in a conflicting outcome where flooding is worsened.</td></tr>
</table>

ID	Questions	Discussion / context
5	Are your identified risks manageable into the future? • Could downstream consequence increase in future? • Could external drivers such as climate change increase risks?	Considering future consequence is highlighted in ANCOLD (2022). DES (2019) among others highlight the need to consider climate change in infrastructure planning. It may be prudent to review latest literature on the risks of climate change upon dam design (see also Section 2.9).
6	Have you considered all practicable steps to reduce or appropriately mitigate risks? • Are there operational and management aspects that could be implemented to further reduce risk? • Are there consequence avoidance measures that could be implemented?	Section 2.7, RDMW (2023), ANCOLD (2022) and ICOLD (2001) highlight non-structural measures that can be considered to reduce risks associated with a dam.
7	Is there a sense of urgency regarding the timing of the risk reduction activity? • Is there justification for the timeframe to reduce the risk that is commensurate with the severity of the risk?	See also Section 5.0.
8	If the dam failed and there were life safety consequences, could you confidently answer the above questions?	As described in Robinson et al (2020), '*it is now essential to have positively demonstrated safety due diligence in a way that can withstand post-event judicial scrutiny*'.
9	Is PLL > 1,000? • Explain how the benefits outweigh the risks. • How do you compare to established industry good practice? • Describe how the dam safety management program applies good practice commensurate with the life safety risk of the dam, highlighting any aspects that are above and beyond minimum requirements described in DNRME, 2020. • Describe the emergency response measures in place (see RDMW, 2023).	USACE (Snorteland 2019) recognises that '*a failure producing more than 1,000 fatalities would be considered a catastrophe*' and '*requires special consideration to ensure everything reasonably practicable has been done to reduce risk. A thoughtful and careful examination of risk reduction activities is required'.* The listed bullet points provide prompts that should lead to a thoughtful and careful examination of risk reduction activities: • The first bullet point (which is consistent with Question 3) tests if the risks posed by the dam are tolerable to society. In many instances high consequence dams are essential water supply infrastructure with significant societal benefits. • The second bullet point (which is consistent with Question 2) recognises that the owners of high consequence dams should be well regarded in industry, with better-than-average dam safety resource and processes and in-depth dam infrastructure knowledge, expertise and capacity. • The third bullet point recognises the value of an effective dam safety management program, described in DNRME 2020, that is '*a demonstration of a dam owner's commitment to dam safety*', to reduce risks. It is expected that the program '*reflects the dam safety values that are a part of the dam owner's organisational culture'.* • The fourth bullet point recognises that effective emergency response can reduce (or avoid) consequence should a dam failure occur. RDMW (2023) provides guidance on emergency response measures.

3.6 Use of fuse plugs at auxiliary spillways

Auxiliary (or emergency) spillways are a secondary spillway at a dam, designed to be operated infrequently as a result of major flooding or in the event of incapacity or damage to the primary spillway.

Fuse plugs, constructed of material designed to erode in a controlled manner when overtopped, are sometimes used as auxiliary spillways. Once initiated the fuse plug erosion and subsequent release of flow is irreversible. Fuse plugs have inherent risks associated with reliability of erosion rates and the inability to control releases once activated (WGI 2003).

USBR (1987) suggests that '*in general, fuse plugs should be designed to operate only for floods with recurrence intervals that are long relative to the economic life of the project. Specifically, fuse plugs should not be designed to breach for floods with recurrence intervals less than 100 years*'. Application at existing dams generally consider activation at a threshold rarer than 1 in 100 years AEP (for example 1 in 750 at Warragamba dam and 1 in 2,000 at Copeton dam (WaterNSW 2021)).

3.7 Technical review

A technical review that is expert and independent of owner, designer and constructor can be a valuable, affordable resource to promote better dam design and construction, especially where novel construction methods are proposed. Such a review can provide detached advice and scrutiny that is unlikely to be influenced by the time and commercial constraints under which designers and contractors usually operate.

Safety assessments are to consider technical review in line with requirements described in DNRME (2020).

3.8 Reporting

A safety assessment is often a component of larger studies associated with a dam, such as to inform its design and construction or as a component of a safety review. Reporting requirements for these works (e.g. a design and construction report or safety review report) are described in DNRME (2020).

Table 9 provides a checklist of content for a safety assessment report to consider.

Table 9 Safety assessment report checklist to consider

<table>
<tr><th>Category</th><th colspan="2">Checks</th></tr>
<tr><td>General</td><td colspan="2">☐ Administrative details (name, location, lot, owner, etc)
☐ Dam features (type, size, capacity, etc)
☐ History (date of construction, investigations, etc)</td></tr>
<tr><td>Data</td><td colspan="2">☐ Historical data
☐ Recent investigations</td></tr>
<tr><td>Consequence assessment</td><td colspan="2">☐ Methodology to establish PAR / PLL
☐ Identification of PPAR
☐ Parameters applied and assumptions made
☐ Statement of accuracy and uncertainties
☐ PAR (total and incremental)
☐ PLL (total and incremental)
☐ Consequence category</td></tr>
<tr><td rowspan="3">Standards / Risk Assessment</td><td colspan="2">☐ Justification of assessment approach</td></tr>
<tr><td>Standards-based
☐ Hydrologic / hydraulic assessment
☐ AFC
☐ Identify and assess potential failure modes</td><td>Risk-based
☐ Hydrologic / hydraulic assessment
☐ Identify and assess potential failure modes
☐ Estimate risk for each failure mode
☐ Consider risk reduction measures
☐ Assess individual risk tolerance
☐ Assess societal risk tolerance
☐ Test CSSL</td></tr>
<tr><td colspan="2">☐ Other considerations in Section 3.5.</td></tr>
<tr><td>Statement of risk position</td><td colspan="2">☐ Describe risk reduction measures
☐ State risk position</td></tr>
<tr><td>Timings</td><td colspan="2">☐ Recommended timings for risk reduction</td></tr>
<tr><td>Certification</td><td colspan="2">☐ See DNRME (2020)</td></tr>
</table>

4.0 Construction risks

During construction works on referable dams life safety risks should not be aggravated above pre-construction levels.

Construction risks associated with reservoir level variations and flooding are subject to variations in the weather (especially rainfall) which are often not constant in time and difficult to predict. To assess whether weather related construction risks exceed pre-construction levels requires consideration of:

- The probability of rainfall events of magnitude and duration sufficient to cause concern and whether those events are more or less frequent on any given day.
- How much warning time is available to address the risk prior to the arrival of the weather event.

Addressing these risks requires an understanding of the nature of the rainfall and runoff at a particular construction site, including temporal variability and likely cause (e.g. likelihood of events of sufficient intensity and the influence of seasonality, climatic variability, dependence upon cyclonic activity, monsoon trough, etc). It also requires an understanding of the timeframes required to prepare for and effectively manage the risk.

If maintaining construction risks at or below pre-construction levels is impractical to achieve then the dam owner should consider the matters set out in Section 3.5 and the following factors:

- Rescheduling construction activities, or limiting critical construction activities, to limit exposure to unacceptably high risks.
- Flood forecasting, with flood event predictors at lead times that correspond to realistic response timeframes.
- Establishing warning and response procedures to address the risks prior to arrival of the flood event.
- Stockpiling of materials and equipment on-site to use at short notice if required.
- See also DNRME (2020).

5.0 Timeliness of addressing intolerable risks

5.1 Categories

A referable dam has intolerable risks if:

- When standards-based assessed, does not achieve 100% AFC, does not satisfy requirements for other potential failure modes (Section 3.3) or does not satisfy considerations in Section 3.5.
- When risk assessed, does not satisfy individual risk tolerances, societal risk tolerances, CSSL (Section 3.4) or considerations in Section 3.5.

The timeliness of dam safety risk reduction can be categorised as follows:

- Risks requiring immediate action
  - Response is described in an emergency action plan (RDMW, 2023).
  - DSCs and the DNRME (2020) provide direction on remedial works and addressing incidents at dams.
- Short term risks
  - If the risk is not an immediate threat to life and property, or if immediate action has already been undertaken and further action is required, risk reduction measures to consider include a reduced full supply level (Section 5.2), strengthening of emergency preparedness measures and/or emergency works.
- Long term risks
  - If the risk can only be managed by major works to the dam then a dam safety upgrade will be required (Section 5.3). This will take time to budget, plan, investigate, design, construct and commission. Depending upon the nature of the risk, a sequence of prioritised risk reduction measures may be appropriate. Alternatively, dam decommissioning could be considered.

How soon a risk reduction measure should be applied should consider a variety of factors including what is timely and proportionate and whether a sense of urgency is being applied.

How soon a risk reduction measure should be applied should be determined considering a range of factors, including (see also Section 3.5):

- What is timely and proportionate.
- The assessed life safety, economic and business risks.
- The level of risk relative to the limit of tolerability, and probability of load condition to initiate crucial failure modes.
- Meeting approval requirements, efficient delivery and available resources.

5.2 Reducing full supply level for safety reasons

5.2.1 Background

Under section 399B of the Act, a referable dam owner may reduce the full supply level of a dam if the owner believes, based on the advice of a registered professional engineer (RPEQ), that there is an ‘unacceptable risk’ of a failure of a dam if it were to operate at the full supply level for the dam stated in the resource operations licence. The dam owner may reduce the full supply level of a dam to a level that lowers the risk to a level acceptable to the owner, based on advice from an RPEQ.

The matters set out below are intended to describe situations that may represent an ‘unacceptable risk’ of dam failure for the purpose of s399B and considerations relevant to that assessment.

5.2.1.1 ‘Unacceptable risk’

The dam is to be upgraded to bring long-term risks (such as spillway inadequacy) within tolerable limits. Section 5.3 describes the schedule to complete these works.

In the meantime, the ‘belief’ of the dam owner and the advice of the RPEQ mentioned in s399B about an ‘unacceptable risk’ should take into account whether there is strong justification for interim risk reduction measures (such as by reducing the full supply level) having regard to:

1. the extent to which the risk of a failure of a dam is above the tolerable risk limits (as a guide only, if the risk is greater than one order of magnitude above the tolerable risk limits, it is likely to be unacceptable); and
2. the gravity of any dam failure if it were to eventuate, including its consequences for the community and for the dam itself; and
3. the extent to which maintaining the FSL of a dam during emergency works would prohibit the immediate implementation of risk reduction measures; and
4. the period for which the risk would otherwise subsist before the scheduled dam upgrade.

5.2.1.2 Short term risks

It is recognised that short term risks arising from emergent circumstances such as embankment instabilities or concentrated leaks where dam failure could be initiated within a short period of time ought to be investigated and addressed within immediate timeframes. These short-term risks are generally outside the limits of tolerability and ought to be addressed as emergency works, separate from scheduled upgrades, to improve the safety of a dam. It is not intended that these risks would trigger a change to upgrade schedules to achieve acceptable flood capacity or bring forward scheduled works.

In these situations, reducing the full supply level may be an appropriate action to reduce the risk of a dam failure.

5.2.1.3 Particular scenarios

Events and circumstances that could initiate dam failure include spillway scour damage that is likely to continue or be exacerbated in future floods and would likely fail the dam embankment or spillway.

Lowering of the reservoir during emergency construction works that are required to address a deficiency, incident or failure at a dam and mitigate additional risks during the construction works.

A possible failure in progress (confirmed or suspected) may be indicated by identified seepage that indicates internal erosion is occurring and without intervention could lead to piping failure.

The vulnerability of the dam is informed by:

1. the identification of a potential seepage pathway that is likely to lead to initiation of internal erosion and piping failure or
2. a stability assessment that indicates that the dam or spillway is unstable or
3. a deficiency that does not meet good dam safety engineering practice, such that dam failure is a significant probability under a normal load on the dam.

Or, damage to the dam of a relevant kind might be initiated by:

1. earthquake damage has occurred that is highly likely to lead to piping failure of an embankment or
2. slope failure or other damage to the embankment has occurred that would lead to embankment failure or
3. damage to a spillway gate that would retain water when the dam is at the normal full supply level.

If a situation is not listed above, it may mean that the risk may not be significant enough to warrant the consideration of reducing the full supply level under section 399B or that reducing the full supply level is not an effective method for lowering the relevant risk.

In all circumstances a proportionately conservative position to the avoidance of harms is recommended.

5.2.1.4 RPEQ's report on advice

The RPEQ who gives advice which leads to the dam owner's belief under s399B must:

1. prepare a written report stating why in his or her view there is an 'unacceptable risk' of dam failure having regard to the matters identified above in this section and
2. in doing so, state whether and how the situation falls within the matters stated above or the situations outlined below and
3. undertake an inspection of the dam and review all relevant information in forming these opinions.

5.2.2 Giving notice of reduced full supply level

If a dam owner takes action under s399B of the Act to reduce the full supply level of a dam, as soon as practicable after reducing the full supply level, the owner must give notice of the reduced level to the chief executive and if the *Water Act 2000*, s813, is not administered by the same department, also give notice to the department that administers that section. The notice must:

1. include the reasons why it is necessary to operate the dam at the reduced full supply level, and
2. include the period for which it is necessary to operate the dam at the reduced full supply level, and
3. be accompanied by a copy of the registered professional engineer's advice about the reduced full supply level.

5.2.3 Reporting requirements while full supply level reduced

If the dam continues to operate at a reduced full supply level under s399B for more than one year, pursuant to s399C of the Act, the owner must, within one month after the end of each 12-month period after the full supply level is reduced, give a report to the chief executive and if the Water Act 2000, s813, is not administered by the same department, also give a report to the department that administers that section, stating:

1. when the owner intends to allow the dam to return to the full supply level stated in the resource operations licence for the dam; and
2. if the owner is a service provider:
    a) the impacts the reduced full supply level has had on the provider's customers since its reduction, and
    b) the likely future impacts on customers for the period for which the provider proposes to keep the dam at a reduced full supply level, and
    c) the impacts the reduced full supply level has had or is likely to have on achieving the water plan outcomes for a water plan under the *Water Act 2000*.

5.3 Upgrade schedule

5.3.1 Timeframes to conduct dam upgrade projects

A reasonable timeframe for a major dam safety upgrade project is provided in Table 10.

Factors that may influence suggested timeframes include:

- The severity of risk exposure prior to upgrade.
- Consideration of project staging, where unacceptably high risks may be addressed initially.
- The timeframe required to develop and implement a dam upgrade project (Table 10).
- The availability of resources required to deliver the project.
- Risks of poor project outcomes associated with unrealistic time constraints.
- Risks posed by other dams in a dam owner's portfolio and the need to prioritise risk reduction measures and resourcing across a number of dams.
- Affordability should not be a consideration when deciding upgrade schedules (see also Section 2.4).

Dam owners should be guided by the suggested timeframes, have a sense of urgency about their upgrades and be aware of their risks and consequences.

Table 10 **Estimate of timeframe for a major dam project**

Stage of dam project	Timeframe	Commentary
Project development considering finance and budget allocations, potential incorporation of enhanced benefits, assessment of project impacts and mitigations and level of detail required for investigation and design.	2 to 5 years	Expected to be shorter than 5 years if the dam project requirement has been known for some time.
Investigations and design	1 to 3 years	Can be accompanied by business case development and impacts assessments to support the project.
Construction to commissioning	2 to 5 years	Industry analysis (Petheram and McMahon, 2019) provides data indicating that new dam construction in Australia takes a median of 4.5 years to complete (with 25% to 75% variability of 1 to 10 years). This timeframe likely incorporates elements of investigation and design.
TOTAL	**5 to 10 years**	A 10-year project timeframe for major infrastructure projects (not only large dams) is considered an industry norm. DELWP (2015) notes that '*in practice, the timeframe for implementing a major dam safety upgrade from identification of risk through to investigations, approvals, design, implementation and commissioning can range from a few years to up to about ten years*'. Recent major dam projects in Queensland include Hinze Dam (2006 to 2011; 6-year timeframe) and Wyaralong (2008 to 2011; 4-year timeframe). Recent works at Paradise dam considers a staged project, where unacceptably high risks were addressed within a shorter timeframe and subsequent risks are to be addressed over a longer timeframe[17]. It is expected that upgrades to smaller dams, or upgrades requiring minor works, can be conducted in a shorter timeframe. Timeframes should consider that referable dams already have a history of conducted assessments and reviews and that dam owners should already be aware of their obligation to conduct upgrades. It is recognised that all projects are challenged to be delivered in a timely manner. Clarity of need, appropriate allocation of responsibility and the establishment of a sense of urgency among stakeholders is expected to assist in achieving timely project delivery.

[17] The essential works for Paradise Dam were largely completed in a 2 year timeframe which is considered commensurate with the identified risk. These essential works were an initial risk reduction exercise prior to a more thorough dam upgrade project expected to take a period longer than 2 years. See Nielsen (2021).

5.3.2 Determination of upgrade schedule

It is the responsibility of the dam owner to determine and justify a reasonable upgrade date to the satisfaction of the regulator. To assist with this determination:

- It is expected that referable dams, that have been assessed as requiring an upgrade, complete upgrades within a 10 year period following identification of the intolerable risk unless there is a reasonable and justified alternative timeframe.
- Owners of a portfolio of five or more referable dams can consider a portfolio risk reduction approach where dams are upgraded sequentially, prioritised according to life safety risk reduction, so that overall risks are addressed in a timely manner. A timeframe beyond 10 years to upgrade all dams in the portfolio may then be justifiable.
- If justifiable a staged upgrade approach could be applied to a dam that progressively addresses risk reduction over more than one dam upgrade project.
- The chief executive can only consider upgrade timeframes to 1 October 2035.

The chief executive has the power to impose or change DSC on referable dams and may elect to require a specific upgrade date for a specific referable dam.

5.3.3 Upgrade project plan report

A referable dam with intolerable risks requires action to reduce those risks in a timely manner. Evidence for this is provided in the submission of an upgrade project plan report and the ongoing acceptance of the report by the chief executive. It also provides a means to adjust an upgrade schedule.

Dam owners of referable dams that have been assessed as requiring an upgrade to address an intolerable risk are to provide a report to the chief executive annually, submitted by 1 October in conjunction with the annual safety statement (see DNRME, 2020).

The first submission of the report will describe the upgrade timeframe for the referable dam. The submission is to address all sections in Table 11 (1 to 8 as listed).

Subsequent submissions can be incremental, addressing sections 7 and 8 in Table 11 unless circumstances require further clarification and review of all sections.

The upgrade report does not require background information or a description of dam features, should be concise, and address specific requirements of the sections listed in Table 11.

The report is to be issued to the chief executive by an individual who is authorised by the dam owner's organisation and is cognisant of the organisation's standard of care as a referable dam owner.

5.3.4 Upgrade project plan report assessment process

The first submission of the report will establish the upgrade timeframe for the referable dam.

Subsequent submissions of the report, due 1 October in subsequent years, will track performance relative to the first submission.

The dam owner will be notified of the outcome of the review.

- If accepted, the report will be noted as a record of compliance.
- If not, the dam owner will be notified and may be requested to provide further information or to consider adjustments to the upgrade project plan.
- Failure to respond to requests may result in non-compliance, following which the chief executive may respond according to internal non-compliance response procedures.
- The chief executive retains the discretion to impose additional DSC as required.

Table 11 Upgrade project plan report template

Section	Checks	Discussion and references
1. General	☐ Administrative details (Dam ID, dam name, location, lot, owner, etc) ☐ Dam features (type, size, capacity, etc) ☐ History (date of construction, investigations, etc)	The history is to be a brief summary of the dam that includes: • Date of construction and first fill • When the referable dam was first identified as requiring an upgrade • Any interim works or risk reduction activities that may have occurred in the past
2. Version history	☐ A history of submitted upgrade project plan reports with descriptions of changes since previous report	The version history should list submitted upgrade reports (not draft versions created by the dam owner prior to submission).
3. Reason for upgrade	☐ Why the referable dam requires upgrading, citing relevant evidence of risk position ☐ Present FN plot, AFC percentage, etc	Reference the report containing the safety assessment (i.e. the method to assess whether a referable dam is of a deficient safety standard, as defined in the guideline glossary). Briefly state the risk position of the referable dam. As described in Table 1, a referable dam has intolerable risks if it does not achieve 100% AFC or does not satisfy requirements for other potential failure modes (when standards-based assessed) or does not satisfy individual risk tolerances, societal risk tolerances, CSSL or other considerations (risk assessed).
4. Works required	☐ Documentation (or reference to documentation) that demonstrates that the upgrade will meet safety standards ☐ Brief description of works required for the upgrade (to the best of the dam owner's knowledge as at the reporting date)	If available at the reporting date, reference the documentation that describes the upgrade option and demonstrates that the upgrade option meets safety standards. Note this may be the same document referenced in Row 3 of this table. Briefly summarise the upgrade works to be conducted, for example "*anticipated upgrade works includes works to the primary spillway (post-tension anchors along the ogee crest and extending the concrete lined spillway apron) and main embankment (replace toe drain and stabilise embankment slope)*". If relevant, describe design options yet to be finalised, for example "*two options are being considered as part of a detailed business case that include either post-tension anchoring of the primary spillway or a concrete buttress*".
5. Upgrade timeframe	☐ Proposed upgrade timeframe (per project stages, see Section 7 in this table) ☐ Justification for the timeframe (considering aspects described in Section 5.3.2)	State upgrade completion date (noting that more details of the proposed upgrade timeframe are to be provided in Section 7 in this table). Justify the upgrade timeframe, noting the constraints described in Section 5.3.2. The justification may include commentary on factors listed in Section 5.3.1. Examples include:

Section	Checks	Discussion and references
		• The severity of risk exposure prior to upgrade. For example, describe decisions on whether or not a dam with significant intolerable risks should be given priority and/or have an accelerated upgrade schedule applied. • Consideration of project staging, where unacceptably high risks may be addressed initially. For example, describe decisions that considered staged upgrade works, interim measures, reduction in full supply level etc. • The timeframe required to develop and implement a dam upgrade project. For example, describe how decisions surrounding upgrade timeframes reflect observations summarised in Table 10. • The availability of resources required to deliver the project. For example, describe how the availability of those resources were considered and what contingencies may be necessary to ensure a good project outcome. • Risks of poor project outcomes associated with unrealistic time constraints. For example, describe how constraints associated with critical investigations that may result in unavoidable but necessary delays have been considered. • Owners of a portfolio of dams should consider describing how risk reduction measures, and resourcing, are prioritised across a number of dams. • Affordability should not be a consideration when deciding upgrade schedules. Any justification should reflect upon the contents of Section 2.4 and consider whether affordability has influenced adopted timeframes.
6. Interim risk management	☐ Interim risk reduction measures, being applied between now and when the dam will be upgraded, and their anticipated impact on the risk position	List any risk reduction measures (reduced full supply level, amendments to emergency action plans, heightened dam surveillance, etc) applied now, or intended to be applied in future, and the expected risk reduction achieved. Consider any obligations to inform the community of any changes in risk (see Section 2.8).
7. Progress report	For each stage in the project provide current progress compared to projected progress. Include stages already completed as well as upcoming stages and highlight projected completion date. Note the emphasis of the report is on timeliness (not financial performance).	Provide a tabular summary of project stages and progress (or Gantt chart / spreadsheet etc).

<table>
<tr><th>Section</th><th colspan="2">Checks</th><th>Discussion and references</th></tr>
<tr>
<td></td>
<td>Project stage:
☐ Funding arrangements
☐ Procurement and tendering status
☐ Investigation
☐ Design
☐ Construction
☐ Commissioning
☐ Preparations for ongoing management and operations</td>
<td>For each stage provide project status:
☐ Original projected timeframe
☐ Current projected timeframe
☐ Current progress relative to projected timeframe (percentage completion of each phase)
☐ Highlight any delays or slippage, cross-reference to justification statement (item 5)</td>
<td>A simple example is provided below, noting that additional description of key, time-critical milestones may be of value.
<table>
<tr><th>Project Stage</th><th colspan="2">Original Project Timeframe</th><th colspan="2">Current Project Timeframe</th><th>Current Progress (%)</th><th>Commentary on achieved milestones, highlighting any delays or slippage, cross-reference to justification statement (item 5)</th></tr>
<tr><th></th><th>Start Date</th><th>End Date</th><th>Start Date</th><th>End Date</th><th></th><th></th></tr>
<tr><td>Funding arrangements</td><td>Jan 2018</td><td>Jul 2020</td><td>Jan 2018</td><td>Nov 2020</td><td>100%</td><td>Funding secured on schedule, budget secured for project</td></tr>
<tr><td>Procurement and tendering status</td><td>Feb 2020</td><td>Mar 2022</td><td>Feb 2020</td><td>Nov 2022</td><td>100%</td><td>Procurement, tendering for construction activities delayed subsequent stages</td></tr>
<tr><td>Investigation</td><td>Sep 2020</td><td>Sep 2021</td><td>Sep 2020</td><td>Aug 2022</td><td>100%</td><td>Investigations completed (scope greater than initially anticipated), design team have reviewed</td></tr>
<tr><td>Design</td><td>Aug 2020</td><td>Mar 2022</td><td>Nov 2020</td><td>Oct 2022</td><td>100%</td><td>Additional constraints to design identified through investigations</td></tr>
<tr><td>Construction</td><td>Mar 2022</td><td>Dec 2022</td><td>Apr 2023</td><td>Dec 2023</td><td>50%</td><td>Construction delayed 1 year due to risks associated with wet season</td></tr>
<tr><td>Commissioning</td><td>Jan 2023</td><td></td><td>Jan 2024</td><td></td><td>0%</td><td>Target commissioning prior to 22/23 wet season</td></tr>
<tr><td>Preparations for ongoing management and operations</td><td>Sep 2022</td><td>Dec 2022</td><td>Sep 2022</td><td>Dec 2023</td><td>20%</td><td>Recruitment process for dam operators and engineers commenced</td></tr>
</table>
</td>
</tr>
<tr>
<td>8. Declaration</td>
<td colspan="2">☐ Name, title and signature of issuer (can be electronic) who is authorised by the dam owner’s organisation and is cognisant of the organisation’s obligations as a referable dam owner.</td>
<td>For example:
I declare that the information I am supplying in this upgrade project plan report is true and correct and that I am an authorised representative of the dam owner <company name>.
Signature:
Name and Title:</td>
</tr>
</table>

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Appendices

Appendix A Aspects considered in the selection of individual risk tolerability threshold

As individuals, we are concerned about how a risk affects us and the things we value personally. We may be willing to live with a risk if it secures us certain benefits and if the risk is kept low and clearly controlled. We are less tolerant of risks over which we have little control.

ANCOLD (2022) identifies an individual risk threshold as being one where '*the increment of risk imposed on any person by a facility, such as a dam (or by several facilities in densely settled regions), should not be more than a specified value, usually a small fraction of the average background risk that the population lives with on a daily basis*'. This is a principle of equity, where '*all individuals have unconditional rights to certain levels of protection*' (HSE, 2001). The definition of population at risk applied to Queensland's referable dams (DNRME, 2018), being individuals within a residence or workplace and not participating in any risky activities such as driving a vehicle or walking through flooded waters, provides further justification of this right.

In practice addressing societal risk tolerances and other considerations may result in individual risks being substantially lower than the thresholds. This may not always be the case and, irrespective, should not distort the purpose of the individual risk tolerance test; the principle of equity that drives individual risk tolerability has foundations in our societal values and is easily and widely understood as a core value. This should be succinctly described when justifying expenditure on risky infrastructure such as dams.

Selection of the threshold individual risk tolerance considers aspects described in Table 12.

Table 12 Aspects considered in the selection of individual risk tolerability threshold

Aspect	Discussion
Life safety risks a person is normally exposed to	Individual risk tolerability considers background life safety risks in the community, not just the average across the entire population but averages for particular individuals or groups within that population. AGA (2019) provides statistical analysis of mortality rates in Australia over the past century. It has sufficient granularity to identify mortality rates for each age group and gender, see Figure 3. The following trends are noted: • Noting the logarithmic y-axis, there is a significantly higher mortality rate in early childhood and beyond 80 years of age. • Mortality rates during the first year of life are relatively high for both males and females, primarily due to congenital abnormalities and perinatal conditions. • After the first year of life an increasing capacity to ward off disease and limited exposure to life threatening situations results in rapidly dropping mortality rates. The mortality rates reach a minimum during school ages (6 to 12 years) where the probabilities of dying within the year are all less than 1 in 10,000 for both males and females. • Accidents are the single largest cause of death in childhood. The 'accident hump' peaks in the late teenage years then decreases in the twenties. The 'accident hump' has progressively flattened over past decades and is more pronounced in males compared to females. • Beyond the age of 20 to 30 mortality rates start to rise again as the falling mortality from accidents is more than offset by increasing rates of death due to disease. • The shapes of the mortality curves for males and females are similar, but the absolute rates are different, with female mortality being less than male mortality at all but the oldest ages. • The lowest mortality rate in the Australian community is 6.4×10^{-5} for 9- and 10-year-old girls.

Aspect	Discussion
	Compared to other countries, observed patterns of mortality in Australia are typical of developed countries (Figure 3): • Australia has the 6th highest life expectancy globally (ABS 2020). This is reflected in age dependent mortality rates. • All countries demonstrate similar trends in mortality distribution across age groups. Australia, Canada and the European Union all show very similar trends and magnitudes. • Australia's minimum mortality rate is close to an order of magnitude lower than the global average. In the context of dam safety, the population weighted average mortality rate and the minimum mortality rate is relevant (Figure 4). • There is a trend of steady reduction in mortality rates since 1880. • Rates of decline in mortality are consistent between genders. • Minimum mortality rates have declined faster compared to the entire population which is likely to be influenced by an aging population (AGA 2019a). • The data indicates a transition in trends after 1970 to 1980 where the rate of decline in mortality appears to be approaching an asymptotic minimum. Prior to 1960 a more linear trend is apparent. IHME (2020) provides forecasts of mortality to 2100 based upon analysis and modelling conducted prior to 2018 (Figure 4). • The forecasts predict a decline in average mortality across the population resulting from an anticipated trend of lower birth rates and longer life spans. This does not however diminish a predicted trend of reducing mortality rates for children of school age. • Forecasts suggest that minimum mortality rates in Australia will be around half of present-day rates in the next 50 to 100 years but are likely to remain above 10^{-5}. • Compared to other countries the projections of future mortality are consistent with those for Australia, noting an expectation of more rapid reduction in rates in developing countries. Figure 5 presents leading causes of death by age group in Australia (AIHW, 2020). • Chronic health conditions are the leading causes of death in Australia for the majority. For the younger age groups external causes such as transport accidents, injury and poisoning, and suicide rank highest. • For the 1 to 14 years age group, land transport accidents are the leading cause of death, accounting for 11% of all deaths. If this percentage is applied to the background mortality rate for the 1 to 14 years age group (around 10^{-4}) then the annual probability of the leading cause of death is around 10^{-5}. In comparison, across all age groups in 2020 the fatality rate for land transport accidents was 4.4×10^{-5} (BITRE, 2021).
Tolerable excess risk exposure to an individual	If dam safety risks are to be maintained to be close to average background risk for any group in the population then the threshold individual risk tolerance should be lower than the minimum mortality rate of $6.4 \text{x} 10^{-5}$ (i.e. that of a 10 year old girl). Setting an individual dam safety risk threshold of 10^{-4} would more than double the risk exposure to around 11% of the total population and would represent the most likely cause of death for this age group. It is questioned whether such a threshold meets the principle of equity stated above. Setting an individual risk threshold of 10^{-5} would increase the risk exposure of this group by around 10%. Note however that this threshold is of comparable magnitude to deaths from land transport accidents, which is the leading cause of death for this age group. Based on these considerations a single threshold individual risk tolerance of less than 10^{-5} per annum (or 1 in 100,000 years) is considered to meet the principle of equity so long as there are justifiable benefits to the broader society, it is subject to site-specific considerations of the particular age group of PAR most at risk and tested successfully through standard of care considerations.

Aspect	Discussion
Separate values for existing dams and new dams (or major augmentations)	Specification of two threshold risk tolerances in ANCOLD (2022) is justified by the impracticalities of bringing an existing dam up to the safety standards of a well designed and constructed modern dam. This justification is considered to diminish the principle of equity of risk; application of two values creates an impression of bias towards individuals downstream of new dams compared to old dams. It arguably combines the equity principle with a question of reasonableness of expenditure of public resources, which should instead be considered separately as part of ALARP considerations. There is also often some confusion as to what constitutes a major augmentation. A major dam upgrade with costs well in excess of that spent on its original construction is often described as being 'good as new'. Current definitions of major augmentation differ to this perception.
Exposure factor	Exposure factor is the fraction of time that a person is at risk of dam failure. Standardised exposure factors (Maslin, 2012) vary from 0.3 to 1.0 and consider whether a person is at work, home, school, etc and whether those locations are within a dam failure inundation extent. Exposure factor is incorporated into the methodology to assess individual risk. Other aspects associated with the effectiveness of emergency response, including lead times available to respond and effectiveness of evacuations, is incorporated into the methodologies available to estimate PLL.
Consistency with industry guidelines and jurisdictions	ANCOLD (2003) references mortality rates from 1998 which show an annual minimum mortality rate at or above 10^{-4}. It recommends that '*risks higher than 10^{-5} per annum should only be regarded as tolerable after the most careful consideration of such factors as the age of those at risk and thus average background risk levels; the limit of 10^{-5} per annum, which is being strictly applied in The Netherlands; observation of the UK Health and Safety Executive (HSE) that maximum risks actually imposed on individuals are generally much lower than their limit of 10^{-4} per annum; the benefit which the dam provides in the wider interests of society; and the ALARP principle*'. ANCOLD (2022) retains a value of 10^{-4} for existing dams '*having regard, among other considerations, to the HSE criteria, which are for a country with a similar culture and legal system to Australia*' but highlights that adoption of this value would require careful consideration because '*imposed risk equal to that limit value would slightly more than double the average background risk of females aged 12*'. It is noted that HSE references are dated from 2001, at which time mortality rates were greater than 10^{-4} for all age groups. USACE adopts a threshold of 10^{-4} but notes that the minimum mortality rate in the USA is greater than 10^{-4} and that the average failure rate for dams in the USA is close to 10^{-4} probability of occurrence. Other jurisdictions, including HSE, USBR, FERC and CDA also adopt a threshold of 10^{-4} (Snorteland, 2019), noting again that these references may not reflect most recent mortality data.
Voluntarily risky behaviour and its influence on risk threshold	If risky behaviours are excluded then mortality rates from involuntary events, such as disease, are significantly rarer. Choice of which risky behaviours should be excluded is challenging and, arguably, land transport accidents, which is the most likely cause of death for children, is involuntary. Consideration of inclusion of voluntary risks is also a component of assessment of PLL and PAR.
Reasonable balance between individual safety and expenditure of public resources	This aspect is addressed as part of considerations outlined in Sections 3.4.4 and 3.5. Note that HSE (2001) suggest that individual risk tolerability limits '*rarely bite … hazards that give rise to levels of individual risks also give rise to societal concerns and the latter often play a far greater role in deciding whether a risk is unacceptable or not*'. **Appendix B** discusses societal risk threshold.

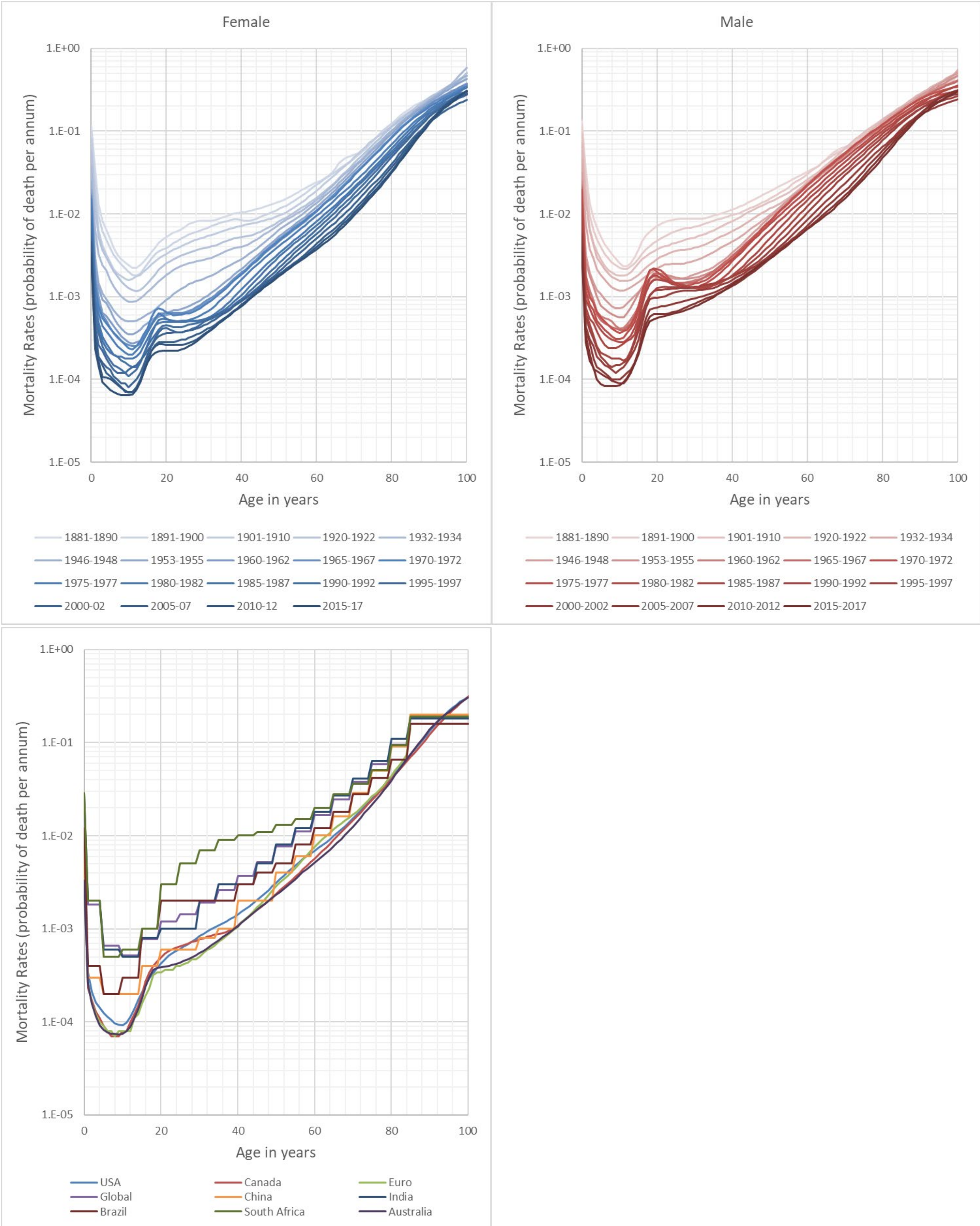

Figure 3 Historical mortality rates by age and gender in Australia for females (top left) and males (top right) (AGA 2019). Mortality rates globally and for a selection of countries (bottom left) (WHO 2020, SSA 2017, Statcan 2020, Eurostat 2021, AGA 2019). Vertical axis is logarithmic scale.

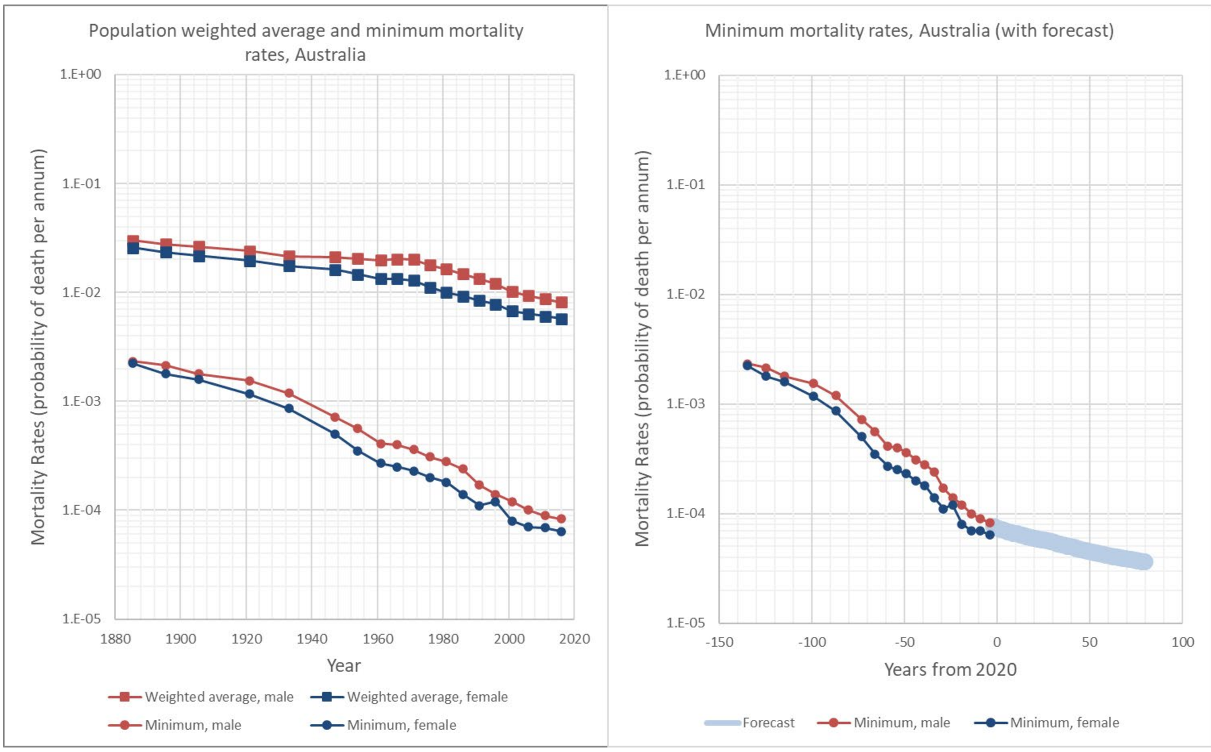

Figure 4 Historical population weighted average and minimum mortality rates in Australia with forecast (AGA 2019, IHME 2020). Vertical axis is logarithmic scale.

Age group	1st	2nd	3rd	4th	5th
Under 1	Perinatal and congenital conditions	Other ill-defined causes	Sudden infant death syndrome	Accidental threats to breathing	Cardiomyopathy
1–14	Land transport accidents	Perinatal and congenital conditions	Brain cancer	Accidental drowning and submersion	Suicide
15–24	Suicide	Land transport accidents	Accidental poisoning	Assault	Other ill-defined causes
25–44	Suicide	Accidental poisoning	Land transport accidents	Coronary heart disease	Breast cancer
45–64	Coronary heart disease	Lung cancer	Suicide	Colorectal cancer	Breast cancer
65–74	Lung cancer	Coronary heart disease	COPD	Colorectal cancer	Cerebrovascular disease
75–84	Coronary heart disease	Dementia including Alzheimer disease	Cerebrovascular disease	Lung cancer	COPD
85 and over	Dementia including Alzheimer disease	Coronary heart disease	Cerebrovascular disease	COPD	Influenza and pneumonia

Figure 5 Leading causes of death by age group 2016-2018 (AIHW, 2020)

Appendix B Aspects considered in the selection of societal risk tolerability threshold

History has demonstrated that multiple fatality events, which are worsened when the event is human derived (as opposed to a natural event such as flood, cyclone or bushfire):

- Provoke a socio-political response that is a disproportionate reaction above and beyond the economic.
- Cause adverse repercussions for the institutions responsible for protecting us.
- Can cause political instability, loss of confidence in the provisions in place for protecting people, loss of trust in regulators of safety and trauma and disruption to the social fabric.
- Often trigger step-changes in public safety policy.

Reasons proposed for this (from Snorteland, 2019):

- If multiple deaths happen at one time then the impact on families make the scale of loss appear more significant.
- If the death toll is from the same community then the impact appears larger compared to when separate communities are involved.
- If the deaths occur in one place the scale of loss seems more apparent than otherwise.
- If all deaths are attributed to one event the immediate perception is that one event or one fault caused such large consequences.
- There would be the perception that institutional control of hazards has failed.
- There is more media coverage of such events, often global.
- There is an ongoing and long-lasting fear of a recurrence of such accidents.

Consensus in literature (Ball and Floyd, 1998) is that the greater the number of people at risk, the safer a dam should be. The majority of jurisdictions describe societal risk tolerability using a societal risk curve (or FN-curve).

Selection of the threshold societal risk tolerance described in Section 3.4.3 considers aspects in Table 13.

Table 13 Aspects considered in the selection of societal risk tolerability threshold

Aspect	Discussion
Demonstration of institutional changes resulting from dam failure events	Dam failures have driven engineering improvements but also step changes in infrastructure regulation and legislation and liability laws. Examples include: • Bilberry and Dale dams (UK, 1852 and 1864, 52 and 244 fatalities), dam related legislation in the UK. • Mill River Dam (US, 1874, 139 fatalities), regulation requiring engineers to work on dams. • South Fork (US, 1889, 2209 fatalities), significant developments in liability laws. • Skelmorlie and Coedty-Eigian (UK, 1925, 5 and 16 fatalities), Reservoirs Act legislated and the concept of panel of qualified engineers. • St Francis Dam (US, 1928, 431 fatalities), requirement for engineers to be registered in California. This event influenced the commencement of RPEQ in Queensland in 1929, reflecting public safety concerns from the Depression era. • Samarco and Brumadinho (Brazil, 2015 and 2019, 19 and 270 fatalities), global industry response to improve tailings dam management, significant legal claims upon dam owners including criminal charges.

Aspect	Discussion
Anchor point and slope of threshold curve	An anchor point of 10^{-3} and a practically risk neutral curve slope (i.e. risk tolerance is proportional to PLL) is applied in the majority of jurisdictions and has generally remained unchanged since at least 1999 (Ball and Floyd, 1998). Based on the literature reviewed there does not appear to be a strong link between individual and societal risk tolerability thresholds. Literature suggests selection of anchor point relates to what society considers acceptable and how the anchor point and curve slope interact. Ball and Floyd (1998) provide a table of anchor points and refer (as one example of several) to ACMH (1976) in the statement that '*a serious accident frequency of 10^{-4} per year might be regarded as 'just on the borderline of acceptability'. The term 'serious accident' was never defined …. but it has been a fairly widespread practice amongst QRA practitioners to presume that this might be taken as 10 or more fatalities. This anchor point (10,10^{-4}), as this report shows, can be observed in many FN criterion lines which are used to this day*'. Similar statements (such as in HSE 2001) suggest that selection of anchor point is one of professional judgement, rather than (say) one linked to individual risk tolerance. Zielinski (2017) considers societal risk limits based on consistency with individual risk limits but goes on to note that '*it seems that the risk limits developed for dams followed predominantly the <other> path*'. The principles of individual risk (tests equity) differ from societal risk (tests social intolerance to human-derived, multiple fatality events). It is therefore considered reasonable to apply different approaches to assign thresholds. Similarly, the thresholds applied to the standards-based assessment, noting the lowest standards-based assessment range is $2 \leq PAR \leq 10$, are considered to relate to societal risk principles above individual risk principles.
Separate curves for existing dams and new dams (or major augmentations)	See corresponding commentary in **Appendix A**.
Horizontal truncation	ANCOLD (2003) applies a horizontal truncation at PLL>100 and risk of 10^{-5} on the basis that predicting risks rarer than 10^{-5} is beyond present knowledge and dam technologies and methods. No horizontal truncation is proposed on the basis that industry's risk assessment skill is considered sufficient to consider risks rarer than 10^{-5} (or other arbitrary assignment that a horizontal truncation requires). This is supported by ANCOLD (2022).
Special consideration above a PLL threshold	USACE (Snorteland 2019) considers PLL>1,000 to be a situation where dam failure would be considered a catastrophe. It requires that '*any case where the annual failure probability is less than 10^{-6} and the potential exists for more than 1,000 fatalities requires special consideration to ensure everything reasonably practicable has been done to reduce risk. A thoughtful and careful examination of risk reduction activities is required*.' There are a number of dams in Queensland with PLL>1,000 which also provide critical water infrastructure for our major population centres. Life safety risks aside, failure of these dams would have catastrophic and long-term consequences to those population centres. ANCOLD (2022) and Ball and Floyd (1998) refer to some authorities decision to apply a vertical truncation, meaning those authorities are not prepared to consider facilities with potential for life loss above 1,000 lives. ANCOLD (2022) goes on to suggest that the '*concept of a vertical truncation is not considered practicable or appropriate for existing dams with large populations already living downstream*'. Table 8 raises matters to consider if PLL > 1,000.
Consistency with industry guidelines and jurisdictions	Ball and Floyd (1998), Snorteland (2019) and Rigby (2015) provide summaries of approaches across industry and jurisdictions that shows general consistency of approach to societal risk. Noted variations are described above.
Reasonable balance between societal safety and expenditure of public resources	This aspect is addressed as part of considerations outlined in Sections 3.4.4 and 3.5.

Appendix C How the science of rainfall has made dams deficient

This appendix discusses very rare and extreme events that are influenced by the estimation of the upper limits of these events (the probable maxima). It explains key terms, how knowledge has changed historically over time and what could influence these events in future.

Terms associated with very rare and extreme floods that influence dam safety requirements

The upper limit of rainfall is the **Probable Maximum Precipitation (PMP),** defined as '*the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year*' (WMO, 2019).

A **Probable Maximum Flood (PMF)** occurs when a PMP falls with optimum spatial extent, duration and timing upstream of a dam.

As a further complication, ARR (2019) considers a probable maximum precipitation flood (PMP Flood) as being '*the flood derived from a PMP using probability neutral assumptions*' and the PMF as being '*the limiting value of flood that could reasonably be expected to occur*'.

PMP and PMF are maxima that, if calculated accurately, should not be physically possible for an event to exceed. But the probability of an event close to these maxima can be estimated; the annual exceedance probability (AEP) of the event, which leads to the description of the **'AEP of the PMP'** and the '**AEP of the PMF**'.

PMF, and its AEP, are significant drivers of dam design in Queensland. Standards often require dams to be built to withstand the PMF but, even if a dam does not need to be designed to withstand the PMF, the frequency of less extreme flood events can change because the AEP of the PMF acts as a 'pin' that fixes the upper extreme end of probabilities.

In general, the AEP of the PMP is rarer for smaller catchments and less rare for larger catchments. This is the subject of ongoing research, and recent studies for several dams in Queensland with large catchments have resulted in significant revision, with corresponding changes to dam design requirements.

Changes in the understanding of the science of extreme floods

Dam safety requirements consider very rare and extreme floods that, for higher consequence dams, approach the maximum limit of PMF.

Being so rare, these floods are not often contained in historical records. The science of meteorology and hydrology, supported by statistics on available data, is used instead. Over the years knowledge and skill has improved and, in some instances, revealed an underestimation of the likelihood and intensity of flood events.

Figure 6 highlights key historical events and investigations that have contributed to the understanding of the science of extreme rainfall and flooding.

Consequently, depending upon the location and catchment area associated with a dam in Queensland:

- Rare to extreme rainfall events can be more likely than previously thought.
- Flood runoff into dam catchments from extreme rainfall events can be greater than previously thought.
- The intensity of the theoretical maximum rainfall can be greater than previously thought.
- The impact of climate change further challenges our capacity to predict extreme floods. See Section 2.9.

Date	Event
1950s	Extreme rainfall predictions were based upon the largest rainfall records at a given location. These methods were limited by a scarcity of records and differed significantly across similar areas (Pearce and Kennedy, 1993).
Mid-1970s	Development of 'generalised' methods which analysed multiple rainfall records over large regions of Australia. These methods separated storm portions into both 'regional' meteorological conditions and 'site specific' conditions.
1980s	Introduction of an assessment method for cyclones, which have a significant influence over extreme rainfall in Queensland[18].
1984	A rainfall event occurred that exceeded the theoretically assumed maximum (Dapto 1984 storm, BOM 2003). This supported the need for further research into extreme climate in Australia.
1987	A consistent framework for predicting rainfall was developed called Australian Rainfall and Runoff (ARR, 2019). This set the platform for design rainfall and runoff prediction in Australia.
1999	A method was developed to predict the probability of occurrence of a theoretical maximum storm (Laurenson and Kuczera, 1999). This allowed designers to assign a probability to the biggest possible flood event that might occur at a dam.
Early-2000s	Methods were developed that provided more confidence in predicting rainfall in the rare / extreme range[19].
2003	The assessment method for cyclones was revised to include longer duration events which are often more relevant to dam design[20].
2010s	Significant flood events prompted a rethink on how rainfall and runoff is predicted. This led to an ARR revision in 2016, which included updated design rainfall predictions and new methods for predicting floods that recognised the variability of rainfall and how this influences floods. ARR continues to be revised, the latest in 2019 (ARR, 2019).
Today	In recent years there have been more sophisticated investigations into the probability of the theoretical maximum rainfall. These new investigations suggest that the probable maximum precipitation is rarer than previously estimated for larger catchments often associated with major dams in Queensland.
Future	Climate change impacts on extreme rainfall are uncertain and is the subject of current research.

Figure 6 Key historical events that have contributed to the knowledge of extreme rainfall and flooding predictions associated with dam safety design in Queensland

[18] The Generalised Tropical Storm Method (GTSM) was first developed by the Bureau of Meteorology (BOM) during the early 1980s for regions of Australia impacted by tropical storms (Kennedy 1982, Kennedy and Hart, 1984). The Generalised Short Duration Method (GSDM) was then first developed by BOM in the early 1980s for estimating PMP over small areas and updated again in 1994 (Bureau of Meteorology, 1985; Bureau of Meteorology, 1994).

[19] CRCFORGE method (Hargraves 2004).

[20] BOM (2003) revised GTSM for estimating probable maximum precipitation (PMP) for longer duration events (up to 120 hours) and the GSDM for events up to 6 hour durations.

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