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A risk-based framework for hydrologic design decision-making under non-stationary climate conditions

Alexander Rogan [a,*], **Vinny Kim** [a], **Sid Rastogi** [b]

[a] *PSM, Australia*

[b] *Yallourn Mine, EnergyAustralia, Australia*

Abstract

The annual exceedance probability (AEP) of a surface water event has traditionally been used to convey the design aim for a hydrologic assessment. This conventional method has begun to lose its utility due to the introduction of non-stationary aspects, such as climate change. For example, to assess a design flow for a closure surface water infrastructure element, a climate scenario (shared socio-economic pathway) and a prediction year may need to be selected to determine a design flow. Further, there have been significant updates to the prediction approaches over the past decade, such as global warming predictions [e.g. updated Coupled Model Intercomparison Project Phase 6 (CIMP6) predictions] and the hydrologic design approaches (e.g. Version 4.2 of Australian Rainfall and Runoff), with more updates likely to occur over the coming decades. Additionally, other non-stationary aspects, like evolution of a closure landform (e.g. pre- and post-pit lake formation), can provide varying risks in different phases of the mine closure period that require differing mitigations.

The implication of this is that the use of AEP can become less meaningful as a means of communicating likelihood and the associated level of design risk control. This paper presents a framework to aid decision-making in the selection of surface water design events within a more traditional risk-based process, represented by the likelihoods and consequences. By using common recommendations for design life and AEP for a range of surface water infrastructures, the equivalent likelihood can be estimated, allowing a design screening chart to be developed that is linked to typical industry risk acceptance levels. This is then further linked to economic, environmental and loss of life consequence metrics to support determination of a consequence category, and then an associated design likelihood band for hydrologic design event screening.

An illustrative example is presented of the risk-based framework for a conceptualised mine void peripheral catchment in Victoria.

Keywords: *risk-based approach, hydrologic design events, non-stationary climate*

1 Introduction

This paper presents a risk-based framework to aid decision-making in selecting hydrologic design events for application to mine closure that account for non-stationary aspects such as climate change. Mine closure requires consideration of many non-stationary aspects, including the progressive nature of the rehabilitation prior to relinquishment, maturing of vegetation, recovery of groundwater tables, and potential pit lake formation and climate variability (including droughts and high rainfall periods), as well as the potential for long design intent periods for remaining infrastructure. Further overprinted with this is the additional uncertainty linked with climate change, which currently represents a wide band of predictions due to numerous possible shared socio-economic pathway (SSP)/representative concentration pathway (RCP) options and the ability for global climate models to predict potential future changes. This can create

* Corresponding author. Email address: alexander.rogan@psm.com.au

challenges for both a miner and regulator as to what is a 'reasonable' design standard for closure surface water infrastructure and increases the risk of 'moving goal posts' in preparation for relinquishment.

Where there is the potential for multi-faceted uncertainties, a risk-based approach is commonly utilised within design and decision-making. Risk is typically considered as the combination of likelihood and consequence. However, in current hydrology practice it is common to assess design events in terms of an annual exceedance probability (AEP). The AEP of a design event is effectively shorthand for the event 'likelihood'; in a stationary climate this is the likelihood of a design event occurring at least once within the infrastructure design intent period (P_D), which can be calculated via:

$$P_D[-] = 1 - (1 - AEP)^L \quad (1)$$

where:

- L = the infrastructure design intent period in years
- AEP = a fraction (e.g. 0.01 for a 1 in 100 AEP).

In the context of a non-stationary climate, the challenge of using solely the design AEP to size surface water infrastructure is that this needs to be linked to a design SSP/RCP scenario as well as a year or point in time at which this AEP is to be assessed. For example, if a design AEP flow is estimated in 2026 for the year 2075, this inherently requires an assumption of which SSP scenario to adopt, and if the 2075 design flow for the same AEP was to be reassessed in 2036 with the current climate science at the time, it is highly likely that a different flow would be predicted (as discussed further in Section 2). So, despite aiming to design for the same AEP, there is no guarantee that this actually achieves the desired level of risk mitigation, and other risk mitigation decisions made in 2026 based on the 2026 hydrologic flows can become very opaque when attempting to reassess the risk balance in 2036 with the 2036 hydrologic flows. Consequentially, the current typical industry approach of assigning a design AEP linked to the type of surface water infrastructure has decreasing efficacy (as it now inherently requires consensus on a climate change scenario to adopt for design). Thus, there could be greater benefit, due to improved 'visibility' of the risks, in making design-decisions more directly within a risk-based framework.

This paper has analysed common industry design AEP benchmarks and infrastructure design lives to develop an equivalent event likelihood (P_D) that can be used more readily within a risk-based design decision-making framework. The equivalent 'conventional design wisdom' likelihoods have been contrasted against various consequences to produce a tool that is considered useful to aid decision-making in conjunction with using an as low as reasonably practicable (ALARP) design approach. The benefits for a mine closure context are a more transparent and understandable decision process, as well as an opportunity to target the hydrologic design event of closure infrastructure more directly with the consequences, such that post-relinquishment failure probabilities are, at worst, consistent with other state- or council-owned surface water infrastructure.

The approach borrows on that routinely applied within the dam industry, where a consequence assessment is typically first undertaken for identified hazards, with minimum acceptance levels defined within design tools with respect to the likelihood of exceedance depending on the consequence. The ALARP risk assessment approach is then used to assess if the controls (and/or design event selection) are adequate, where risks lower than the limit of tolerability (LoT) are tolerable only if further risk reduction is impracticable or if costs are grossly disproportionate to the improvement gained (Australian National Committee on Large Dams [ANCOLD] 2022). The risk assessment and ALARP approach for mine closure is also advocated for within De Graaf et al. (2025).

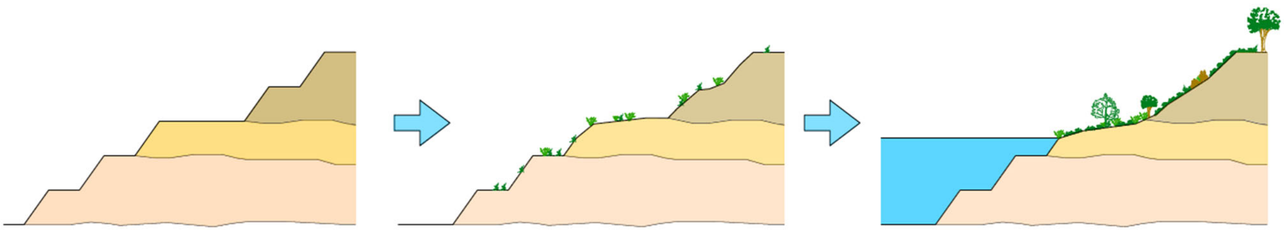
2 Hydrologic design event selection challenges

2.1 Mine site evolution and post-mine land use

The evolution of a mine site during progressive rehabilitation and post relinquishment, along with the post-mine land use (PMLU), have the potential to give varying risks over time. Further, the coming decades are likely to be vital in the resulting climate change impacts, especially with global momentum building towards ‘net zero by 2050’, meaning that some of the more adverse SSP/RCP scenarios (such as RCP 8.5 or SSP5-8.5) may end up being conservative (especially in the later parts of this century).

Figure 1 shows a conceptual example mine slope where the closure approach is to form a pit lake with a public recreation PMLU. A number of the key aspects for the slope over time include:

- during operations
  - potential for deformations of the slope due to mining-induced processes, and no benefit from the pit lake
  - current or near-future conditions such that significant changes due to climate change would not be anticipated
  - no public access and the mine can implement controls for personnel safety to mitigate potential risk to life consequences
- progressive rehabilitation
  - increase in mine slope deterioration/degradation over time due to landform processes; in particular, in ‘unrehabilitated’ and/or disturbed areas
  - flattening of pit face angles above the lake level give some benefit in pit slope stabilisation but disturbance of the slope clears vegetation and likely increases run-off coefficients
  - longer time period gives increased potential for climate change risks, and increasing uncertainty in climate change predictions
- pit lake formation and vegetation maturing
  - further progression in mine slope deterioration/degradation in exposed areas over time due to landform processes, but formation of the pit lake adds a significant stabilising influence to the slope
  - longer time period gives increased potential for climate change risks but the maturing vegetation is likely to reduce run-off coefficients
- PMLU (i.e. post relinquishment)
  - highest potential exposure to impacts of climate change and widest range of uncertainty but vegetation will continue to mature, likely further reducing run-off coefficients
  - slope above the lake level will likely continue to deteriorate/degrade over time
  - public access occurs, changing the potential for development of a population at risk if a failure were to occur, and administrative risk controls (such as safety signage) may not be followed.



PERIOD	OPERATIONS	PROGRESSIVE LANDFORM REHABILITATION	PIT LAKE FORMATION & VEGETATION MATURING	PMLU & MATURE VEGETATION
RESPONSIBLE PARTY	← MINER →		MINE RELINQUISHMENT	STATE & POST MINE LAND OWNER
TIME DEPENDENT MINING SLOPE DETERIORATION	FRESH EXCAVATION (BUT WITH HIGH POTENTIAL FOR MINING INDUCED DEFORMATIONS)	↑	↑ (LESS SLOPE EXPOSURE)	↑ (LESS SLOPE EXPOSURE)
SLOPE STABILISING INFLUENCES	LOW	↑ (MINING STOPS, BUT NO PIT LAKE & FULL HEIGHT SLOPE FAILURE POSSIBLE)	↑ +	– NO CHANGE
DESIGN RAINFALL	– (BASELINE)	↑	↑	↑
RUNOFF COEFFICIENT	– (BASELINE)	↑ (PRE-VEGETATION)	↓ (EARLY VEGETATION)	↓ (MATURE VEGETATION)

Figure 1 Conceptual example of closure phases for a mining pit and non-stationary aspects

To decide on a single design AEP for a closure surface water infrastructure element that can address the varying factors over the rehabilitation and closure period becomes very challenging, as there are multivariable factors and changing consequences over time such that it is not immediately clear which of the 4 periods in the above example will govern the design. In contrast, a risk-based approach, supported by engineering analysis and judgement of the influence of the various evolving factors on the catchment hydrology over time, can be well suited to assessing each period and identifying a critical period (or periods) that will govern design requirements.

2.2 Climate change predictions

Figure 2 shows an example of the predicted changes in mean air temperature (relative to a 1995 baseline) for the Gippsland region in Victoria, Australia. The predictions include:

- the Coupled Model Intercomparison Project (CMIP) 5 predictions, which were released between 2010 and 2014 and are commonly assessed against RCP scenarios
- the CMIP 6 predictions, which were typically released around 2021 and are commonly assessed against SSP scenarios.

Each scenario prediction includes the mean line and a 10th to 90th percentile confidence limit.

Figure 2 highlights the increasing uncertainty in predictions in the coming decades and the potential for overdesign of closure infrastructure if, say, an upper bound climate change impact was assumed for 2090 and global efforts are successful in achieving a less adverse SSP. Also, as climate change science continues to evolve, these predictions have the potential to change each time the CMIP predictions are updated; for example, modelling for CMIP 7 is already well underway.

Within the Australian Rainfall and Runoff (AR&R) guideline (Ball et al. 2019), Version 4.1 (2019) and 4.2 (2024), the impacts of climate change are linked with Equation 2:

$$I_p = I \times \left(1 + \frac{\alpha}{100}\right)^{\Delta T} \tag{2}$$

where:

I_p = the climate change adjusted rainfall intensity or depth

I = the historic climate rainfall intensity or depth

α = an adjustment factor

ΔT = the change in mean air temperature between the reference time period (i.e. the basis of I) and the future climate (for I_p).

In AR&R Version 4.1, the α factor was set as 5. In AR&R Version 4.2, the α factor was significantly updated, varying with respect to the rainfall event duration, with the median value of α set as 15 for short duration storms up to 1 hour, and then linearly reducing to 8 for storm durations of 24 hours or longer. That is, the hydrologic science with respect to predicting climate change impacts was significantly updated.

The effect on rainfall resulting from climate change is commonly found to be the most significant impact on increases in design storm flows (Ho et al. 2025). Figure 3 shows the estimated design flow at 2070 for a theoretical 3 km^2 catchment in the Gippsland region of Victoria for different combinations of RCP (i.e. from CMIP 5) and SSP (i.e. from CMIP 6), and either using the rainfall scaling from AR&R Version 4.1 or AR&R Version 4.2. Assuming a surface water infrastructure element has a design flow capacity of 13 m^3/s, Figure 3 shows that, depending on the assumed climate scenario and the AR&R approach at the time, the AEP of the design flow would be a 1 in 160 AEP for stationary climate conditions and vary between a 1 in 60 and 1 in 100 AEP with climate change. Further, even if a designer adopted the most conservative climate change parameters in 2019 (i.e. RCP8.5 with AR&R V4.1 scaling factors), the predicted design flows do not remain conservative under current climate science (e.g. SSP3-7.0 and AR&R V4.2 scaling factors).

This highlights an inherent challenge with using AEP as the design criterion for surface water infrastructure as it needs to be linked to both the climate scenario predictions (which will be updated every 5 to 10 years as new CMIP releases occur) and hydrologic scaling approaches (with advances in the AR&R methodologies anticipated over time). There is also the challenge of which SSP scenario to select for design, with reducing uncertainty anticipated as global efforts to reduce emissions progresses into this century. Where progressive rehabilitation can occur over a period of decades, this potential for change means that a design AEP assessed at one point in time may not achieve the desired risk control at a future point in time as climate science progresses, giving a high risk for changing goal posts in the design requirements.

For mine closure it is not uncommon to consider a design intent period linked to ‘evidence based design periods’ of 100 to 200 years (De Graaf et al. 2025; Logsdon 2013). In the additional context of climate change, where the next 50 to 100 years are likely to be critical in curtailing global emissions, and that climate change predictions are commonly only provided out to 2090, it is very challenging to consider evidence based design periods in excess of 100 to 200 years for surface water infrastructure design for mine closure.

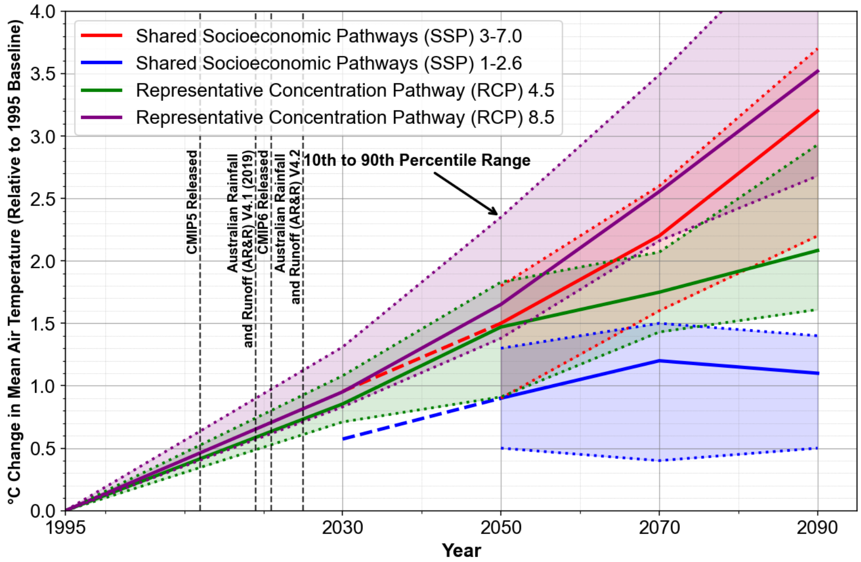


Figure 2 Coupled Model Intercomparison Project (CMIP) 5 and 6 predictions for Gippsland, Victoria, Australia

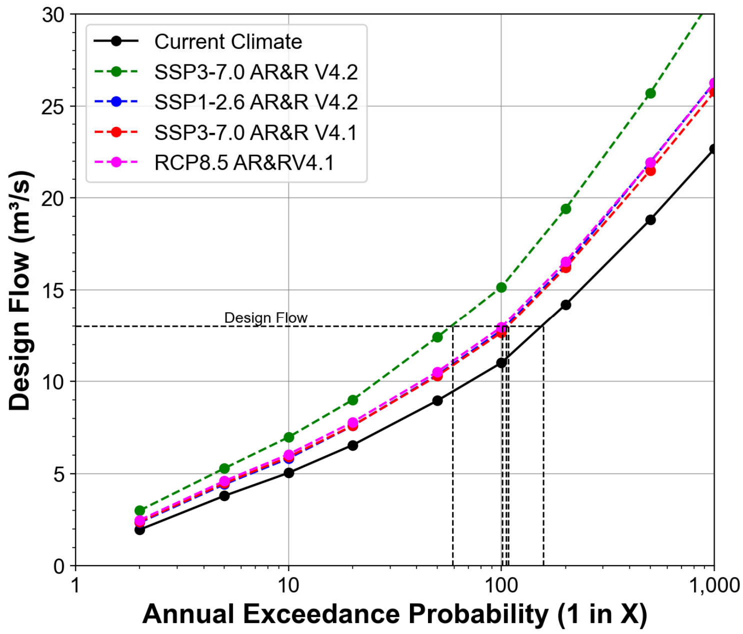


Figure 3 Variability in design flow estimation (for 2070)

3 Proposed hydrologic design event selection framework

To facilitate a risk-based design approach for the design of mine closure surface water infrastructure that can respond to updates in climate change predictions and science and the different stages of mine closure, Figure 4 presents the proposed framework to aid decision-making in selecting the hydrologic design event. The framework is quite similar to that adopted for the design of dam spillways within the ANCOLD guidelines. The main stages are:

- Stages 1 and 2 relate to identification of hazards and key phases within the mine closure process, and then undertaking a consequence assessment (with this paper presenting potential semi-quantitative criteria for consideration). This can be considered an initial screening phase of design.
- For the associated consequence, a screening likelihood LoT threshold is defined (with recommendation presented in Section 4 of this paper), which is Stage 3. The LoT has been

developed based on the references used and judgements made by the authors as presented in Section 4, and again is proposed to aid screening for design event selection.

- Stages 4 to 6 relate to assessing hydrologic design flows for the upstream catchments (including for a range of climate change scenarios), assessing the likelihood of a particular design flow occurring over the design intent period, how these likelihoods compare against the LoT and the practicality and/or costs associated with designing the surface water infrastructure for that design flow. This can be considered as a feasibility level of design. During these stages, it is anticipated that a number of design flows will be trialled for the surface water infrastructure to help identify an appropriate design flow.
- Stage 7 is a risk workshop with all relevant stakeholders to assess if the level of risk control is ALARP and if other controls could be required, with the analysis from Stages 1 to 6 aimed to aid the decision-making and risk analysis at Stage 7. It is highlighted that the adopted design likelihood from Stage 7 is an outcome of an ALARP process, with the chart developed in Section 4 of this paper an initial screening tool to aid this selection. The outcomes from the risk assessment then provide a documented, defendable and structure decision-making basis to undertake the detailed engineering design works to prepare for construction (i.e. Stages 8 and 9).

A big benefit from this framework is that using the likelihood of the design flow occurring as the design parameter (as opposed to AEP) as part of the risk-based decision-making process results in design aims that are significantly less linked to climate change predictions or science updates (i.e. it limits the moving goal post risks). This is provided that the consequences do not change, and then the assessed acceptable likelihood to mitigate risks (from Stage 7 of the process) should not significantly change. And, if climate science changes, then the main review is whether likelihood of exceeding the design flow based on the current hydrology at the time exceeds the previously assessed design likelihood, and if further ALARP controls could be required. When there is an update in the mine closure plan and/or an update in climate change predictions or science, then, whilst the existing risk assessments should be revisited, the main checks would be an update of the design flow predictions, assessment of the likelihood of a flow exceeding the design flow and whether the controls still satisfy ALARP aims (i.e. Stages 4 and 7 of Figure 4).

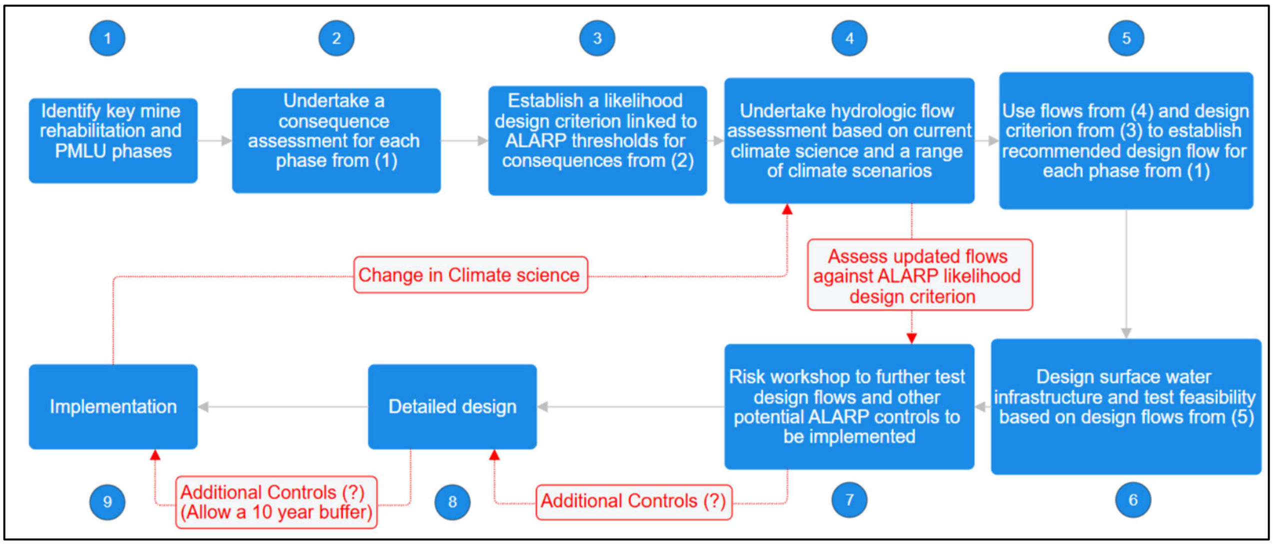


Figure 4 Proposed hydrologic design event selection and decision-making framework

For Stage 5 of Figure 4, a method to account for the variation in the likelihood of a design flow occurring for non-stationary conditions is required. To account for the variation in the AEP of a surface water design flow as a result of climate change, a modification of Equation 1, as presented in Salas & Obeysekera (2014), can be used, where the hydrologic likelihood of a certain design flow occurring by a particular year ($P_{D,Y}$) can be calculated as:

$$P_{D,Y} = 1 - \prod_{t=1}^{Y}(1 - AEP_t) \quad (3)$$

where:

AEP_t = the AEP (as a fraction) of the design flow occurring in year '*t*' following construction.

Calculating the likelihood of the design flow occurring for each year within the design intent period allows each different phase of the mine closure (and the associated consequences) to be reviewed (like in the example shown in Section 5).

Another benefit of this framework is that it also has good utility for existing infrastructure. For example, if there is existing surface water infrastructure that was designed without specifically accounting for climate change that is intended to be maintained for mine closure, then the potential time frames involved for the design flow likelihoods to exceed the LoT (or the assessed design likelihood from the Stage 7 risk assessment) under climate change can be assessed. This point in time would represent a point under which upgrade of the infrastructure could be required. Mine closure plans are often required to be updated every 5 years (De Graaf et al. 2025), whereas it is not uncommon for there to be a 10-year buffer allowance for upgrades within the dam industry. As such, it could be decided that a new review of the existing infrastructure is required at least 10 years prior to the currently predicted year the LoT and/or design threshold would be exceeded. At the time of the reassessment, the climate change science at that time may indicate that further life extension of the infrastructure is acceptable. Conversely, if the exceedance of the LoT and/or design threshold is anticipated in the near term, then infrastructure upgrade in the short term would more likely be required.

The TPG23-17 (NSW Treasury 2023) provides a good summary of potential approaches to decide on the efficacy of mitigation options for natural disasters (such as floods), with guidance in this document a potential option for consideration as part of Stage 7 in the ALARP and cost-benefit decision-making. A key concept is that risk can be considered as a combination of the hazard (for example, the AEP of a certain flood occurring), the exposure (for example, the population and infrastructure within the flood zone) and the vulnerability (for example, if the floods are expected to exceed safe levels for people to escape flood waters). Mitigation can be achieved through adjustments to one or more of these factors: for example, constructing a flood detention basin to reduce the hazard, creating a warning system to reduce the population exposure or decreasing the vulnerability by improving infrastructure resilience. In the context of the ALARP design approach for mine closure, in some cases concepts to reduce vulnerability and exposure are also viable alternatives to increasing the design flow of the closure surface water infrastructure and could be key components in the decision-making as part of the Stage 7 risk assessment. This could include, for example, implementing road closures and/or limiting public access during extreme storm events, noting that this will require 'buy in' from post-mine landowners as part of the progressive mine closure planning and consultation process.

4 Likelihood screening chart

Where there is a risk to life, f-N charts, which plot the number of fatalities (N) against the frequency (or probability or likelihood) (f) of occurrence, are a common tool used to communicate societal tolerance to risk. The societal risk can then be incorporated into an ALARP design chart, such as those for the dam design industry (ANCOLD, 2022).

Where there is not a risk to life, similar design tools to an f-N chart can be developed to plot of the likelihood of an event occurring against other consequences, such as the economic, environmental and geotechnical consequences. The likelihood reference charts presented below aim to create a screening tool to support Stage 3 to 6 from Figure 4. It is noted that the screening tool has been developed for where there is not a risk to life. If there is a risk to life then societal fatality f-N charts, such as in ANCOLD (2022), are recommended for use.

4.1 Economic consequences

A storm flow exceeding the design flow of a surface water infrastructure element has the potential to fail the infrastructure and require replacement. As such, the cost of replacement and/or the cost to construct the infrastructure (if not yet implemented) is a useful consequence metric. By considering industry literature for typical surface water infrastructure design lives and design event AEPs, the hydrologic likelihood can be calculated via Equation 1 (noting that existing references were developed assuming a stationary climate) and contrasted against the cost of construction and/or replacement (as informed from state government and council cost estimation tools).

The basis of Figure 5 for common surface water infrastructure elements is outlined in Rogan & Kim (2025). Additionally, a reference zone for mine pit slopes during operation has also been plotted based on Silva et al. (2008), with the economic costs scaled up using the Australian dollar inflation rate to an equivalent 2024 cost and an assumed typical slope design life of 25 to 50 years.

As discussed further below, a zone for a single fatality was also plotted based on the Cost to save a statistical life (CSSL) and the Value preventing a fatality recommended for dams (dams VPF), in conjunction with a 1 in 1,000 to a 1 in 10,000 AEP (based on ANCOLD 2022, Societal risk acceptance for a single fatality) and a common 'small' dam design life of 100 years. This is included to provide an upper bound to the screening tool range, given it is aimed to address situations where there is not a risk to life.

Figure 5 shows, as anticipated, that there is a general trend between the equivalent design event likelihood over the infrastructure element design life and the economic cost, with higher costs indicating a lower equivalent design likelihood. This trend is based on a summary of typical design ranges and design lives from conventional surface water infrastructure design 'wisdom' (where there is no risk to life).

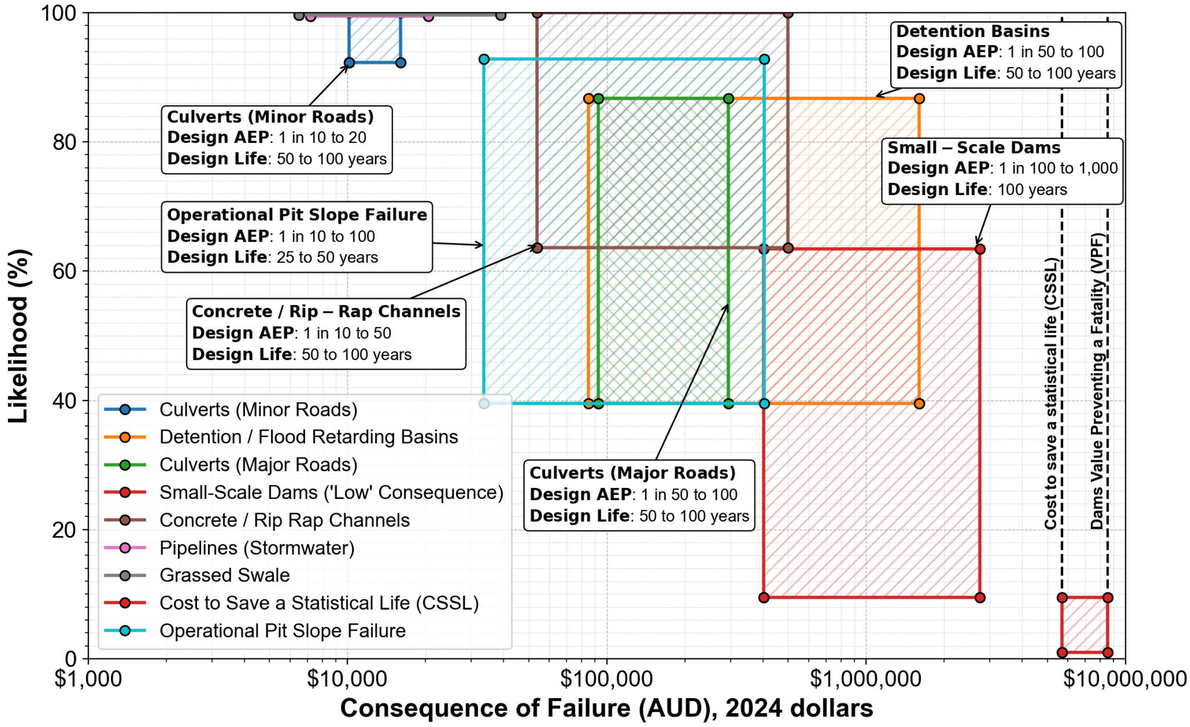


Figure 5 Economic consequences likelihood design chart for common surface water infrastructure (Rogan & Kim 2025)

4.2 Semi-quantitative risk assessment tools

Whilst the trends in Figure 5 are useful, they do not provide a risk screening tool on their own. To extend the findings to a semi-quantitative risk screening tool, a number of surface water semi-quantitative risk assessment tools from literature were utilised, including:

- mine rehabilitation – Queensland Government (2021), Western Australia Government (2025), Victorian Government (2020) and De Graaf et al. (2025)
- climate change – Australian Standard 5334 (2013)
- dam design – Queensland Government (2024), ANCOLD (2000) and ANCOLD (2019)
- Hazardous Products Industry – New South Wales Government (2011)
- environmentally sensitive projects – Victorian Government (2017)
- other (coastal hazards and circular economy) – Western Australia Government (2019) and Victorian Government (2025).

Figure 6 shows a comparison between the semi-quantitative risk assessment bands for likelihood and economic consequences, with:

- high consistency between band definitions for likelihood, with variations in band boundaries only varying by 5 to 10%
- higher variation in band definitions for economic consequences. This is likely due to different references being more geared for particular types of infrastructure; for example, for a tailings dam, ANCOLD (2019) indicates a minor consequence for an economic impact less than AUD10 million, whereas this would typically represent a catastrophic consequence from the references shown in Figure 6b.

A series of horizontal dashed lines have been drawn on Figure 6 to show the adopted band definitions for this paper, which have been selected based on comparison with the various literature definitions as well as comparison with the trend from Figure 5 (noting that the adopted bands align very closely with the available mine rehabilitation guidelines in literature). The adopted economic consequence bands are also presented in Table 1.

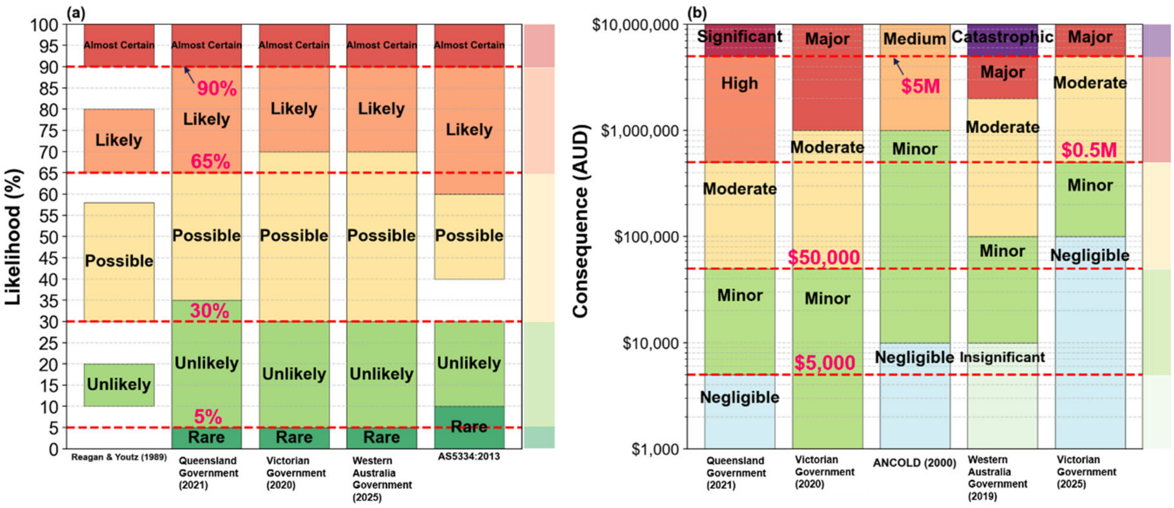


Figure 6 Risk assessment matrix: (a) Likelihood; (b) Economic consequence band comparison

Risk bands (i.e. low to very high) are defined in Figure 7 based on those recommended within AS5334 (2013), which defines a risk-based approach for climate change, with the only change being that the combination of an insignificant consequence with an almost certain likelihood has been defined as a 'medium' risk, as opposed to 'low' from AS5334 (2013). The resulting risk bands indicate that economic consequences have typical design precedence equivalent to the lower end of a high risk or the upper end of a medium risk.

The current ALARP approach provided in ANCOLD (2022) is that there is a LoT:

- If the risk exceeds the LoT (e.g. the upper bound of the zone in Figure 7), then the risk is intolerable.

- If the risk is less than the LoT then the risk can be acceptable if ALARP is satisfied (i.e. further reducing the risk is not needed if further reduction is impracticable or if costs are grossly disproportionate to the improvement gained).

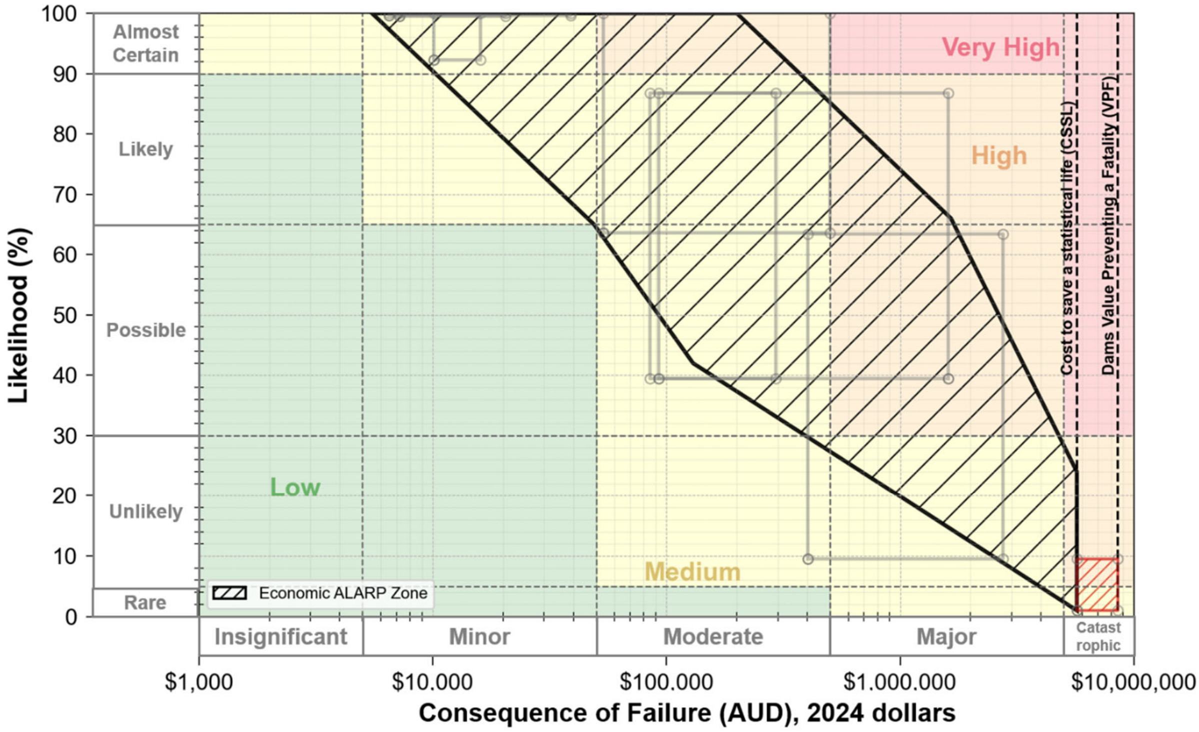


Figure 7 Economic consequence design chart and semi-quantitative risk band overlay

A number of methods exist that can be used to assess if a risk is ALARP, including societal risk and individual risk assessment tools, CSSL and cost-benefit analysis (ANCOLD 2022); as such, there is no single threshold at which ALARP is always satisfied. However, the level of risk metric can provide some general guidance on when risks often satisfy ALARP requirements. The level of risk is defined as the number of orders of magnitude the risk likelihood is below the LoT (for example a level of risk of 2 indicates that the likelihood is 100 times less than the LoT). Glover & Barker (2023) provide that:

- A level of risk of 0 gives the risk as being at the LoT.
- A level of risk between 0 and 2 typically has a low to moderate chance of satisfying ALARP with a robust understanding of uncertainties.
- A level of risk more than 2 often satisfies ALARP but still requires formal proof.

Considering the economic design band in Figure 7, if the upper bound is considered as the LoT, then the ratio between the upper bound and lower bound always exceeds 2, which is analogous to the level of risk. As such, if the likelihood and associated economic consequence were to plot below the upper bound, then an ALARP risk approach would be recommended, and if the risk plotted below the lower bound, then satisfying ALARP would still be required, but for a preliminary screening assessment the risk is often able to satisfy ALARP.

4.3 Environmental consequences

A number of semi-quantitative definitions of environmental consequence were found in literature; most commonly the area impacted (represented either as a km^2 area or a percentage of a habitat) or the environmental recovery time (in years). Further, Marhavilas & Kourouriotis (2021) define a societal acceptance design chart for environmental recovery time. Rogan & Kim (2025) outline the proposed linkage between the above environmental consequence literature references and the recommended semi-quantitative consequence bands from Table 1.

Table 1 Proposed semi-quantitative consequence bands for a screening tool

Base reference	Consequence type	Consequence band				
		Insignificant	Minor	Moderate	Major	Catastrophic
Rogan & Kim (2025)	Economic (2024$ AUD)	< 5,000	5,000 to 50,000	50,000 to 500,000	500,000 to 5,000,000	> 5,000,000
	Environmental recovery time (yrs)	Zero	< 1	1 to 3	3 to 10	> 10
	Environmental impact area (km²)	Zero	< 1	1 to 5	5 to 20	> 20
	Environmental impact area (% of habitat)	Zero	1 to 5	5 to 30	30 to 90	> 90
New Zealand Geotechnical Society, (NSGS, 2025), linked with geotechnical slope instability	Risk to life	No fatalities			Probably no fatalities	Probably 1–10 fatalities
	Expected damage to buildings and property	Little or no damage to land, no damage to structure	Moderate damage to land, no damage to structure	Extensive damage to land, but dwelling(s) has/have moderate or no damage	Extensive damage to single-residence building(s) (or it is only the accessway) requiring major engineering works for stabilisation	Collapse of up to 20 single-residence buildings or one small multistorey building
	Expected damage to roads	Half of one lane of road or shoulder blocked for a short period of time, emergency works limited to clean up only; or footpath destroyed over several metres but alternative access is available	One lane of local road blocked/slipped or several metres of footpath destroyed, with no alternative access available	Both lanes of local road temporarily blocked/slipped (delay of a few hours to a day); or one lane of arterial route blocked, with major delays	Both lanes of a local road impassable for days or weeks; or arterial route blocked for up to a day in both directions	State highway or arterial route blocked for days or weeks in both directions; significant effects to communities for extended periods

Figure 8 shows that when adopting a 100 to 200-year design intent period, the LoT and suggested ALARP band from Marhavilas & Kourouriotis (2021) is not dissimilar to the economic design band from Figure 7. It is also highlighted that there are other potential environmental consequences that are not addressed by the presented semi-quantitative definitions in Table 1, such as the significance of the impacted vegetation and flora. These are often defined in the relevant state guidelines (e.g. Environmental Protection Agency) and are recommended for consideration as part of the overall risk assessment process. Risks must be addressed no later than at Stage 7 in the framework of Figure 4.

4.4 Geotechnical slope instability

For mine closure, control of surface water can often be linked with the geotechnical performance of a slope. For example, if there is poor drainage management then flows could saturate tension cracks in a slope, reducing stability and/or influencing hydro-mechanical coupling, or erosion could undercut a slope. As such, geotechnical design metrics are also considered a useful reference for the design of mine closure surface water infrastructure (acknowledging that the interaction between water and slope instability will always depend on the site-specific conditions).

Silva et al. (2008) present slope Factor of Safety (FoS) thresholds against the annual probability of failure for 4 different categories of project (with the category a function of the consequence of failure). NZGS (2025) further extends these relations to link the AEP of a failure with semi-quantitative consequence bands (as replicated in Table 1), with a suggested slope FoS based on the project category.

For a 100 or 200-year design intent period for a closure slope, Figure 8 plots the geotechnical slope failure risk bands based on the consequence definitions from Table 1 and the AEP ranges defined in NZGS (2025). The resulting bands in Figure 8 plot within the medium risk zone from the semi-quantitative risk assessment tool.

4.5 Risk to life

Risk to life can produce much higher design requirements than purely the potential economic cost or environmental impacts. The dam design industry has longstanding societal risk f-N design chart tools to assess the potential design AEP of a dam spillway relative to the number of fatalities, such as the ALARP LoT thresholds recommended in ANCOLD (2022). These thresholds can be further compared against other industries, with other f-N curves summarised within Williams (2021). Where there is a risk to life, these f-N tools are recommended to be used in lieu of the screening chart presented below (in Figure 9).

Economic impacts can be notionally related to fatalities via concepts such as the CSSL or VPF. OIA (2024) gives the value of statistical life, which is considered an equivalent of CSSL, as AUD5.7 million (2024). ANCOLD (2022) guides that the VPF is the average estimated dollar impact on society of a life lost, and that for dam failures a 50% increase to the CSSL be made to estimate the VPF, giving AUD8.55 million (2024). For surface water infrastructure with an economic consequence exceeding the CSSL or the dams VPF, risk to life metrics for a single fatality were used to define a typical design precedence (shown in Figure 5). The intent of this is to provide an upper bound for the range of applicability in the economic consequence for the proposed screening tool.

ANCOLD (2022) provides that the ALARP threshold for a single fatality is 1 in 1,000 AEP for an existing dam and 1 in 10,000 AEP for a new dam. With the design intent period of a particular surface water infrastructure element, the failure of which could result in a risk to life, a design likelihood can easily be calculated via Equation 1. For example, for a 100-year design intent period, the likelihood of a 1 in 1,000 AEP event occurring at least once is 9.5%. This can be used for scenarios with risk to life to estimate an equivalent design likelihood (i.e. from a f-N design chart, such as ANCOLD 2022). Otherwise, Table 1 is based on where any risk to life is a catastrophic consequence.

4.6 Potential for change in societal acceptance levels

A key concept with risk design is that there is a societally acceptable level for risk tolerance for certain consequences. There is, however, a chance that the impacts of climate change, for example, due to increasing frequency of extreme events, result in a shift in the level of societal acceptance. For the design of new mine closure surface water infrastructure there could be an opportunity to pre-emptively accommodate such a shift into the design or, alternatively, account for such a potential shift in a review of existing infrastructure to understand when it could require an upgrade.

Outside of the random chance of an extreme event occurring in any year, an anticipated impact of climate change is an increasing frequency of extreme events occurring. If this were to result in a cluster of events, this could trigger a shift in what is societally acceptable and require an uplift in design infrastructure to achieve the desired level of risk mitigation. Nohrstedt (2022) provides a good summary of different response scenarios to policy reform following a disaster, with the 'bouncing forward' (where rapid policy uplift occurs following a catastrophic event) or 'lagged effects' (where gradual accumulation of events triggers policy transformation) considered possible shifts that could occur in response to the impacts of climate change.

Further to this, it is predicted that by 2061 the cost of disaster damages could approximately triple relative to 2020 levels (NSW Treasury 2023); for example, NSW increasing from approximately AUD5.1 billion to between AUD15.8 and 17.2 billion. This also has the potential to drive a shift in approach from policy setters.

As discussed in Section 3, responses to the impacts of climate change could be addressed via adjustments to the hazard, exposure and/or vulnerability. As such, responses to climate change may not necessarily be to adjust design standards that would effectively cause a shift in the acceptable design region for surface water infrastructure to lower likelihoods than current levels, but it is one potential option.

Conceptually, the potential for a shift would be the greatest for the lower economic consequence, as whilst there are low consequences, the annoyance factor of having to replace infrastructure more frequently and the low costs could result in a relatively larger shift. In contrast, at the high economic consequence end there are already low likelihoods and there could be significant increases in costs to achieve greater levels of mitigation, such that more modest shifts in acceptance criterion could occur. Currently, as in Figure 7, the design economic precedent classifies at the lower end of a high risk and the upper end of a medium risk. A postulated possible shift as a response to climate change is that the acceptable design zone moves out of the high risk zone and more into the medium risk zone, as shown in Figure 8 (acknowledging that this is speculation by the authors).

4.7 Proposed screening chart

Figure 8 compiles the different potential design bands for the various consequences, including:

- economic (see Figure 7), where the upper bound of the band represents the LoT
- environmental, from Marhavilas & Kourouriotis (2021), which defines both a LoT and a 'generally acceptable ALARP' threshold
- geotechnical instabilities, linked with NZGS (2025), with the 'suggested' LoT based on the central lines within the provided 'bands'
- risk to life, which is only used in this chart to provide an upper bound range of applicability with respect to economic costs (via the CSSL and dams VPF)
- the potential for a societal shift in acceptance levels for the economic design band, as a sensitivity, based on the discussion in Section 4.6.

Considering the different zones in Figure 8 there is reasonable alignment in the LoT around the upper to middle zone of the medium risk band. Similarly, the threshold for risks that often satisfy the ALARP criterion plots at around the top of the 'low' risk band. From this, a unified screening chart is proposed in Figure 9 (with an overprinting of the proposed thresholds shown in Figure 8 to allow comparison with the base references). The screening band is potentially conservative for current economic acceptance levels but better addresses the other consequences and also provides some redundancy in economic risks for a societal shift in acceptance thresholds as a result of climate change if that were to occur in the future.

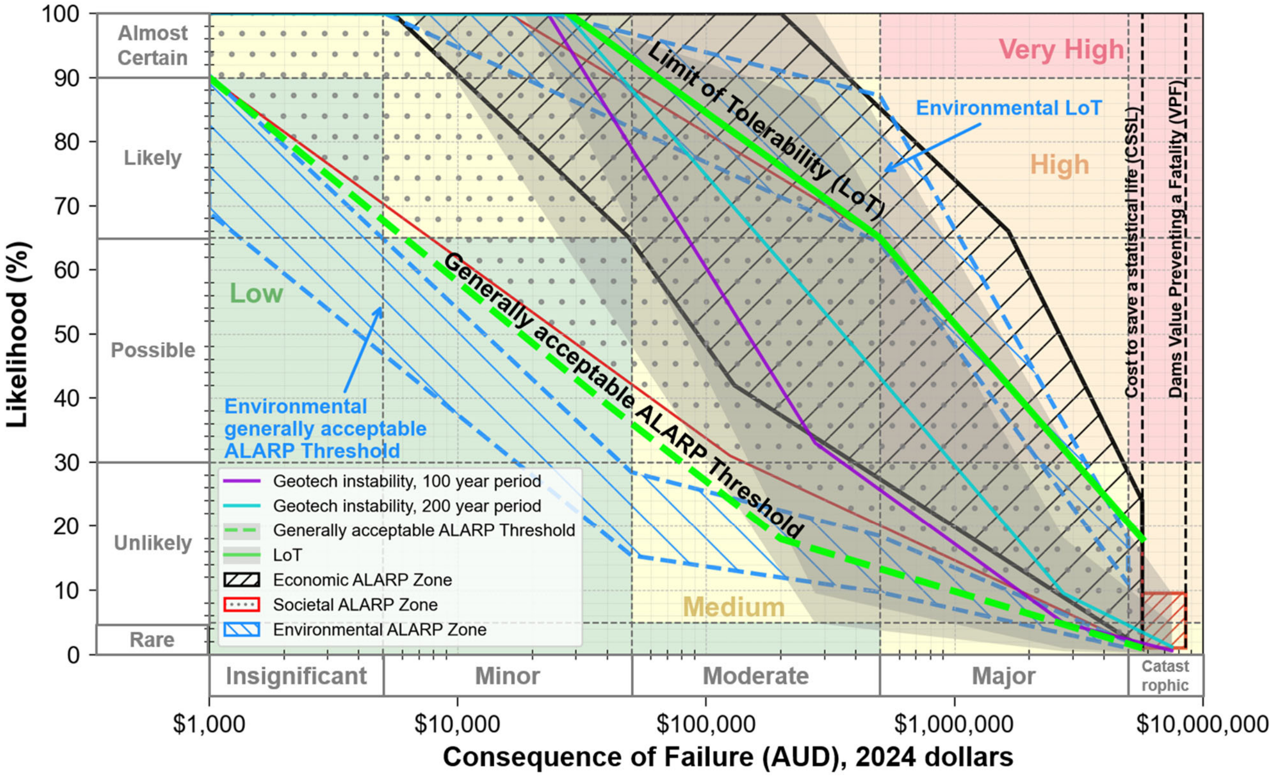


Figure 8 Compiled likelihood screening chart zones for different consequences

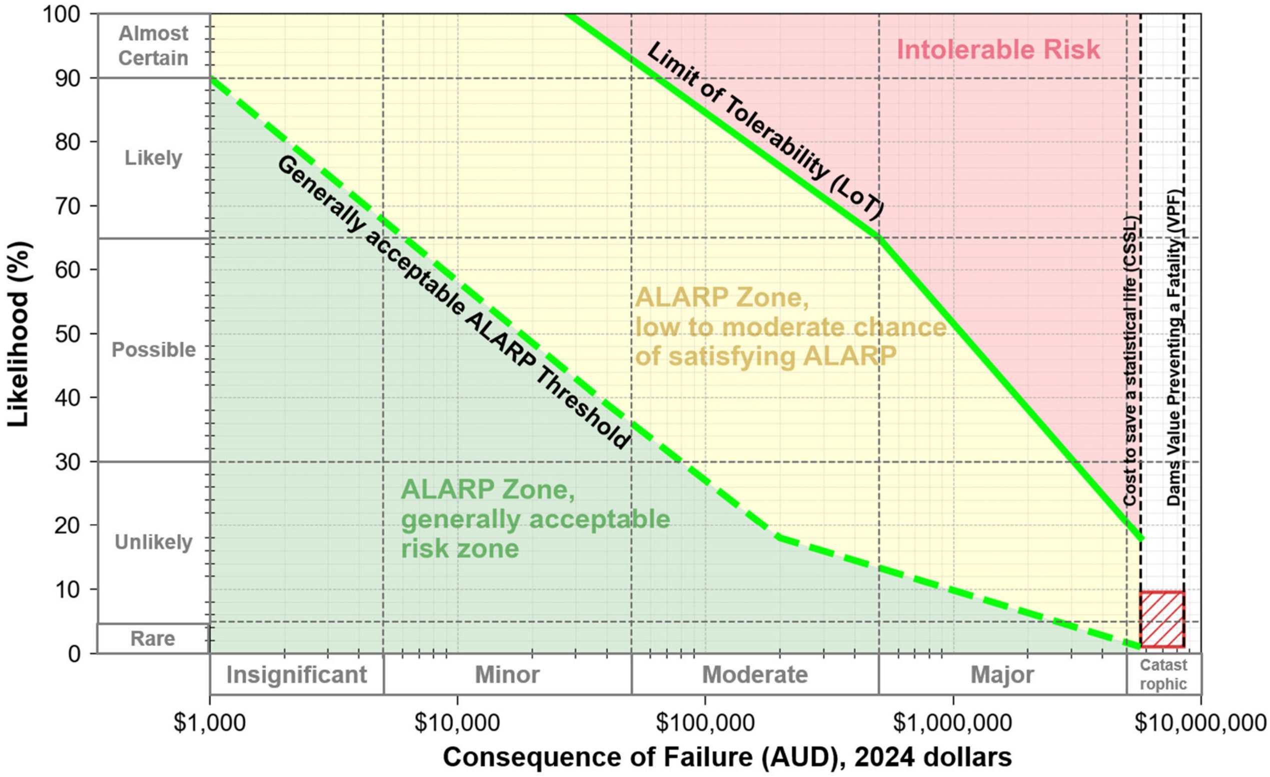


Figure 9 Proposed screening chart

From Figure 9:

- If risks plot above the LoT they are intolerable.
- Once risks are below the LoT they must satisfy the ALARP principle.
- If risks plot below the dashed threshold this does not mean they are automatically acceptable, just that often they can be found to be acceptable via ALARP principles. The dashed threshold is a ratio of at least 2 less than the LoT, similar to the level of risk metrics discussed in Section 4.2.

Using the framework from Figure 4, it is proposed that the LoT from Stage 3 be defined from Figure 9 for the initial design screening, based on the preceding consequence assessment for the various phases in the mine rehabilitation process.

5 Victorian mine closure illustrative example

An illustrative example is presented for a theoretical coal mine in the Gippsland region of Victoria. The climate change predictions from Figure 2 apply to this region. The case study considers that:

- The pit will transition from operations into closure in the coming years, with a pit lake and a recreation access post-mine land use proposed for the lake. Filling of the lake is expected to take 20 to 30 years, and have closure phases and sequencing similar to that in Figure 1.
- The pit slopes consist of thick low-density coal seams that are prone to the formation of tension cracks and block sliding geotechnical failure mechanisms due to groundwater pressures and/or surface water flowing into the tension cracks (i.e. there is strong interaction between surface water and geotechnical stability, such that the geotechnical consequences from Table 1 are considered relevant for the consequence assessment in this example).
- Peripheral catchments exist around the pit and are aimed to be drained into the pit lake to reduce the potential for interaction with tension cracks, if and when they occur.
- Significant public infrastructure exists around the pit at an offset to the pit crest, including a state highway and numerous local arterial roads. The example presented below focuses on a peripheral subcatchment that is conveyed under the state highway via existing culverts before being drained into the pit lake, with the design flows for this subcatchment presented in Figure 3.
- A recreational pathway is proposed between the state highway and the closure pit crest, but no car park or recreation node (e.g. camp ground, picnic area etc.).

Using the proposed framework from Figure 4, Table 2 presents the initial consequence assessment for 3 key phases in the mine rehabilitation and the associated design likelihood thresholds (i.e. Stages 1 to 3). It is highlighted that review of the consequence definitions in Table 1 is recommended as part of Stage 2 of the framework process to account for site-specific aspects and/or to add further consequence categories (e.g. such as state or site-specific environmental criteria, as discussed in Section 4.3). Further, in Table 2, a single value for the LoT has been adopted as part of Stage 3 of the framework (for ease of presentation), however, there should be consideration of whether a range should be considered for the site. This could be based on the range over the consequence band in Figure 9, or a selected value from Figure 8 (such as lowering the LoT if the geotechnical consequences are considered critical in the relevant scenario).

Assessment of design flows was undertaken using the CIMP 6 SSP1-2.6 and SSP3-7.0 climate change predictions and the AR&R Version 4.2 rainfall scaling factors (i.e. current climate science) seen in Figure 4 (i.e. Stage 4). The 2 climate change scenarios are linked with those recommended for strategic planning and decision-making in DCCEEW (2025). As an illustration of the first part of Stage 5 of the framework, a design flow of 13 m^3/s was trialled for the closure drain design flow. By combining Figures 2 and 3, the AEP of this trial design flow occurring at different years can be plotted, like that in Figure 10. It is highlighted that multiple design flows are recommended to be trialled for application in the second part of Stage 5.

By using the AEP variation of the design flow occurring in Figure 10, in conjunction with Equation 3, the likelihood of the drain design flow occurring at least once can be calculated for each year, with these likelihoods plotted against the screening likelihood thresholds from Table 2 in Figure 11a (i.e. part 2 of Stage 5). Figure 11b shows an equivalent chart for a design flow of 9 m^3/s.

Table 2 Example illustrative initial consequence assessment

Mine closure phase:	**Early rehabilitation, with no pit lake (2030 to 2040)**	**Pit lake filling (2040 to 2060)**	**Post-mine relinquishment (2060 onwards)**
Hazards:	Geotechnical instability causing the blockage of one lane of the state highway and impacting < 1 km^2 of environment. Closure drain construction costs between AUD 50,000 and AUD 500,000	Pit lake reduces geotechnical instability consequence such that impacts to the state highway are not anticipated but could impact < 1 km^2 of the environment. Closure drain maintenance is less than AUD 5,000	Pit lake reduces geotechnical instability consequence such that impacts to the state highway are not anticipated, but could impact < 1 km^2 of environment and impact a walking track with no alternative access. Ongoing closure drain maintenance is less than AUD 50,000
Consequence:	Moderate	Minor	Minor
Figure 9 Screening likelihood LoT (%):	65	94	94
Figure 9 Screening likelihood broadly acceptable ALARP threshold (%):	15	40	40

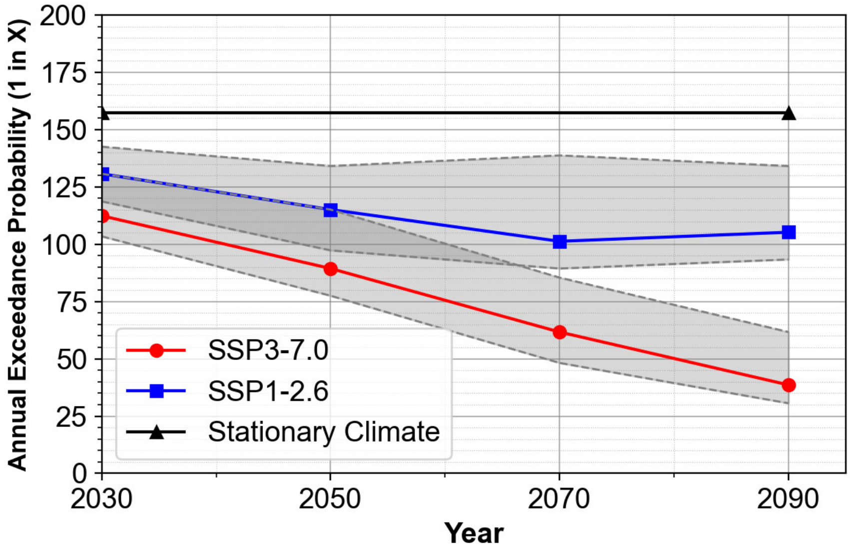


Figure 10 Example annual exceedance probability variation due to climate change for a trial design flow of 13 m^3/s

The likelihood screening thresholds in Figure 11 vary over time in line with the consequences for each phase of the mine rehabilitation, whereas the likelihood of the design flow occurring always increases with time.

As expected, the SSP3-7.0 scenario provides higher likelihoods than the SSP1-2.6 scenario, with the results from Figure 11 able to be compared to assess the sensitivity in impacts due to climate change.

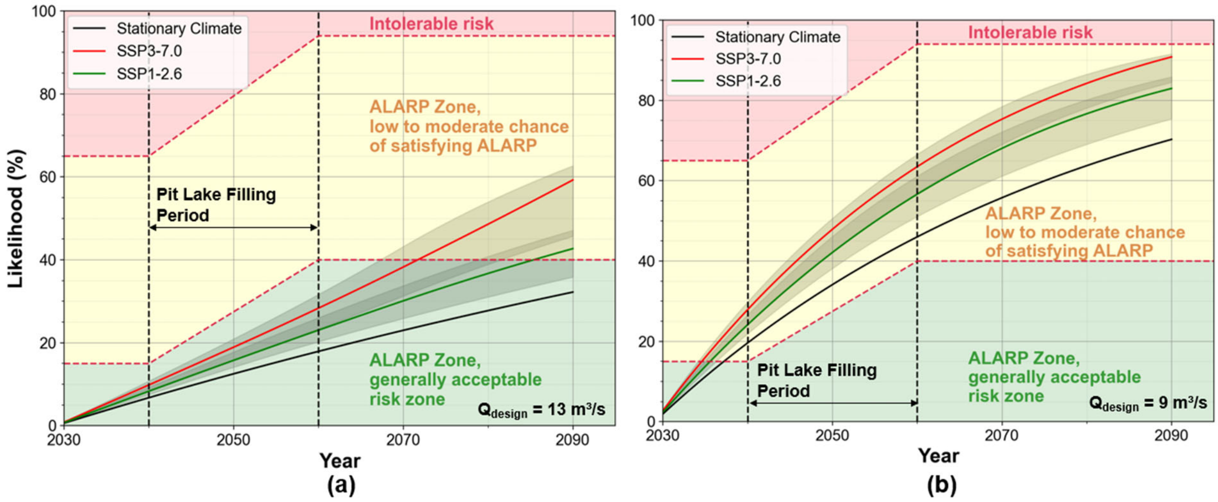


Figure 11 Example design flow likelihood variation over time against screening thresholds for: (a) 13 m³/s; (b) 9 m³/s

Figure 11 shows that the likelihoods always remain below the LoT threshold for the trialled flows. As such, the design flows could be acceptable, provided that ALARP is proven. However, the comparison between Figures 11a and b does show that a 13 m³/s design flow provides much lower likelihoods than a 9 m³/s design flow.

Further, for a 13 m³/s design flow (Figure 11a) early in the mine rehabilitation period, and despite the higher consequences of failure, the likelihood is likely to be sufficiently low such that the critical design case for the drain is post-lake filling. The likelihood's first 'cross' into the yellow ALARP zone is between 2070 and 2090, depending on the climate change scenario. Given this, one consideration for ALARP controls could be that a review of the drain be undertaken at the end of lake filling (e.g. 2060), with the climate science at the time, to review the risks. This would give a nominal 10-year buffer for the implementation of any additional controls. In contrast, for a design flow of 9 m³/s, all phases in the mine rehabilitation plot within the zone where there is likely to be a low to moderate chance of satisfying ALARP.

Following selection of the initial design flow (or a range of flows) from Stage 5, the drain design, feasibility costing, implementation of an ALARP risk assessment, detailed design and construction then follow traditional design approaches (i.e. Stages 6 to 9).

At future times where climate science and/or predictions are updated or there is an update in the mine progressive rehabilitation plan, and whilst a review would be recommended, the consequence of failure and design screening thresholds from Table 2 (or the outcomes from the existing Stage 7 risk assessment) would not necessarily change. Any updated predictions of the likelihood of the design flow occurring could then be replotted on an equivalent chart as in Figure 11 to provide screening of any change in the risk that may support subsequent risk assessment and whether implementation of further controls could be required.

6 Conclusion

This paper presents a proposed framework to support decision-making within an as low as reasonably practicable risk-based approach, with an associated screening limit of tolerability that can be applied to the design of surface water infrastructure for mine closure. The approach allows for a more transparent setting of design aims within a risk-based assessment, founded on the consequences at each stage of the mine rehabilitation process. Removal of the direct use of annual exceedance probability as the design aim is considered to improve visibility in the decision-making process and help reduce the risk of 'moving goal posts' as a result of updates in climate change predictions, emission scenarios or climate science affecting design flow predictions over time, as the assessed consequences of failure are likely to be less variable than hydrologic flow estimates at future review stages.

The proposed screening tool, aimed at aiding the early stages of the framework, incorporates economic, environmental and geotechnical instability consequences, as well as the potential for a shift in the societal acceptance of risks resulting from climate change. The approach can also be extended to scenarios with potential fatalities through use of other industry f-N charts, such as those from ANCOLD (2022).

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