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A risk-based approach to hydraulic modelling for the design of mine closure flood management structures

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Abstract

Maintenance or reinstatement of surface water flows through the post-mining landscape is often required to sustain sensitive environmental and cultural heritage receptors over the long term. The design of flood management controls requires selection of an appropriate rainfall annual exceedance probability (AEP) event for hydraulic modelling.

In Western Australia, there is an absence of regulatory guidance or industry standard for the selection of the design AEP rainfall event, resulting in a range of AEP events being adopted for closure at different mines, often within the same catchment. Example design AEP events adopted for closure design range from the probable maximum flood (PMF) to the 1:1,000 AEP event, reflecting the high variability in interpretation of site-specific risk considerations by mining companies.

This paper proposes a risk-based approach for selecting design AEP rainfall events for hydraulic modelling, which is undertaken to inform surface water management design through the post-mining landscape. Key aspects of this approach include establishing the intended design life of the surface water control measures, evaluation of risk to downstream receptors, assessment of available materials required to construct controls as well as constructability and feasibility considerations.

The paper also presents a structured risk-based framework for the development of a sustainable surface water strategy, including phases of modelling, iterative assessments and scenario modelling. These proposed approaches aim to provide improved consistency of approach and clarity for closure planners, hydrologists, regulators and other key stakeholders to understand the factors influencing the surface water closure strategy.

Keywords: *mine closure, surface water management, hydraulic modelling, risk-based design, design life, annual exceedance probability*

1 Introduction

In Western Australia, the Department of Mines, Petroleum and Exploration (DMPE) *Guideline for preparing Mine Closure Plans* (2025) does not prescribe specific rainfall or flood design events for closure. Instead, the guideline requires that closure designs apply a risk-based approach to design criteria such that unacceptable risk to public safety, cultural heritage and environmental values is avoided, and long-term physical and geotechnical stability of mining landforms is demonstrated.

Regulatory and societal expectations with respect to mine closure in Western Australia have evolved from a focus on end of mine decommissioning to a life of mine, outcomes-based approach that reflects increasing community expectations for safe, stable, non-polluting land that can sustain the post-mining land use (Risbey 2024; Hamblin & Gardner 2022). Historically mine surface water management focused on avoiding and

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minimising operational risks by protecting mine voids (underground and open pits) and mine infrastructure within the mine development envelope; considering surface water management in the post-closure period and beyond the mine development envelope has not been widely addressed unless specifically conditioned during approvals. As regulatory and societal expectation evolve, management of surface water for the post-closure period has pivoted towards reinstatement of the hydrological regime through the post-closure landscape, where possible. This is evidenced in the standard surface water closure outcome established in the DMPE (2025) that states 'C6.0 Surface drainage patterns, flows and characteristics are reinstated in a manner consistent with the regional drainage function and/or post-mining land use.'

Industry experience shows that there has been a reliance on operator selection of AEP-based design without closure-specific industry or regulatory guidance. This has led to a spectrum of design AEP events being adopted for closure, sometimes within the same catchment by different mining companies (Figure 1).

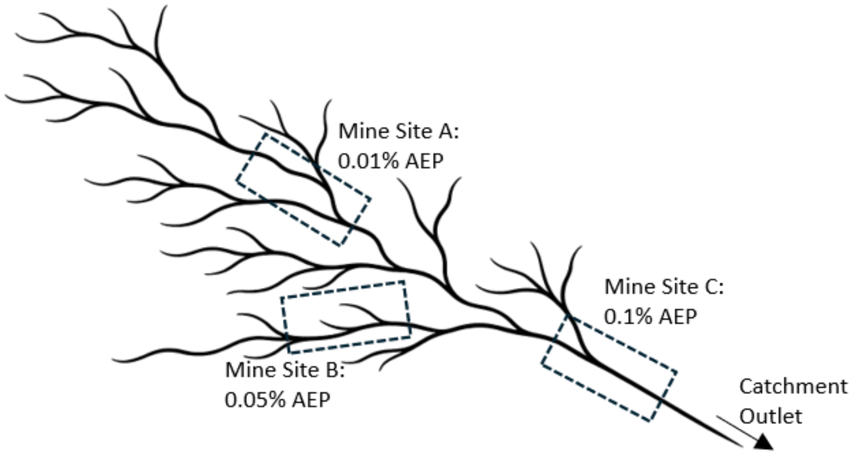

Figure 1 Example catchment with mining operations and adopted closure design annual exceedance probability event

Additionally, application of extreme design rainfall, such as probable maximum precipitation (PMP) events may not be credible and exceed the risk posed to receptors, resulting in over-design of controls and constructability issues. Conversely, inappropriate selection of design rainfall events may result in under-design and long-term risk or permanent impact to receptors.

2 Terminology and concepts

2.1 Annual exceedance probability and annual recurrence interval

Closure flood management structures are designed to meet a design rainfall event within hydraulic (flood) models. The design rainfall event is selected based on the probability of an event occurring, with varying terminology used to describe this probability. The 2 commonly applied approaches as defined by *Australia Rainfall and Runoff 2019* (ARR2019) (Ball et al. 2019) are average recurrence interval (ARI) – the average period between occurrences equalling or exceeding a given rainfall value, and annual exceedance probability (AEP) – the probability of a rainfall event being equalled or exceeded within a year.

The use of ARI has led to confusion among non-hydrologists as *recurrence interval* implies that an event will only occur after the specified interval. If a 1 in 100-year ARI event occurs, it will not necessarily be another 100 years before that event recurs. This common misunderstanding has led to the preferred terminology of AEP in ARR2019 (Ball et al. 2019), which describes the likelihood of a rainfall event, of a given magnitude in a single year, independent of when previous rainfall events may have occurred. For example, a 1% AEP rainfall event has a 1 in 100 chance of being equalled or exceeded in any given year and may occur in consecutive years or not occur for many years. As shown in Table 1, AEP may be expressed as a percentage, or in 1:x event; the former expression is favoured as the latter may lead to the same confusion as for ARI.

Table 1 Common annual exceedance probability events used in surface water design

AEP event (x%)	AEP event (1:x)	Description
50–40%	1:2–1:2.5	Frequent flows, environmental flows, river and creek geomorphologic (shape) controls
10–5%	1:10–1:20	Design event for operational surface water drainage
1%	1:100	Design event for flood protection of mine infrastructure
0.2–0.01%	1:500–1:10,000	Design event for closure surface water assessment
Probable maximum precipitation/flood (PMP/PMF)	–	Conceptually, the largest possible rainfall event that could occur

The rainfall depth for a given AEP event is determined from statistical analysis of historical rainfall data and varies by location. In Australia, design rainfall depths are published in intensity–frequency–duration curves available on the Bureau of Meteorology (BoM) website. Conceptually it is essential to note that the probability of event occurring is not proportional to the design rainfall; while a 0.1% AEP is 10 times less likely to occur than a 1% AEP event, the rainfall is not 10 times the magnitude (Table 2).

Table 2 Annual exceedance probability and intensity–frequency–duration rainfall depths (BoM 2026) at 3 locations in the Pilbara region, Western Australia

AEP event (24-hour duration)	Paraburdoo	Newman	Dampier
10% AEP	104 mm	131 mm	150 mm
1% AEP	189 mm	241 mm	282 mm
0.1% AEP	292 mm	356 mm	438 mm
0.01% AEP	433 mm	508 mm	639 mm

Figure 2 provides an example of hydraulic modelling of a creek system adjacent to a mine pit that was undertaken to inform closure design. Results for the 0.05% AEP and 0.01% AEP are shown, along with the magnitude of flood depths and velocities to inform levee design height and rock protection, respectively. While the probability of the 0.05% AEP is 5 times greater than the 0.01% AEP occurring in any given year, from a surface water management perspective, the flood depth is approximately 15% lower and flow velocities are 18% lower. These reductions are not proportional to the difference in AEP.

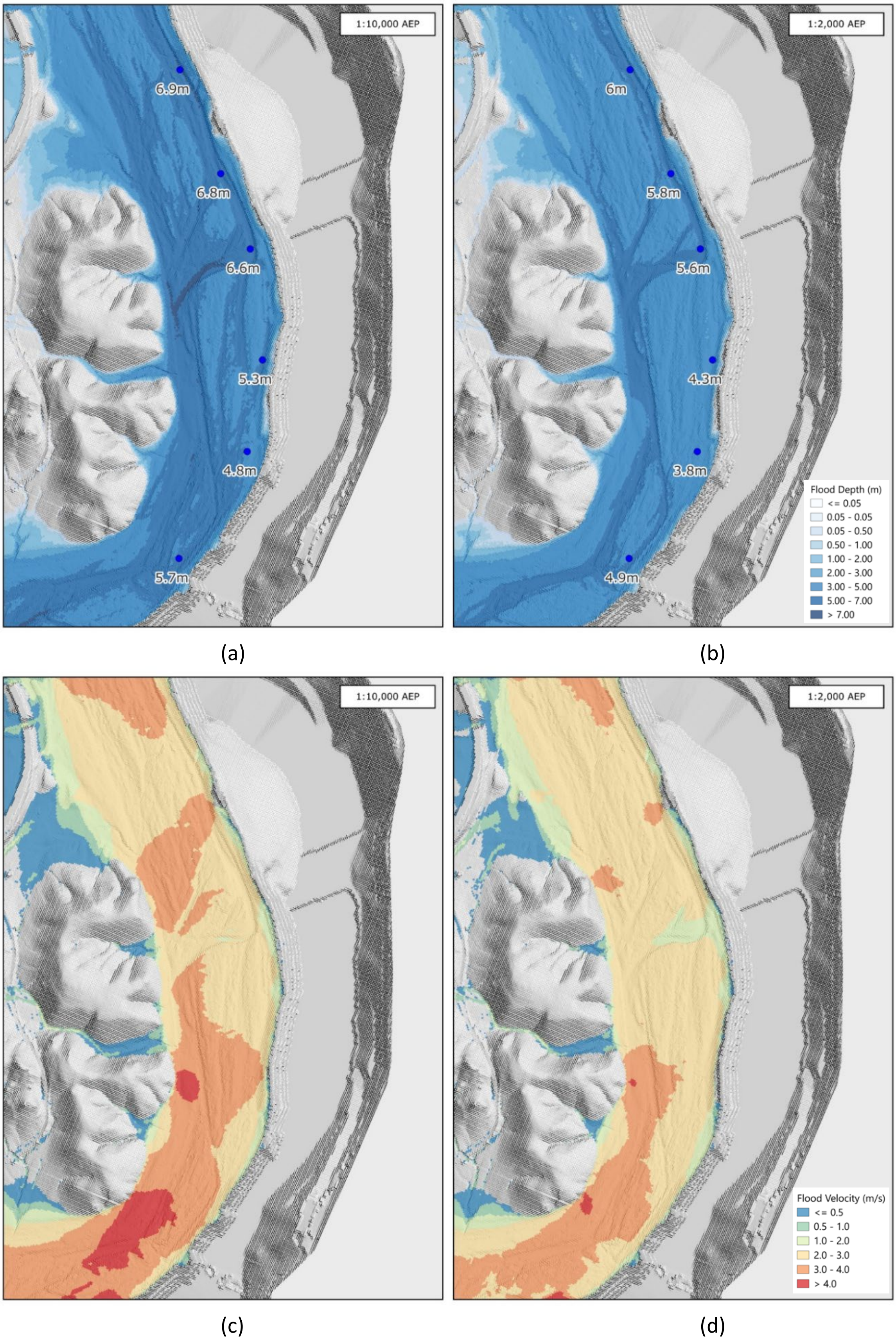

Figure 2 Example hydraulic model outputs for the 0.01% and 0.05% annual exceedance probability events; (a) 0.01% flood depth; (b) 0.05% flood depth; (c) 0.01% flood velocity; (d) 0.05% flood velocity

2.2 Probable maximum precipitation and probable maximum flood

There is no consistent approach to the selection of closure design AEP events across Australia. A common approach, which has been adopted within Western Australia for example, has been to initially consider the PMP/PMF event, hypothetically the largest flood event that could occur within a catchment. The PMF event is generally adopted for design of tailings storage facilities, water storages and spillway design in Australia, where an extreme consequence of failure exists for the downstream area (ANCOLD 2019). However, there is high variability in design AEP adopted for development of other surface water control measures for mine closure.

Defaulting to extreme events such as the PMP/PMF for closure design can result in structures that are impractical or infeasible to build, excessively costly and paradoxically detrimental to cultural heritage and environmental outcomes (Smedley et al. 2019; Harvey et al. 2020). The use of a single extreme event as a design criterion confuses the low probability of such an event occurring and ignores the smaller and higher probability flows (Harvey et al. 2020). Importantly, there is no documented observational precedent of an event of this magnitude occurring globally (International Committee on Large Dams 2025).

ARR2019 (Ball et al. 2019) considers the PMP to be a design concept that cannot be readily assigned an AEP (potentially in the order of one in several million) and is beyond the credible limit of extrapolation of rainfall data (Figure 3).

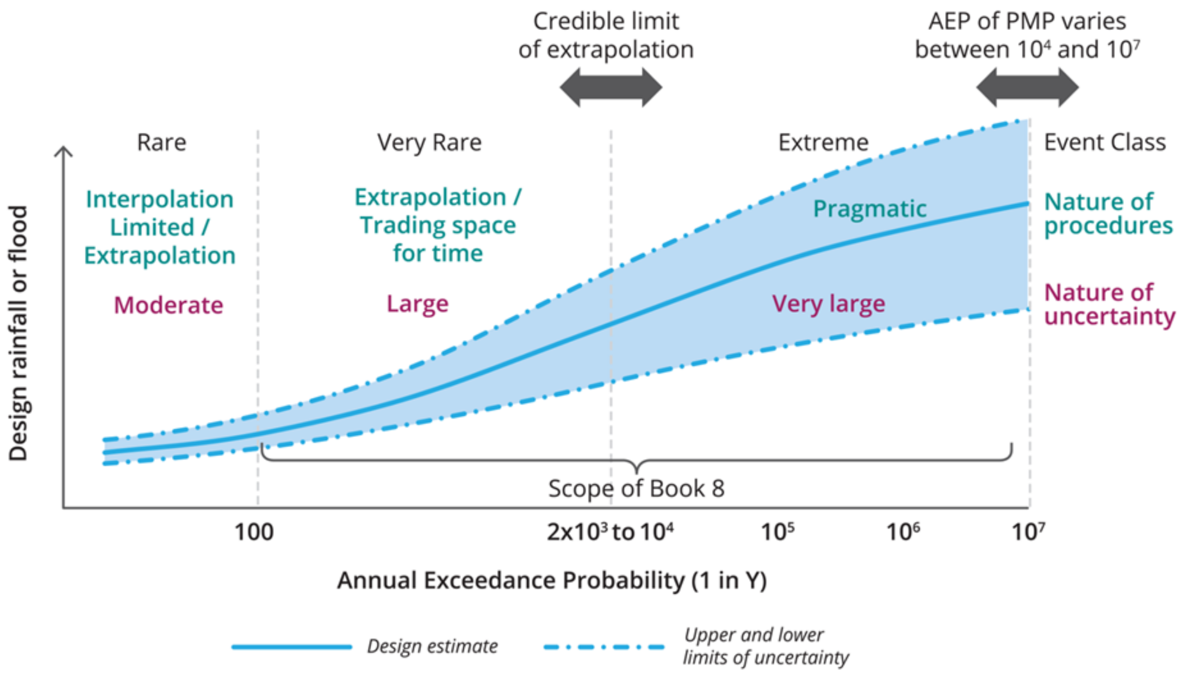

Figure 3 Design characteristics of notional event classes (Ball et al. 2019)

2.3 Other closure design annual exceedance probability events

Where the PMP/PMF is not considered suitable or feasible for general closure design, AEP events in the range of 0.2% to 0.01% have been commonly adopted across the mining industry in Western Australia. As shown in Figure 3, the 0.01% AEP is classified as a very rare event and is considered to be the upper credible limit of extrapolation (Ball et al. 2019). The 0.01% AEP event, however, may not be suitable for all mining operations based on the creek setting or risk profile. A potential approach to defining AEP events is to consider major or minor creeks, based on catchment size, or to define the risk of creek capture or environmental sensitivity, with fixed AEP events based on these factors. For example, BHP (Rea 2023) suggested a large catchment could be approximately 1,000 km^2 with a design AEP of 0.01% (assumed high risk), whereas a medium catchment is 10–100 km^2, with a design AEP between 0.2% and 0.1% based on (undefined) environment risks.

2.4 Guidance for design life for closure

Design life is defined as the assumed period for which a structure, or part of it, is used for its intended purpose with anticipated maintenance, but without major structural repair being necessary (Standards Australia 2017, 2021).

There is limited regulatory or industry guidance on the numerical definition of design life for closure, as similar to AEP definition, it can be difficult to conceptualise and regulators and industry therefore tend towards conservatism. Example guidance includes statements such that closure should create physically stable landscapes that limit long-term erosion potential and environmental degradation (International Council on Mining and Metals 2025). Additionally, specifying a design life for a closure control is often contentious (Beale et al. 2025) and implies that the control will fail at some point in the post-closure period, which elicits concern from regulators and Traditional Owners.

ANCOLD (2019) guidelines refer to a 1,000-year design life for tailings storage facilities, which are classed as major hazards with a significantly different risk profile to other closure landforms. More recent guidance from the Western Australian DMPE (2025) refers to 300 years with regards to numerical modelling of the long-term environmental performance of the structures such as waste rock landforms; this could be inferred as a design life of 300 years.

A period of 300 years still represents a timeframe that is difficult to conceptualise from an engineering and hydrological perspective. There are very few examples of river diversions or large-scale water management structures in Australia more than 150 years old and those that do exist are subject to ongoing monitoring and maintenance which would not necessarily occur after tenement relinquishment. An example structure is the Serpentine River in Western Australia that was channelised in the late 1800s to prevent flooding of surrounding farmland. The channelised form of the river is still subject to ongoing maintenance by state and local government agencies and while it is effective with regards to flood protection, the aquatic habitat, water quality and geomorphic values are suboptimal (Department of Water and Environmental Regulation [DWER] 2023). Designing a hydraulic structure that can last several centuries and meet closure principles over longer design life periods is unprecedented in Australia and requires consideration of what is achievable within the limitation of engineering rather than tending towards conservative design life estimates.

Dixon et al. (2025) recommend a design life in the order of 100–200 years as an evidence-based design period; these values will be applied within this paper to demonstrate the approach presented, with the DMPE (2025) 300 years as the upper limit.

3 Developing a sustainable surface water closure strategy

The development of a sustainable and adaptable surface water closure strategy requires consideration of the broader catchment outside the development envelope and iterative assessment of surface water interactions and management options. Figure 4 presents proposed phases of hydraulic modelling; although this is presented as a linear process, hydraulic modelling must be considered an iterative process that is revisited when conditions or guidance changes and to address stakeholder feedback.

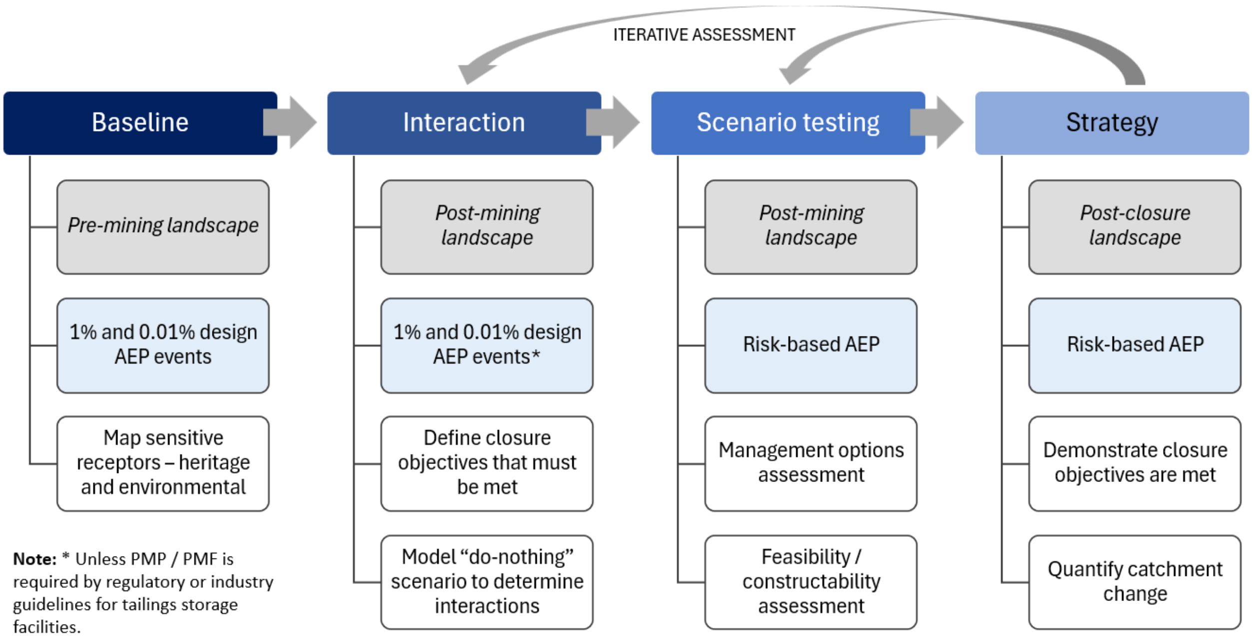

Figure 4 Phases of closure hydraulic modelling – from baseline to post-closure

Iterative assessment of the surface water closure strategy is required where any of the following triggers occur:

- Change within the mining development envelope from expanded or amended mine layout, new or amended approval conditions or commitments to local and community stakeholders and future land use managers.
- Change to upstream or downstream catchment conditions, particularly where other mining operations exist. Technical collaboration between mining operations within a catchment will assist with the identification and management of closure risks.
- Change to assumptions in the hydraulic model, relating to retention of infrastructure and mining landforms driven by revised closure planning and stakeholder engagement.
- Assessment of the practicality, feasibility and constructability of management options once the design AEP has been selected using the receptor risk-based approach.
- Updated guidance on climate change such that modelling reflects the latest technical guidance.
- Reduction in major knowledge gaps across the mine, including site geotechnical investigation relating to suitability of in situ material or mined material for surface water closure controls (e.g. spillway and levees).
- Addressing feedback through stakeholder engagement with regulators, Traditional Owners and the post-mining land use manager. The surface water closure strategy may require additional scenario modelling to revise or support the closure strategy.

3.1 Baseline modelling

Assessment of the baseline hydrological regime should form the basis for all mine development studies and approvals. This step identifies the low flow paths within the 1% AEP floodplain and identifies interactions of large flood events (AEP between 0.1% and 0.01%) with the pre-mining landscape and sensitive receptors.

While sensitive receptors will differ for each mining project, they will include cultural heritage sites and values, environmental values and third-party infrastructure.

Baseline modelling will enable later assessment of the quantum of change when compared to modelling across the post-mining and post-closure landscape. This will assist in defining the closure objectives the surface water closure strategy must meet and will inform residual risk associated with the closure strategy.

3.2 Determine interactions

Determining interactions of the altered hydrological regime across the post-mining landscape, and within the development envelope, is a critical step to determine areas where further risk-based assessment is required in order to meet the closure objectives for the mine and inform the closure strategy.

A key aspect of determining interactions is modelling the ‘do nothing’ scenario, which will identify where surface water flows interact with mining landforms, voids and sensitive receptors. Where pit voids are within the floodplain, the model must include a ‘glass wall’ aligning with the centreline of the associated safety bund to ensure surface water continues to flow after closure.

Table 3 is a summary of possible surface water interactions that may exist, and associated risk pathways.

Table 3 Possible interactions of surface water flows across the mine development envelope and surrounding catchment

Type	Interaction	Risk pathways
Pit void	Rainfall run-off into pit void via ramp	Pit overflow resulting in instability of pit crest; Release of low-quality water
Pit void	Creek or upstream catchment inflows into pit void	Pit overflow resulting in instability of pit crest; Release of low-quality water
Pit void	Pit void within floodplain – not backfilled to surface	Safety bund eroded (short-term); permanent creek capture (medium to long-term); geotechnical instability beyond initial pit zone of instability (medium to long term)
Pit void	Pit void within floodplain – backfilled to surface	Local scour and downstream sedimentation; Differential settlement of backfill
Landform	Landform impounds surface water	Geotechnical instability, piping or overtopping; Seepage of low-quality water
Landform	Landform abuts elevated natural topography	Scour at intersection of landform and natural slope; run-on to berms resulting in overtopping
Landform	Rainfall run-off onto the top of the landform exceeds crest bund design	Overtopping or failure of crest bunds and/or berms
Landform	Landform within floodplain	Scour of bottom bench resulting in geotechnical instability and downstream sedimentation
Receptor	Flood waters interact with a sensitive receptor	Increased flood extent, flood depth or peak velocity results in inundation, scour or other impact
Receptor	Surface water flows are impounded or redirected	Reduced flows to the downgradient receptor alter ecohydrology

3.3 Scenario testing

Scenario testing consists of modelling different surface water management controls, mine planning and closure planning decisions to evaluate the outputs against the defined closure objectives established by approval conditions and commitments to local and community stakeholders and future land use managers.

This is the step where risk-based rainfall events are introduced. Previous modelling phases applied standard design AEP events as shown in Figure 4.

This is where most of the modelling will occur as different scenarios are tested and rejected or refined. Evaluation of material properties, quantities and in situ geotechnical conditions will be required where specific surface water controls are proposed. Constructability and feasibility should also be considered when assessing surface water controls.

3.4 Closure strategy

The final piece of modelling is required to demonstrate the overall surface water closure strategy across the post-closure landscape. This will clearly demonstrate the final site landscape and surface water controls, providing enabling comparison of the post-closure hydrological regime to the baseline regime.

4 Risk-based selection of closure rainfall events

The proposed risk-based approach to selecting rainfall events includes 5 consecutive steps (Figure 5). Applying this approach clearly demonstrates how the final design rainfall event is determined and enables sensitivity analysis of the hydraulic model by amending one or more variable.

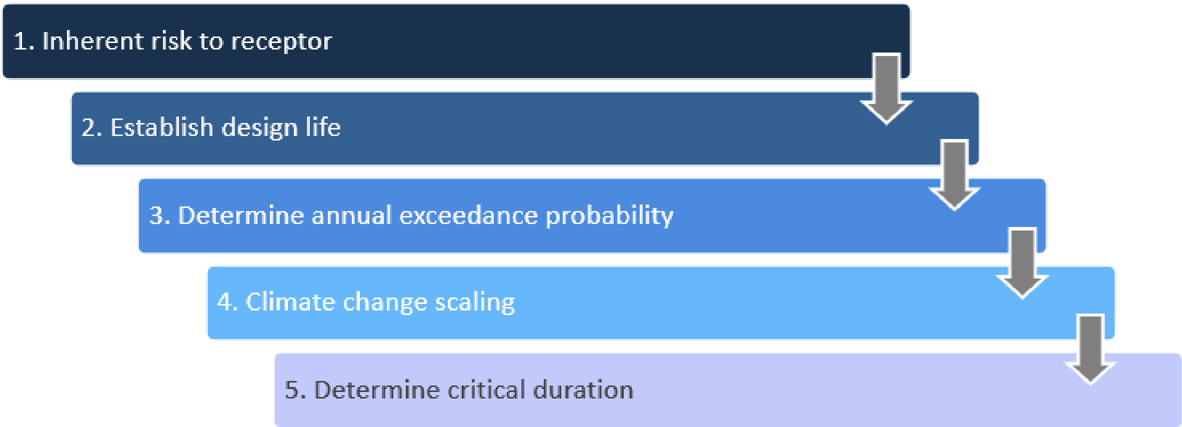

Figure 5 Steps to determine the risk-based closure design rainfall event

4.1 Step 1 – establish inherent risk to receptors

In establishing the inherent risk to sensitive receptors within or downgradient of the mine development envelope, it is important to note that inherent risk ratings may differ between discrete receptors. Depending on the mine layout, catchment setting, and location and sensitivity of receptors, part of the mine may have lower inherent risk and therefore require design against a more frequent (lower) AEP event. This needs to be considered when evaluating discrete risk for specific catchments or areas within the mine; applying a variable, risk-based design AEP across the mine develop envelope will result in a more sustainable surface water closure strategy than applying the highest design AEP universally.

Any regulatory or organisational risk framework can be adopted in this step – provided consequence descriptors are specific to surface water and likelihood relevant to closure timeframes. The inherent risk rating is determined by evaluating the most credible consequence level and likelihood of occurrence for an impact to surface water (Figure 6); this risk rating is carried through to Step 2.

Indicator	Insignificant	Minor	Moderate	Major	Severe
Surface water quality	Negligible changes to local surface water quality.	Short term (1–5 years) change to surface water quality.	Medium term (5–0 years) change to surface water quality.	Long term decline (20–50 years) in surface water quality.	Very long-term (>50 years) to permanent changes to surface water quality.
Surface water quantity	Incidental, short-term changes to local surface water volumes.	Short term (1–5 years) change to local surface water volumes.	Medium-term (5–20 years) changes to surface water volumes.	Long-term (20–50 years) changes to surface water volumes.	Very long-term (>50 years) to permanent modification to surface water volumes.

Descriptor	Description
Almost certain	Likely to occur/commence within a 1 year period from closure commencement. **AND/OR** Occurs 5 to 10 times in 2 years.
Likely	Likely to occur/commence within a 1–5 year period from closure commencement. **AND/OR** Occurs 5 to 10 times in 10 years.
Possible	Likely to occur/commence within a 5–20 year period from closure commencement. **AND/OR** Occurs 5 to 10 times in 20 years.
Unlikely	Likely to occur/commence within a 20–50 year period from closure commencement. **AND/OR** Occurs 5 to 10 times in 50 years.
Rare	Unlikely but possible to occur/commence within a 100 year period from closure commencement. **AND/OR** Occurs 1 to 5 times in 300 years.

Risk Matrix		Most Credible Consequence Level				
		Insignificant	Minor	Moderate	Major	Severe
Likelihood	Almost certain	Medium	High	High	Extreme	Extreme
	Likely	Medium	Medium	High	Extreme	Extreme
	Possible	Low	Medium	Medium	High	Extreme
	Unlikely	Low	Low	Medium	High	High
	Rare	Low	Low	Medium	Medium	High

Source: Adapted from DMPE (2025)

Figure 6 Using a risk framework to determine inherent risk

4.2 Step 2 – establish the design life

Establishing the design life of the specific surface water control will require input from experienced hydrologists, civil and geotechnical engineers. This paper suggests 3 options for the purpose of defining AEP for the surface water closure strategy; however, this variable can be amended to other periods provided there is evidence that they are risk-based and achievable within the limits of engineering.

4.3 Step 3 – determine annual exceedance probability

The relationship between design life and AEP is termed 'encounter probability' (Gordon et al. 2019) and can be determined through the following formula (Naghettini 2017):

$$P_e = 1 - \left[1 - \left(\frac{1}{T}\right)\right]^n$$

where:

P_e = probability (likelihood)

T = return period (design AEP)

n = period (design life).

This formula represents the likelihood of an AEP occurring or being exceeded over the intended design life, thereby converting AEP for any given year into the probability of exceedance over the intended design life. Applying this formula to a range of design life periods produces the occurrence likelihoods shown in Figure 7.

Using the adopted design life from Step 2 and applying the inherent risk rating from Step 1, the risk-based AEP event can be determined, as illustrated in Figure 7.

Frequency	AEP (%)	AEP (1:X)	Probability of single occurrence or exceedance within Design Life (years)		
			100	**200**	**300**
Rare	10%	1:10	~100%	~100%	~100%
	5%	1:20	99%	~100%	~100%
	2%	1:50	87%	98%	~100%
	1.0%	1:100	63%	87%	95%
Very rare	0.5%	1:200	**39%**	63%	78%
	0.2%	1:500	**18%**	**33%**	45%
	0.1%	1:1,000	**10%**	**18%**	**26%**
Extreme	0.05%	1:2,000	**5%**	**10%**	**14%**
	0.02%	1:5,000	2%	**4%**	**6%**
	0.01%	1:10,000	1%	2%	**3%**
	0.005%	1:20,000	0.5%	1%	1.5%
	0.002%	1:50,000	0.2%	0.4%	0.6%

Risk rating
Low
Medium
High
Extreme

Figure 7 Using inherent risk and design life to determine the annual exceedance probability

Note that a probability of approximately 100% (i.e. ~100%) is shown in Figure 7 as there is no certainty that an AEP event will occur.

4.4 Step 4 – climate change scaling

Once the AEP event is established, and prior to determining the critical duration, scaling for climate change is required. Factors for future climate change are dependent on the adopted Intergovernmental Panel on Climate Change (IPCC) temperature projections based on shared socio-economic pathways (SSPs) that cover a range of development options. Figure 8 presents the projected temperature increases and uncertainty for the respective SSPs which require factors to be applied to account for design rainfall. ARR2019 Book 1, version 4.2 (Ball et al. 2019) provides guidance on these factors for each SSP in the current and near term (2021–2040), medium term (2041–2060) and long term (2081–2100). While the design life for closure landforms would likely extend beyond 2100, ARR2019 (Ball et al. 2019) notes that projections beyond this period are speculative and no formal guidance is provided.

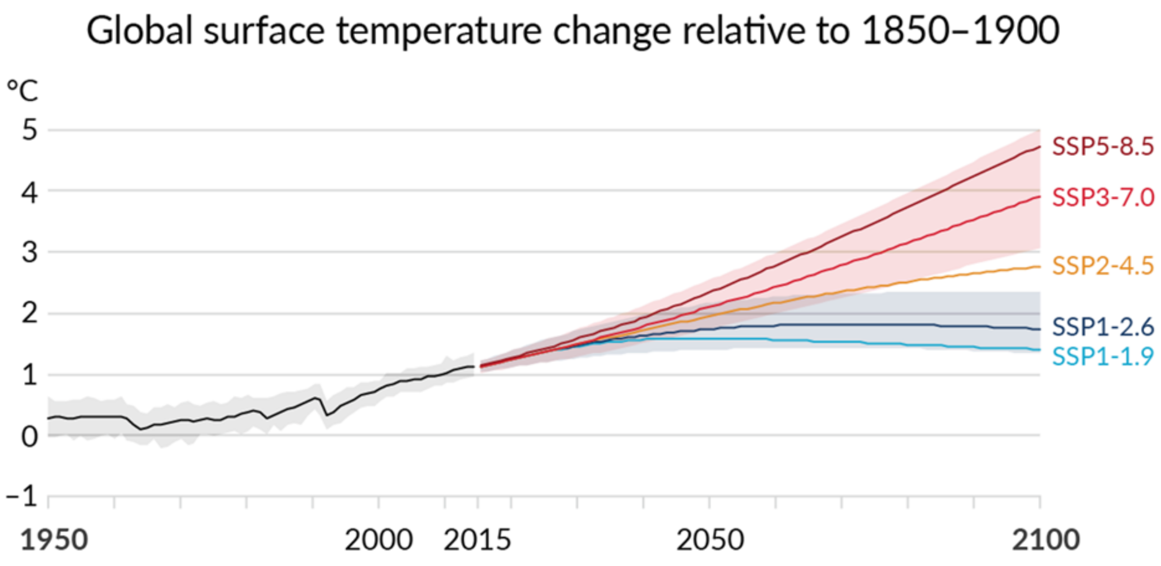

Figure 8 Global surface temperature change 1950–2100 compared to 1850–1900 period (Met Office 2023)

Determining the appropriate SSP and rainfall factor to apply is open to interpretation; Western Australian guidance suggests the SSP3-7.0 should establish the upper limit scenario, rather than SSP5-8.5. No further guidance regarding which SSP to adopt is provided, particularly for closure scenarios, owing to the general uncertainty about how climate change will affect water in the future (DWER 2024).

4.5 Step 5 – determine critical duration

The final step in arriving at a risk-based design rainfall event is to determine the critical duration for the AEP event. The critical duration of a rainfall or flood event is that which produces the maximum response at a given location – discharge, volume, water level or flow velocity (Ball et al. 2019). Smaller catchments are likely to achieve peak flows in shorter duration, higher intensity rainfall events, whereas creeks with larger catchments are likely to peak from longer duration, lower intensity rainfall events. It is likely that the critical duration may vary depending on the area of interest within the catchment and mine site; therefore a range of durations must be modelled to ensure that all maximum flood depths and velocities are identified for engineering design purposes. Table 4 illustrates the difference in rainfall depth under a 1% AEP and various durations for 3 locations in the Pilbara region of Western Australia.

Table 4 1% annual exceedance probability depth–duration–frequency for multiple durations (BoM 2026) at 3 locations in the Pilbara Region of Western Australia

Duration	Paraburdoo	Newman	Dampier
5 mins	16.5 mm	17.8 mm	15.7 mm
30 mins	48.3 mm	50.0 mm	49.6 mm
1 hour	61.5 mm	65.5 mm	65.0 mm
3 hour	87.6 mm	103 mm	101 mm
12 hour	147 mm	191 mm	203 mm
24 hour	189 mm	241 mm	282 mm
72 hour	245 mm	278 mm	383 mm
168 hour	257 mm	292 mm	400 mm

5 Conclusion

Selection of an appropriate design AEP event is a critical determinant of the long-term performance and sustainability of surface water management controls and overall strategies at closure. In Western Australia, the absence of regulatory and industry guidance has resulted in a wide range of adopted design AEP events, sometimes within the same catchment, creating inconsistent outcomes, stakeholder uncertainty and, in some cases, either over-design or residual risk that is not well articulated. While the examples presented in this paper are from mine sites in Western Australia, the proposed approach is considered applicable to a wide range of mine sites and hydrological settings.

A structured, risk-based framework for selecting design AEP events has been presented, integrating inherent risk to receptors, design life, AEP, climate change scaling and critical duration. By linking the probability of exceedance over the intended design life to a consequence-based risk framework, this approach provides a transparent and defensible basis for selecting closure design AEP events that are proportionate to risk and aligned with closure objectives.

The paper also highlights that developing a robust surface water closure strategy requires an iterative, catchment-informed approach, integrating baseline understanding, post-mining interactions and final strategy validation against closure objectives. By revisiting hydraulic modelling in response to stakeholder expectations and evolving mine plans, the surface water closure strategy can be progressively refined to manage residual risks to sensitive receptors. This structured yet iterative process provides confidence that post-closure surface water regimes are sustainable and appropriate for the intended post-mining land use.

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