
# Event-based versus duration-based assessment for long-term modelling of mining impacts

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**ABSTRACT**

*Open-pit mines are increasingly being proposed and implemented along creek beds and river valleys across Australia and worldwide. In many cases, insufficient backfill material is available to reinstate pre-mining drainage paths, and closure plans may include the presence of permanent pit voids adjacent to natural or diverted watercourses.*

*Under current mining regulations in Australia, the demonstration of stable conditions over an extended post-closure timeframe is required for closure planning and mine relinquishment. Compliance with regulatory closure requirements is typically based on the demonstrated conveyance of a single, peak discharge rate using a fixed bed hydraulic model. In reality, diversion failure or creek capture into a floodplain mining pit may result from scour, sedimentation, piping, or other mechanisms that occur over a sequence of successive, smaller flood events rather than overtopping caused by an extreme event.*

*Although hundreds of mine closure plans have been approved and continue to be updated on the basis of the adequate hydraulic conveyance of a single design event, very few mines have successfully been relinquished to the government across Australia, and the long-term performance of unmaintained watercourses adjacent to permanent pit voids is largely untested.*

*The results of this study show that currently accepted modelling approaches may be inadequate for assessing long-term impacts of pit voids located in floodplain areas. Alternative approaches are proposed for the definition of hydraulic structures and for the conditions of relinquishment. Continuing improvements in available hardware, software, and meteorological data allow the re-assessment of predicted, post-closure impacts, particularly for mine sites that will not be closed for many years. Advances in long-term erosion modelling, palaeo-hydrological techniques, Monte Carlo assessments, and other approaches allow increased confidence in asssessing cumulative, long-term impacts over extended time periods.*

*A risk-based approach covering an extended time series is more appropriate for mine closure modelling than the application of a single event with a designated recurrence interval. Improved, long-term modelling approaches are increasingly crucial as additional mineral resources are identified and extracted along watercourses, particularly where downstream communities rely on a mining-impacted water source.*

## INTRODUCTION

The number of open-pit mines being developed within floodplains has been increasing across Australia and worldwide as channel iron deposits are identified and mineral resources in less flood-prone areas are depleted. The available overburden and waste material is typically insufficient to allow complete backfill to surface at closure, particularly in areas with very low strip ratios. As a result, an increasing number of mine closure proposals include permanent pit voids within floodplains.

In some cases, external surface water inflow into post-closure pit voids is prevented by the use of permanent diversions, levees, or other surface water management features. The design level of the hydraulic structures is often based on the conveyance of a single flood with a specified design level that may range from the 1% Annual Exceedence Probability (AEP) or 100-year Average Recurrence Interval (ARI) event to the Probable Maximum Flood (PMF).

Figure 1 shows schematic examples of a permanent diversion or levee for closure conditions. Diversions and levees are designed to prevent the specified design flood event from overtopping the banks and entering the pit void while providing adequate freeboard, which may be assigned based on an adopted, constant depth value or a variable level based on risk and uncertainty analyses.

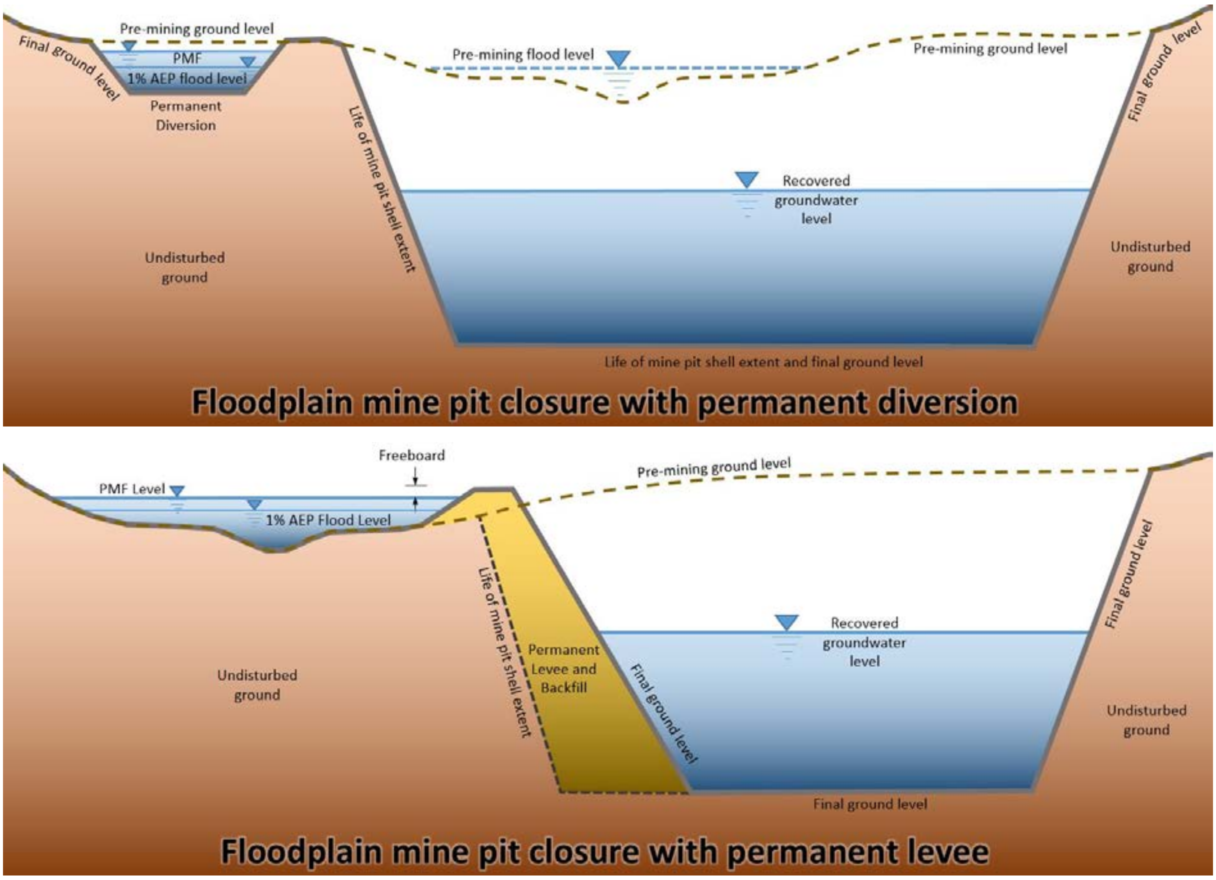


**Figure 1. Typical cross section for closure diversion or levee**

## CURRENT APPROACH

In general, the hydraulic assesments that accompany closure plans in Australia assume that the geometry of pit walls, levee embankments, and diversion channels are constant over post-closure timeframes and that suitable design and construction techniques prevent failure or overtopping of the diversion or levee in the design event. If the diversion or levee fails or is overtopped, flood flows will enter the pit void; over time, erosion associated with flood events may result in the eventual diversion of the low flow channel and the entire volume of flood flows into the pit. Figure 2 shows schematic examples of the progression of erosion in both cross sectional and longitudinal views as indicated by mobile-bed sediment transport modelling and confirmed through observations of historical failure events.

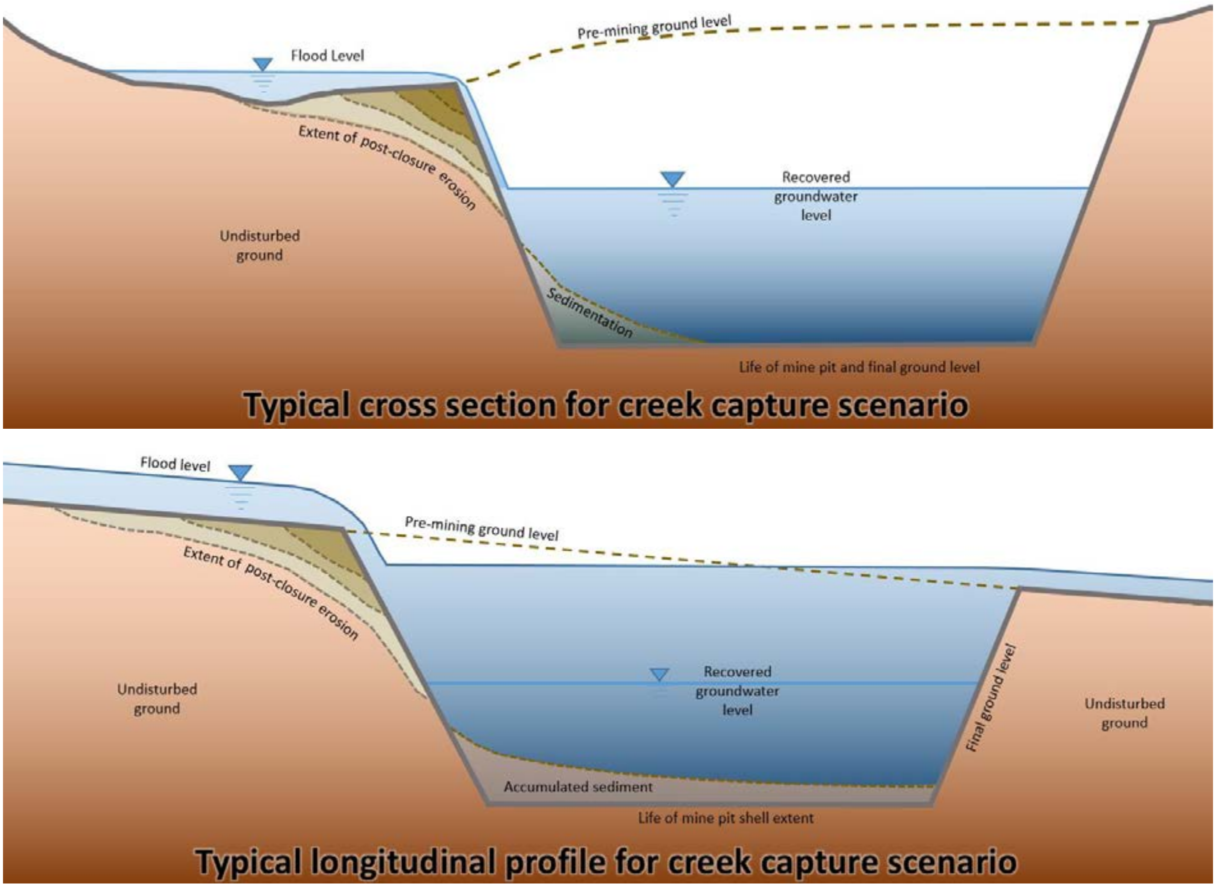


**Figure 2. Levee failure mechanisms (USACE 2011)**

Complete creek capture may have catastrophic consequences for the downstream environment, infrastructure, or downstream water users. Complete creek capture also traps the entire bed load of the creek system for extended periods of time until equilibrium conditions are reached – which in some cases extends to timeframes of thousands of years.

Mine closure plans may include the intentional capture of minor tributaries; for large creek or river systems, however, mine closure plans often focus on the prevention of creek capture in order to avoid the requirement to assess consequences and impacts associated with complete diversion of the watercourse into the mining pit. Historical diversion failures, however, have shown that catastrophic failures can occur even if overtopping conditions do not occur; this paper examines the deficiencies associated with the practice of basing closure designs on single flood events and proposes alternative analysis approaches.

## REGULATORY ENVIRONMENT

Current mine closure guidelines in Australia are typically specified by state authorities. Mine closure guidelines for most Australian states include language requiring post-closure landforms to be safe, stable, non-polluting, and sustainable in the long term (DMP 2015, QDEHP 2014, SAEPA 2016, TEPA 2011). In some cases, the stated goals are further defined as “physically safe, geotechnically stable, and geochemically non-polluting.”

Surface water management measures for floodplain pits are generally focussed on preventing excessive erosion and keeping substantial runoff out of pits in the post-closure environment. To avoid ongoing maintenance obligations, relinquishment criteria typically include demonstration that proposed landforms are self-sustaining at closure; however, the specific design event, duration of analysis, and methodology for testing compliance with these guidelines is generally not specified. As a result, closure approaches across Australian mine sites have varied tremendously, and the adoption of a consistent approach across the mining industry is recommended.

Australian state agency guidance for mining proposal submissions typically requires a mine closure plan to be included with each mining proposal. From 1 July 2011, for example, the Western Australian Department of Mines and Petroleum (DMP) has required all new Mining Proposal applications to contain a Mine Closure Plan prepared in accordance with current mine closure guidelines (DMP 2015).

Because it is complex to accurately model engineering performance over a series of events, most closure plans include references to the specific design event that will be accommodated at closure. The use of an extreme event, such as the 0.01% AEP or 1,000-year ARI event, is often used to demonstrate "long-term" performance.

The Western Australian guidelines include loose definitions ranging from "300 years or longer" (for landforms, voids, and ecosystems) to "500-1,000 years" (for pit lake modelling). The guidelines cite EPA studies stating that changes in water chemistry and water quality may occur "over thousands of years." A period of "1,000 or 10,000 years" is mentioned as an example of typical requirements for modelling geochemical equilibrium in a pit lake. The recommendations state that analyses should ensure that barriers be left in place at closure to prevent "long-term" pollution, and that mathematical models be developed to predict "long-term" environmental impacts or performance.

The only reference to the probable maximum precipitation (PMP) or probable maximum flood (PMF) event in the Western Australian guidelines is as an example of one of the events that might be applied to a water balance model for surface water inflow into a pit lake.

The public comments on the guidelines (DMP 2014) include several requests for temporal context and references to the lack of defined design events or durations. The DMP and EPA responses to these comments generally state "no action" with comments noted for the record. The definition of the closure period to be evaluated is thus left to individual mine owners. Although there is much discussion around the definition of the term "in perpetuity" related to closure designs, the term generally does not appear in Australian state guidelines. The lack of a governing quantitative requirement leads to inconsistent adoption of criteria and potentially the adoption of undue risks; a consistent approach is warranted in order to prioritise risks and to allow state regulatory authorities to consistently evaluate the relative consequence of individual mine closure plans.

The overarching objective of most mine closure plans is to allow the eventual relinquishment of mine sites to the government; however, complete relinquishment of a system that demonstrably meets the maintenance-free requirements over extended periods is not considered to be achievable without extremely prohibitive costs.

## RECOMMENDED RISK-BASED APPROACH

In selecting a consistent set of closure design criteria, a distinction should be made between the recurrence interval of a design event and the design longevity of the structure. A 1% AEP flood event (with a 100-year average recurrence interval), for example, may or may not be designed to last effectively for a period of 100 years or more. In reality, a closure surface water management feature that is designed to the level of the 1% AEP event may effectively convey the design flow immediately after relinquishment; without maintenance, however, that same structure may fail under a succession of smaller events within just a few years of closure.

The use of a specific ARI for closure design can be misleading; references to a 1,000-year ARI closure design, for example, may give the false impression that the structure is engineered with a design life of 1,000 years. In reality, if a hydraulic feature is abandoned at closure and is not subject to routine maintenance, a much lower event could cause failure. Engineers Australia and Australian Rainfall and Runoff (2016) generally recommended discontinuing the term Average Recurrence Interval in favour of Annual Exceedence Probability. Whilst the probability is essentially interchangeable between the two terms, the distinction is being made to avoid similar misconceptions.

For a closure structure designed to a 1 in 1,000 AEP level, the crest elevation is assumed to be sufficiently high to convey the peak design discharge event; however, a 1 in 2 AEP event or smaller could cause a levee breach if piping, cracking, differential settlement, or other failure mechanism were to develop over time. The actual design duration is thus typically less than the design recurrence interval for a single event; as such, the assessment of both approaches is recommended.

In some cases, design to a PMF standard has been adopted for mine closure. Even if all closure designs were undertaken to the PMF level and could demonstrate the effective conveyance of the PMF event, however, the performance of a levee designed to a PMF level may be undermined over time without maintenance, and failure may not require overtopping conditions.

A challenge in implementing a consistent level of protection is that the economic cost and material quantities associated with a range of protection levels can vary widely. In some instances (in systems with very wide floodplains, for example) a 1% AEP operational design can be upgraded to accommodate the PMF with relatively little additional cost; in more confined areas, however, the cost of a PMF design may exceed the 1% AEP design by an order of magnitude or more.

In order to prevent uncontrolled overflow in unpredictable locations, the adoption of a hardened low point or emergency spillway may be warranted. Alternatively, a non-hardened spillway may be implemented as a designated failure point. Because of the potentially excessive costs associated with the construction of a spillway that is intended to function without maintenance, the adoption of a legislated minimum design event and a functional duration is recommended. The selected design event and duration may be used to appropriately assess the performance of post-closure water management features and to ensure that post-closure objectives of safe, stable, and non-polluting landforms are met.

In order to provide clear guidance for the consistent application of design AEPs across multiple resource industries, a quantitative approach such as the ANCOLD requirements for tailings dam and spillway designs (ANCOLD 2015) is recommended. A similar risk-based approach has been provided in Appendix H of the Western Australia mine closure guidelines (DMP 2015). Although this approach is specific to pit lakes and is qualitative rather than quantitative, it provides a framework that can be modified to guide the selection of a design level and duration of analysis for surface water management features.

It is recognised that a risk-based approach can be somewhat circular; impacts may vary with the selected design event. For example, the design event may be selected based on relative impacts; however, the impacts may vary with the level of design. The downstream impacts of the failure of a levee, diversion, or spillway designed to a PMF level, for example, may differ substantially from the impacts associated with the failure of a structure designed to accommodate a 1% AEP flood event.

A risk-based approach can be undertaken in conjunction with the identification of critical risks using single event-based and multiple event, duration-based procedures, including palaeo-hydrological techniques or Monte Carlo simulations of a series of extended hydrologic sequences. Given the long-term nature of the assessments, further geomorphological investigations may be warranted to establish sedimentaton and erosion risks over extended temporal periods at closed mine pits. The potential risk associated with extreme events, including pit capture scenarios for creek diversions, generally requires the generation of synthetic hydrological series that allow consequences to be categorised and quantified in a risk matrix based on potential loss of life, economic costs, loss of environmental value, and other factors.

## HYDRAULIC FORCES

The increasing prevalance of two-dimensional (2D) flood models allows the simulation and prediction of hydraulic forces associated with localised, impinging flows. In some cases, simulations of extreme events such as the PMF exhibit velocities exceeding 6 metres per second or more in the vicinity of proposed hydraulic structures. As shown in Figure 3, the median size of required armour rock for velocities in this range is “off the chart”, and quarrying rock to withstand velocities in that range may not be possible. In the post-closure environment, particularly in systems that must adjust to new flow paths and gradients, impinging flow paths would generally be expected to migrate over time. In order to protect closure designs for hydraulic structures against meandering, impinging flows – considering the requirement that closure designs are to be maintenance-free – the entire structure may require armouring with impractically large classes of armour rock.

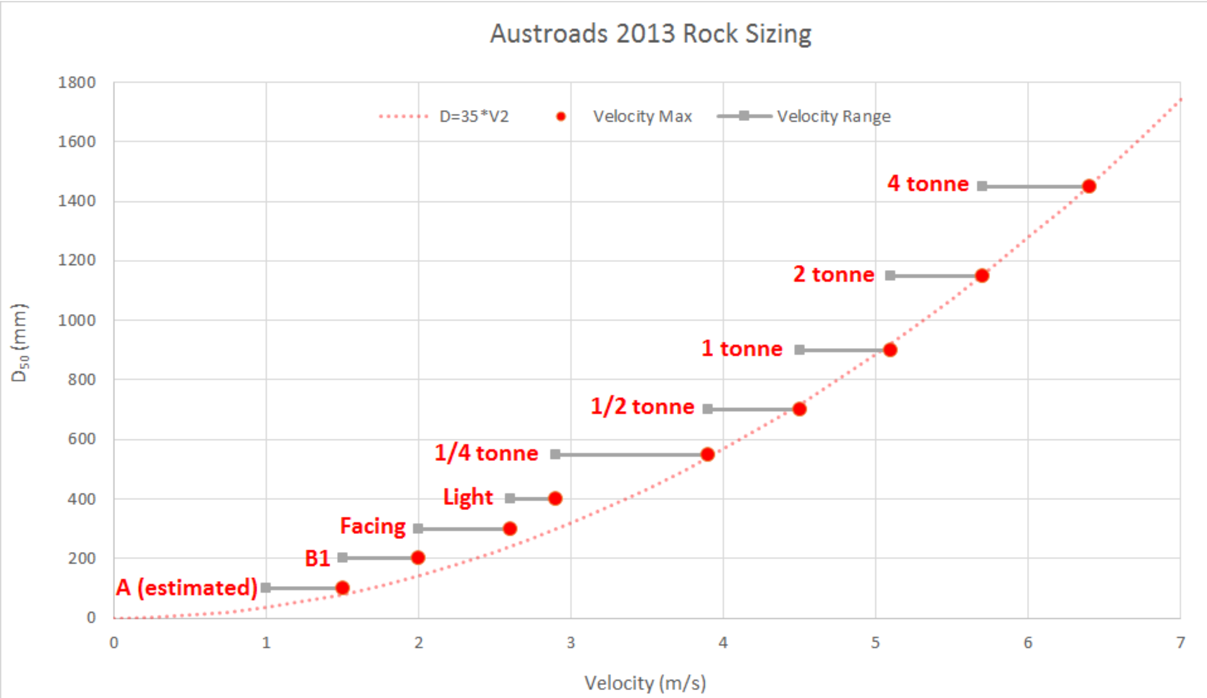


**Figure 3. Velocity-based Rock Sizing (based on Austroads 2013)**

Given the potential hydraulic forces involved, designing and constructing permanent levees, spillways, aqueducts, diversion drains, and other water control features – and demonstrating that those features will be self-sustaining over time – is challenging if not impossible, because regardless of the adopted design level, engineered structures have a limited design life and generally require some degree of maintenance over time to ensure functionality. The demonstration of perpetual sustainability without maintenance is unrealistic for closure plans that rely on hydraulic structures as part of the permanent, post-closure water management plan.

Durations for mine closure assessments are sometimes ommitted in mine closure plans; commonly, the implied duration would exceed 100 years and in some cases is assessed over longer periods of up to 500 years or even 10,000 years. For systems designed to accommodate a design event on the order of the 1% AEP flood, exceedence of the design event over post-closure timeframes is effectively a certainty. Figure 4 shows the probability of an individual flood event being exceeded over durations ranging up to 500 years. As shown in Figure 4, the probability of the 100-year ARI discharge rate being exceeded over a 500-year period is greater than 99%.

Assessment of a long range of events must therefore account for the periodic occurrence of extreme events. Because of the limited available period of record, duration periods assessed for closure must generally rely on synthetic records with a combination of flood events. Fixed bed hydraulic modelling may be inadequate for assessing duration-based design compliance as scour and deposition must be considered over a range of events. A 1,000-year duration model, for example, may include the prediction of aggradation and degradation associated with individual 2-year through 1,000-year ARI events. The assessment may then combine a series of events with the total sedimentation effects quantified for a 1,000-year ARI event, two 500-year events, ten 100-year ARI events, and so on, including 500 2-year events and multiple annual events. In most of the climatic regions across Australia, the volumetric contribution of extreme floods is insignificant relative to the proportion of total runoff associated with more frequent events. Likewise, the cumulative sedimentation effect of multiple smaller events may be far greater than the single, extreme event. The results of an analysis that takes these extended sequences into account may provide indicative scour depths or sediment accumulation that warrant additional toe protection or greater freeboard for the design crest elevation associated with the closure design.

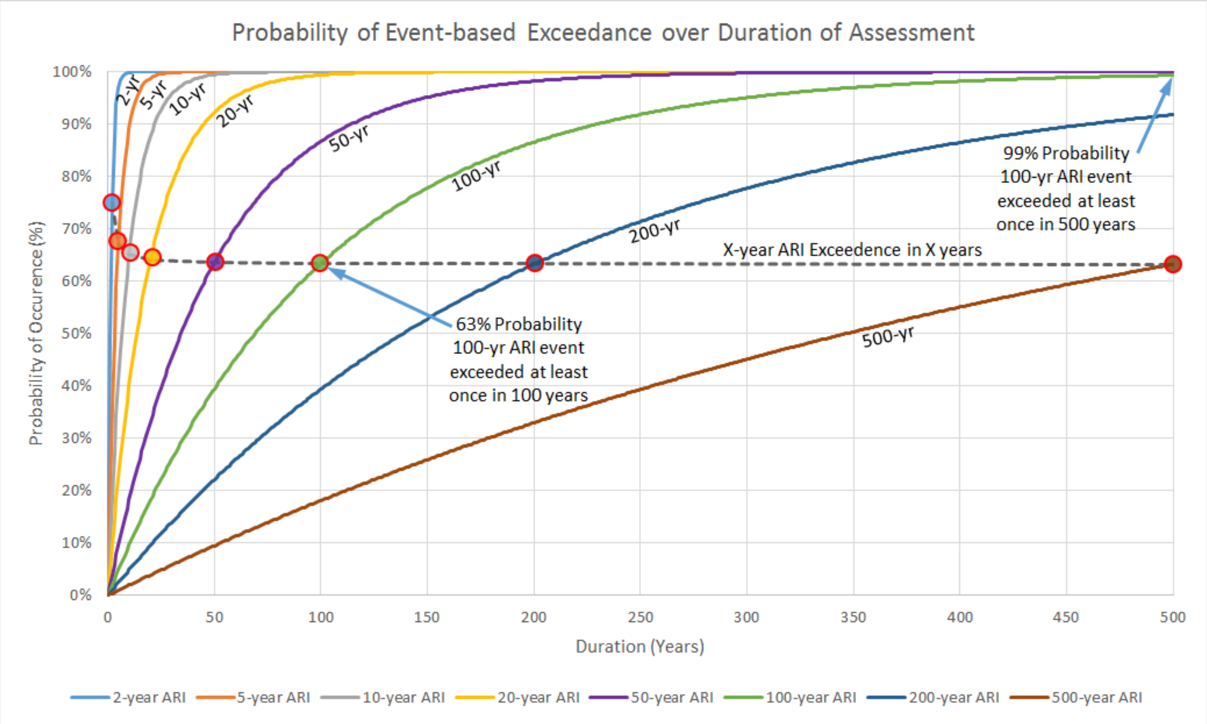


**Figure 4. Probability of individual event occurrence by duration**

## FAILURE MECHANISMS

Levees can fail by a number of mechanisms, including overtopping, geotechnical slope failure, piping, animal burrowing, vegetation overturning, etc. In the United States, the U.S. Army Corps of Engineers maintains a National Levee Database that includes over 2,500 levee systems comprising over 25,000 km of flood control levees. Risks and potential damages are assessed based on a minimum of four failure mechanisms. In order to remain certified in the database, flood control levees require inspection at least every five years. Ratings are based on 125 fields accounting for geotechnical stability, vegetative cover, and other parameters that can affect levee performance.

The certification procedure is based on the principle that levees and dams need only a single failure point to breach and to be rendered completely ineffective – and in some cases contributing toward additional flood risk rather than preventing risks. Historical examples of dam and levee failures have shown that small piping channels can quickly result in catastrophic breaches; as such, the Corps of Engineers certification procedure includes the requirement to clear large vegetation and maintain vegetation-free zones outside of the levee footprint to allow inspection and prevent vegetation-related failures. Levees that fail to meet certification criteria are de-certified; for the purpose of community flood mapping and eligibility for national flood insurance programs, non-certified levees are assumed to have failed, even if they remain within their original design life.

In assessing levee design standards, the Corps of Engineers and other federal agencies in the U.S. have adopted risk and uncertainty principles. In addition to a minimum freeboard to account for waves, settlement, and other factors, risk and uncertainty principles are applied in terms of design upgrades until the desired confidence level is increased. A specified 1% AEP water surface elevation represents the 50% confidence level that the water surface elevation will be exceeded; however, in some cases a 95% level or similar threshold is required. This level has the equivalent 50% confidence level associated with a less frequent event such as the 0.2% AEP or 500-year ARI event. Risk-based approaches allow the optimisation of additional material placement in areas where risks can most effectively be reduced.

Figure 5 shows a number of failure mechanisms that can occur for a levee. Some of the failure mechanisms illustrated in the figure do not require overtopping events for the levee to breach. Levees and spillways recommended as part of mine closure plans would not be maintained under the current assumptions of relinquishment; as a result, failure over time would be highly likely given the wide range of potential failure mechanisms.

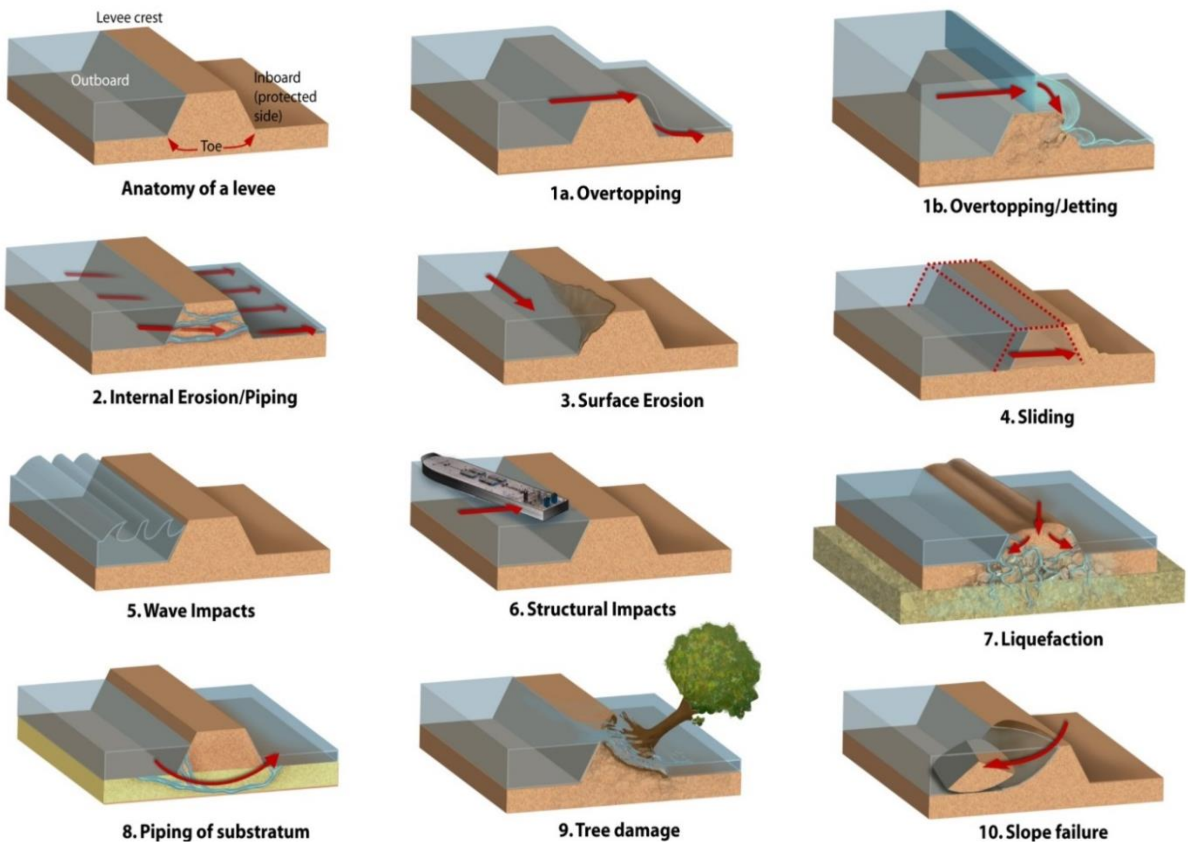


**Figure 5. Levee failure mechanisms (USACE 2011)**

As an alternative approach, the placement of a substantial volume of fill material can serve to buttress the levee embankment. Placement of additional material on the dry side of the levee avoids further constricting flow paths, raising water surface elevations, and increasing velocities. In the mining environment, if the fill placement is sufficiently massive, it can serve to function as a post-closure landform rather than a hydraulic structure. A typical levee designed as a hydraulic structure might have a minimum top width of 5 metres with 3H:1V side slopes, for instance, whereas a typical closure landform may have a minimum top width of 50 metres with 10H:1V batters. The adopted size may vary with the typical duration of flood events and the potential for the formation of subsurface flow routes.

Regardless of the added contingencies, closure plans for diversions that are intended to protect mine pits from creek capture must assume that without maintenance, the structure will eventually fail. With the structure removed, an erosion assessment can be performed over a selected post-closure duration to determine the risk of the floodplain or main channel of the creek being captured in the mining pit. A duration-based assessment can include the determination of a long-term erosion rate and may account for the equilibrium slope created by natural armouring processes over time. For mine pits located in reasonable proximity to a major channel, creek capture becomes a certainty given sufficient time. As such, closure plans that are intended to demonstrate long-term impacts must address the consequences of creek capture by the pit and the benefits of preventing creep capture for a limited time. In some cases, the impacts are lessened to the point of being benign over time due to the establishment of vegetation or water quality improvements, and the temporary prevention of creep capture may be beneficial.

Projects that rely on engineered materials for geotechnical stabilisation, scour protection, or water retention may require special closure considerations. Rock armouring that is suitable for operational timeframes may degrade over time, for instance. If the individual rocks crack over time, the smaller effective particle sizes may not provide the designed scour resistance when subjected to extreme hydraulic forces.

Figure 6 shows shear stress results for a typical pit inflow scenario from a flood in the adjacent river. Rather than allowing uncontrolled overflow into the pit during post-closure floods as shown in the figure, the construction of a hardened spillway may be preferred. Hydraulic analyses of spillway performance requires specialised applications. At the longitudinal slope of most standard spillways, significant differences between vertical depths and those measured normal to the slope arise. These differences are typically ignored in 1D and 2D modelling, and hydraulic results predicted by these models on steep slopes should be treated with caution. Spillway hydraulics may require 3D computational fluid dynamics (CFD) modelling or empirical approaches to properly simulate design conditions and account for cavitation, air entrainment, vertical acceleration, and other terms. Spillway velocities typically exceed 6 m/s, and spillway slopes may require excavation to bedrock or the placement of reinforced concrete in order to withstand design hydraulic forces of this magnitude.

Figure 7 shows typical spillway examples that each require ongoing maintenance to remain functional. Given the hydraulic forces involved, constructing a spillway with available armour rock and expecting the spillway to continue performing hydraulically in the long term without maintenance is in most cases unrealistic.

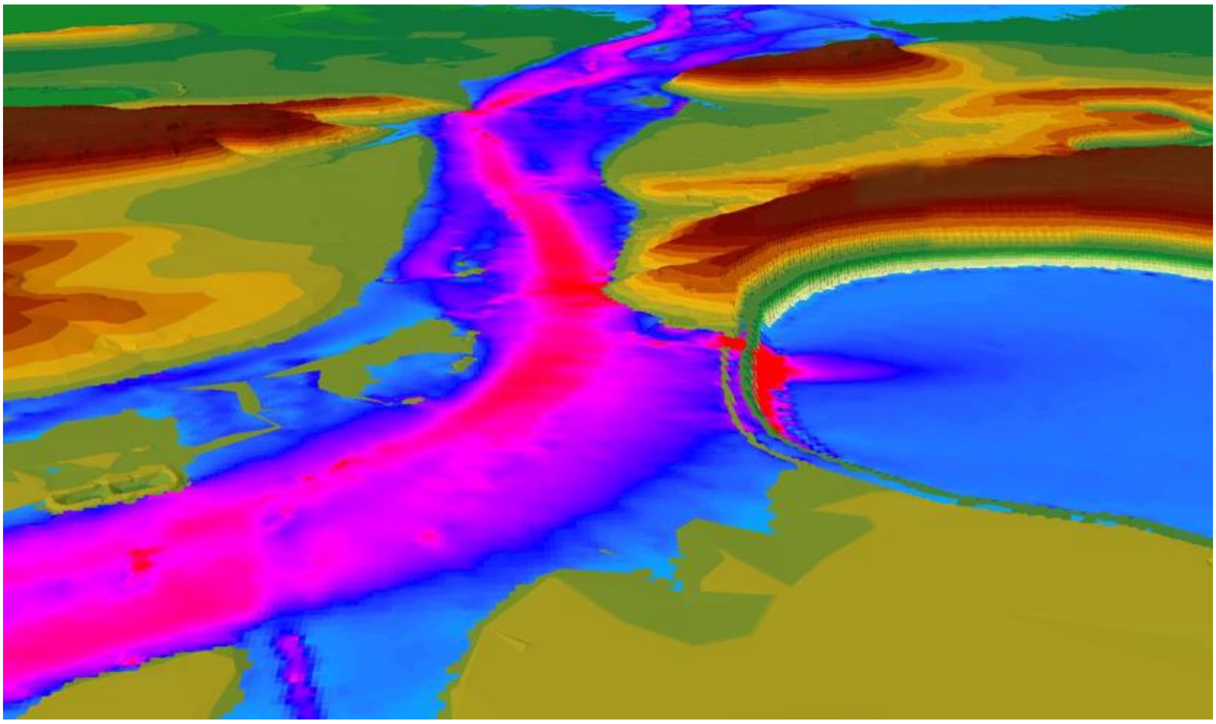

**Figure 6. 2D hydraulic modelling results showing shear stress associated with pit inflow**

**Figure 7. Spillway examples**

Given long enough sequences involving extreme hydraulic forces, sediment transport modelling and erosion analyses typically show complete creek capture over time where permanent pit voids are located within floodplains. Improved modelling capabilities allow the likelihood of creek capture to be further assesed. In some cases, particularly where the underlying substrate comprises alluvial material, complete creek capture can be simulated during a single overtopping flood event. In other cases, natural grade controls limit erosion and arrest head cuts, and armouring over time can result in hardened bed and bank surfaces that resist erosion and reach an equilibrium slope that ultimately delays or prevents complete creek capture.

## FAILURE EXAMPLES

Whilst very few Australian mines have been successfully closed and relinquished to the government, several operational failures provide an indication of potential flood-related issues that might arise post-closure unless adequate contingencies are included in the closure designs to compensate for the lack of maintenance.

Victoria's Morwell River was diverted across the Yallourn open cut coal mine on an embankment in 2005. Despite having been designed to a 1:10,000 AEP flood event, the diversion failed into the coal mine in 2012 due to initial leakage through subsurface tunnels that eventually caused piping and levee embankment failure (See Figure 8, ABC Gippsland 2012). This is an example of a diversion that failed without overtopping; in this case the design level for the crest of the diversion bund became irrelevant due to the nature of the failure.

Diversion failures in Queensland after heavy rains in 2008 and 2011 likewise caused heavy pit flooding of open-cut coal mines during mine operations. In the Northern Territory, the McArthur River also experienced a mine-related failure; revised surface water management plans include modelling of a 1,000-year closure period to demonstrate the suitability of the revised closure plan (McArthur River Mine, 2017).

In Western Australia, the Garden Well mine was filled to an average depth of 50 metres when heavy rains in 2014 caused the adjacent creek to spill into the pit (See Figure 9, Regis Resources 2014).

In addition to these Australian examples of diversion failures, international examples of post-closure failures include a number of rivers failing into underground mine systems, tailings dam failures, and other scenarios; lessons learnt from these failures can be applied in future Australian mine closure designs.

Although not mining-related, the failure of California's Oroville Dam spillway in 2017 demonstrated a case in which a very small failure point can quickly turn into a very large failure, even when the hydraulic structure has been subject to rigorous inspection and maintenance routines over time. The discharge rates that damaged the Oroville spillway were substantially lower than some of the design flows for currently proposed mine closure spillways in Australia. Without remedial maintenance and emergency measures, the Oroville spillway failure would likely have continued and may ultimately have threatened the integrity of the dam itself.

In light of these and other similar failures, a reasonable, minimum design life for engineered structures should be applied to mine closure designs, with the significance of extreme events evaluated along with the impacts related to more frequent flood events. The effects may include environmental impacts related to reductions in downstream floodplain connectivity and water supply in the event of creek capture – and potentially the removal of the entire bed load of a creek system for extended time periods. The consequence of creek capture should therefore be considered for any cases with hydraulic structures adjacent to floodplain mining pits. Once a breach occurs, the longer term consequences may be mitigated through repair of the breach; however, some intervention would generally be required.

When it comes to actual mine relinquishment following the cessation of mining activities, additional scrutiny of the design performance over long-term closure periods may indicate unacceptable risks to the government, despite the demonstrated conveyance of the closure design event. Assessing risks with duration-based assessments and optimised design requirements that withstand not just the closure design event but a long-term sequence of events as well provides additional confidence that actual risks have been adequately assessed.

**Figure 8. Morwell River Diversion Failure (Source: ABC Network)**

**Figure 9. Goldfields pit flooding (Source: Australian Mining)**

**Figure 10. Oroville dam spillway failure (LA Times)**

## CONCLUSIONS

This paper presents a summary of typical hydrologic, hydraulic, and sediment impacts of mine pits along significant watercourses based on historical failures and computer simulations, including the application of landform erosion assessments and mobile-bed sediment dynamics. The results highlight the extreme differences in predicted, long-term performance derived from the application of varying modelling approaches to identical initial ground conditions.

There has been considerable discussion amongst regulatory authorities concerning the adoption of a consistent level of protection for closure planning, for instance whether a hydraulic structure in a closure plan should be designed to convey the 100-year ARI event, the PMF, or a specified interim event. In reality, the design recurrence interval is effectively unrelated to the functional life.

All engineered structures have a limited design life that can typically be extended with periodic monitoring and maintenance, following a regular cycle as typically applied in dam safety and other engineering applications. As demonstrated by catastrophic failures across Australia and worldwide, hydraulic structures in particular require ongoing maintenance to ensure continuing functionality, and failures can occur even when regular maintenance activities are carried out.

State guidelines in Australia generally require mine closure plans to demonstrate safe, stable, and non-polluting conditions; in keeping with these stated goals, permanent diversions and levees have been proposed to support mine closure plans for open pit voids located within floodplains across Australia. The underlying assumption for compliance with legislative requirements is that the hydraulic features associated with these mine closure plans are considered to be sustainable, maintenance-free structures. In practice, however, self-maintaining hydraulic structures are unlikely to be feasible over the long term.

Across Australia, hundreds of pending mine closure plans covering thousands of pits are based on the assumption that the mine sites will be relinquished to the government on the basis of the demonstrated conveyance of a specified discharge rate associated with a single flood event. Whilst the constructed features may be capable of conveying the design flood in the immediate post-construction period, over time, failure may occur due to cracking, piping, wave action, root channels, wildlife burrowing, or other mechanisms that do not require overtopping. These risk factors should be considered in associating a predicted design life with proposed hydraulic structures.

The following recommendations are presented for mine closure planning where watercourses are located adjacent to permanent pit voids:

- In evaluating mine closure proposals, regulators should adopt a consistent, finite design life as a minimum threshold for hydraulic structures. In order to demonstrate compliance with requirements for ensuring a safe, stable, and non-polluting post-closure environment, mine closure plans for pit voids located in floodplains should consider a long-term sequence of events in addition to the specified design event, considering the relative impacts of extreme events against those associated with a series of smaller events.
- The associated analyses should at least qualitatively account for potential soil piping, differential settlement, sedimentation/erosion trends associated with mobile bed dynamics, and other factors that could affect the integrity of the hydraulic structure over time.
- As an alternative to long-term assessment of hydraulic performance, stormwater runoff may be managed with landforms that are sufficiently massive to avoid classification as hydraulic structures.
- In order to demonstrate functionality over long-term periods with unpredictable lateral and vertical migration, closure designs may require excessive rock armouring or other erosion control along the entire potential extent of impinging flows; with periodic monitoring, however, relatively minor maintenance activities can prevent major failures. As an alternative to the current assumption of maintenance-free relinquishment, the creation of bonds that allow ongoing monitoring and maintenance to be performed during the post-relinquishment period may be more practical than the unrealistic demonstration of self-sustaining hydraulic structures.

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