# Rethinking Hydrologic Design Criteria for Mine Closure

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## Abstract

Hydrologic design criteria for mine closure landforms in riverine environments commonly specify that landforms need to be stable under extreme, single hydrologic events such as the probable maximum precipitation or probable maximum flood. The cumulative geomorphic effects of multiple, more frequent, and lower magnitude hydrologic events may well exceed that of a single, extreme event. In addition, failure of a closure landform in the riverine environment may be dictated by non-fluvial factors such as settlement, cracking, piping or mass failure of emplaced fill or pit walls. Factors other than extreme hydrologic events need to be considered in mine closure planning.

**Keywords:** mine closure, design criteria, hydrology, geomorphology

## Introduction

Rehabilitation of creek and river corridors remains, arguably, the most challenging aspect of mine closure in the Pilbara region of Western Australia. This is particularly the case where Channel Iron Deposits (CID) in Tertiary-age paleochannels are open pit-mined in spatially coincident modern drainages and the ratio of waste material to extracted ore is very low and thus pit backfill is an on-going challenge.

Closure in the riverine environment can encompass re-establishment of drainage features over fully backfilled pits, partial pit backfill with land bridges to convey sediment and flows, and total or partial hydrologic disconnection between partially-filled open pits and the channel system. Typical closure scenarios for non-backfilled pits are illustrated in Figure 1 (Price 2018).

In general, fluvial processes in the Pilbara tend to be driven by infrequent, high intensity and short duration hydrologic events that are related to the occurrence of Tropical Cyclones (Harvey et al. 2014, Rouillard et al. 2015, Rouillard et al. 2016). Climate change projections suggest that it is likely that intense rainfall in most locations in Australia, including the Pilbara, will become more extreme, driven by a warmer, wetter atmosphere (Department of Industry Innovation and Science 2016).

## Regulatory Guidance for Design of Closure Landforms in Australian Riverine Environments

Mine closure guidelines in Western Australia include language requiring post-closure landforms to be physically safe, geotechnically stable, geochemically non-polluting and sustainable in the long term (Western Australian Department of Mines and Petroleum 2015) which is in accordance with the hierarchy of closure needs identified by the Asia-Pacific Economic Cooperation Mining Task Force (APEC Mining Task Force 2018).

The Australian National Council on Large Dams (ANCOLD) defines long term as 1,000 years (ANCOLD 2019) which significantly exceeds the limits of engineering practice, which is generally considered to be between 100 and 200 years, and also exceeds the duration of most human institutions that would monitor and regulate the post-closure landscape (APEC Mining Task Force 2018). Leading practice in Australia dictates that a post-closure design life of 1,000 years be adopted as being considered 'in perpetuity' (Department of Industry Innovation and Science 2016).

Guidance from Western Australian regulatory agencies on hydrologic design criteria for closure landforms in the riverine environment is either not clear (300 years or longer for landforms, voids and ecosystems to 500-1,000 years for pit lake modelling) or recommends that landforms are constructed to be stable under single extreme events such as the probable maximum precipitation (PMP) or the probable maximum flood (PMF). While extreme events such as the PMP, or the resulting PMF, may be attractive from a perceived regulatory risk reduction perspective, the very low probability of occurrence of such an extreme single design event means that fluvial processes, and hence the dynamics of the closure corridor, will be governed by multiple events with a much higher probability of occurrence. In addition, while a structure may provide a design level of protection when built, subsequent changes in the river environment such as aggradation may lead to conditions in the future where the design level of protection is not provided.

## Probability of Extreme Hydrologic Events

### *Probable Maximum Precipitation*

The probable maximum precipitation is defined as the "theoretically greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year" (Hansen et al. 1982). Prior to the 1950s, the concept was known as the maximum possible precipitation (MPP). The name was changed to the PMP reflecting the uncertainty surrounding any estimate of maximum precipitation (Wang 1984). There is no known way to develop the PMP from first principles (National Research Council 1994) and proposed estimation methodologies have been the subject of much debate. By another definition, the PMP is the estimated precipitation depth for a given

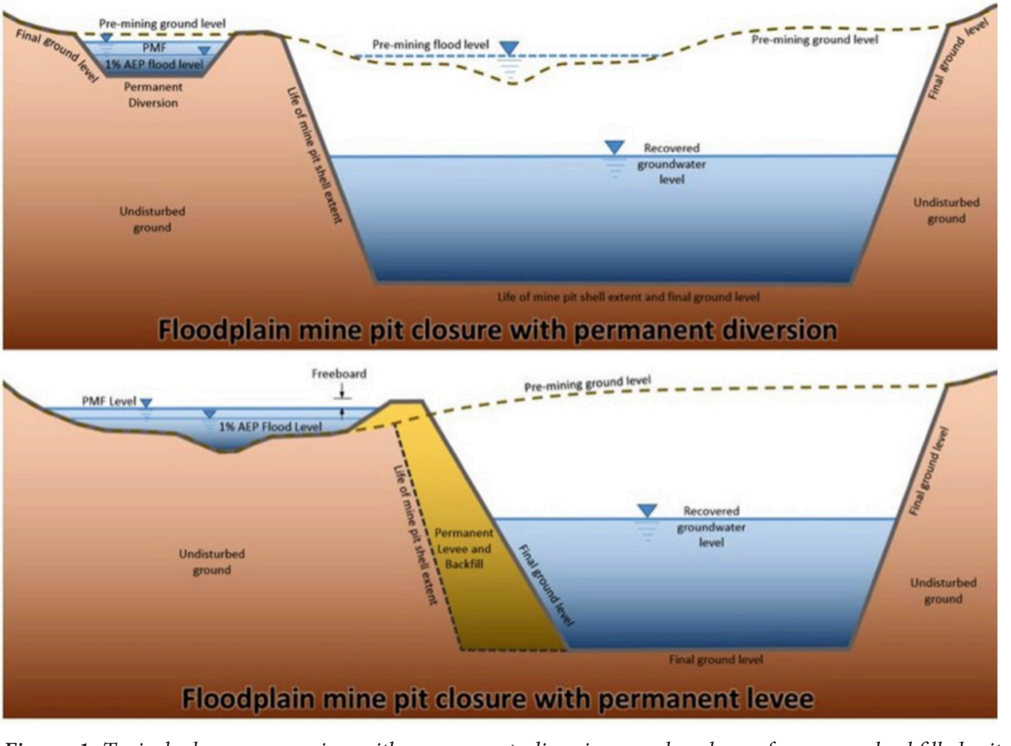


***Figure 1*** *Typical closure scenarios with permanent diversions and a levee for a non-backfilled pit (Price 2018).*

duration, drainage area, and time of year for which there is virtually no risk of it being exceeded (Wang 1984). However, the fact that measured rainfall depths have exceeded PMP estimates in the past clearly indicates that the PMP approach by no means implies zero risk in reality (Koutsoyiannis 1999).

The PMP estimation methodology makes the inherent assumption that the past climate will be representative of future conditions. As global climate patterns continue to change, PMP estimates from previous analyses may need to be updated. The Mine Closure Checklist for Governments (APEC Mining Task Force 2018) describes some of the challenges associated with climate change and mine closure, including changing rainfall patterns, drier climates, rising temperatures, and rising sea levels. Changing rainfall patterns may quite possibly have the greatest impact as areas have more intense and/or more frequent rainfall events or even more prolonged periods of dry weather than in previous years (IPCC 2007).

### *Probable Maximum Flood*

The probable maximum flood (PMF) is defined as "the largest flood that could conceivably occur at a particular location, usually estimated from the PMP coupled with the worst flood-producing catchment conditions" (Douglas and Barros 2003). The temporal and spatial patterns of the predicted PMP rainfall depths, antecedent soil conditions, and precipitation losses will all impact the estimate of the PMF. Use of the PMP to generate the PMF has become the standard for dam design in many parts of the world including the United States, China, India, and Australia (Svensson and Rakhecha 1998). Estimates of the annual exceedance probability (AEP) of the PMF range from 1 in 10,000 to 1 in 1,000,000 in Canada (Smith 1988) to 1 in 1,000,000 in the eastern USA (Shalaby 1994). However, there is considerable uncertainty in estimating both the PMP and PMF (Salas et al. 2014).

Guidance in Australia (Nathan and Weinmann 2019) states that the absolute upper limit of flood magnitude under consideration is the probable maximum flood, which is a design concept that cannot be readily assigned an annual exceedance probability. However, the AEP of the PMP is considered to vary from 1 in 10,000 to 1 in 10,000,000. The stability of hydraulic features that are included in mine closure plans may be undermined by morphological changes that occur as a result of more frequent events with a higher likelihood of occurrence. Given the extremely low probability of occurrence of the PMP/PMF, designing for it is not pragmatic if the features cannot withstand the impacts of a series of more frequent events.

## Fluvial Processes and Geomorphic Change

In general, fluvial processes in the Pilbara, located in the arid subtropics, tend to be driven by infrequent, high intensity and short duration hydrologic events that are related to the occurrence of Tropical Cyclones (Harvey et al. 2014). The morphology of the alluvial sections of the ephemeral-flow, gravel-bed creeks where sediment transport is episodic, tends to be a relic of the last major flow event and results in highly variable channel morphology over both space and time (Graf 1988). Graf (1988) concluded that in arid and semi-arid regions where the flows are ephemeral, infrequent and relatively short-duration hydrological events rarer than the 1 in 100 AEP are the major determinants of overall valley floor morphology, but more frequent events are responsible for defining highly variable channels (macro-channels) within the disturbed landscape. Macro-channel morphology (compound channels) is associated with regions of high hydrological variability (Croke et al. 2013). Macro-channels are characterised by a small inner channel and associated benches set within a much larger channel that operates as a conduit for high magnitude floods (Croke et al. 2016). They have large channel capacities, with bankfull capacities approaching a 1 in 50 AEP, and are laterally stable even during extreme flood events because of the presence of highly erosion-resistant clays (Fryirs et al. 2015) or calcrete and ferricrete-cemented alluvium in their banks (Harvey et al. 2014).

Tooth and Nanson (2004) demonstrated the high variance of morphologic, hydraulic and sediment transport characteristics over relatively short distances in ephemeral flow channels in central Australia and because of this high morphologic variability, it is very difficult to define either channel-forming discharges (Wolman and Miller 1960, Baker 1978, Wolman and Gerson 1978) or design discharges (Harvey and Mussetter 2005). Consequently, channel dimensions within the ephemeral flow channels are unlikely to be related to hydrologic events of any particular recurrence interval, and as such, existing channel morphology provides a very poor template for post-mining channel reconstruction in the Pilbara (Harvey et al. 2014).

## International Approaches to Engineering Design and Long-Term Landform Stability

With the exception of tailings dam design where PMP/PMF criteria are prescribed (ICOLD 2013, Slingerland et al. 2018), the international literature on mine closure generally addresses regulatory goals for reclamation/closure/relinquishment rather than specific hydrologic design criteria. For example, the extensive South African Guidelines for the Rehabilitation of Mined Lands (Chamber of Mines of South Africa and CoalTech 2007) does not specify any hydrologic criteria but rather focusses on achieving post-mining landscape rehabilitation and acceptable future land use.

The U.S. Surface Mining Control and Reclamation Act (SMCRA) of 1977 aims to avoid disturbance of alluvial valley floors and their attendant hydrologic balance (both surface water and groundwater). If stream diversions are required, they must convey the peak runoff from the 1 in 100 AEP, 6-hour precipitation event. There is also an expectation that "good engineering practice" will be employed in design of the diversion structures (Office of Surface Mining and Reclamation and Enforcement 1977).

To accommodate the dichotomy of constructing landforms that are stable over the long-term and the limits of engineering practice, the U.S. Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 requires closure measures to be effective for up to 1,000 years to the extent reasonably achievable and, in any case for at least 200 years (Nuclear Regulatory Commission 1978; APEC Mining Task Force 2018) even though they fall short of the full duration of the hazard (Nuclear Regulatory Commission 2002). These timeframes were formulated to cover periods over which climatological and geomorphic processes could be reasonably predicted given current knowledge of earth sciences and engineering (Logsdon 2013).

Canadian practice is encapsulated within the APEC Mining Task Force (2018) document and addresses the problems of prescribing extreme events as hydrologic design criteria as well as acknowledging the practical limits of engineering design

## Concluding Discussion

Hydrologic design criteria provided by regulatory agencies for mine closure landforms in the riverine environment in the Pilbara region of Western Australia are not clear or recommend that landforms need to be stable under extreme, single hydrologic events such as the PMP or PMF. These extreme hydrologic design events with annual exceedance probabilities in the order of 1 in 10,000 to 1 in 10,000,000 are not appropriate for designing long-term mine closure landforms in the riverine environment of Western Australia

The use of a single extreme event as a design criterion confuses the low annual exceedance probability of a design event with the desired design longevity of the closure landform (Price 2018). A post-closure design life of 1,000 years can be considered to be in perpetuity (Department of Industry Innovation and Science 2016). However, even a design life of 1,000 years significantly exceeds the limits of engineering practice, that is generally considered to be between 100 and 200 years, and also exceeds the duration of most human institutions that would monitor and regulate closure and relinquishment (APEC Mining Task Force 2018).

Engineering analysis for long-term closure (1,000 years) needs to take into account the impacts of a series of design events that have lower magnitude but higher frequency. The cumulative geomorphic effects of multiple more frequent and lower magnitude events may well exceed that of the single extreme event.

Failure of a closure landform in the riverine environment may be dictated by non-fluvial factors such as settlement, cracking, piping or mass failure of emplaced fill or pit walls and as such are not explicitly evaluated in a hydrologic risk-based analysis. Even if the overall probability of failure can be reasonably constrained, the consequences of failure of a closure landform will tend to be location-specific, and thus, a generalised approach to establishing risk is unlikely to be particularly useful.

A more realistic approach to hydrologic design for long-term landform closure is provided by the U.S. Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. The UMTRCA requires closure measures to be effective for up to 1,000 years to the extent reasonably achievable and in any case, for at least 200 years (Nuclear Regulatory Commission 1978, APEC Mining Task Force 2018). However, this approach also requires the development of a site-specific, long-term surveillance plan that involves annual inspections and maintenance, as required, in perpetuity. This approach would require a program to distribute dedicated funds to those groups assuming responsibility for ongoing maintenance.

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