How Long Is Long Enough? Assessing the Critical Storm Duration for Non Discharge TSFs

Heather Thomson[1], Joanna So[2], Justin Walls[3]

[1]*SRK Consulting (Australasia) Pty Ltd., hthomson@srk.com.au*
[2]*SRK Consulting (Australasia) Pty Ltd., jso@srk.com.au*
[3]*SRK Consulting (Australasia) Pty Ltd., juwalls@srk.com.au*

Abstract

Weather hazards are a leading cause of tailings storage facility (TSF) failures, with weather-triggered flow incidents increasing (Rana *et al.* 2021). While spillways are a common means of providing TSF flood discharge capacity, many facilities are designed as 'non-discharge' systems which contain all inflows within the basin. Designing non-discharge TSFs requires an understanding of the critical storm duration, yet guidance is inconsistent and practice often defaults to 24–72-hour events with limited justification. This paper presents a practical method for identifying the critical storm duration for non-discharge TSFs using water-balance modelling in parallel with emergency response assumptions.

Keywords: Tailings, mine waste, freeboard, critical duration, water balance, risk management

Introduction

Weather hazards are the most common contributing factor to TSF failures, with the number of tailings flow incidents triggered by weather events steadily increasing over time (Rana *et al.* 2021). A key aspect of mitigating this risk is designing and operating TSFs to safely manage inflow design floods.

For non-discharge TSFs where all floodwater is retained, the concept of a critical storm duration is nuanced. Industry practice often defaults to adopting 24-hour or 72-hour storm durations, but there is little justification for whether these represent the critical duration for non-discharge TSFs, leaving a gap in both practice and regulation. As such, the objectives of this paper are to:

- Investigate the critical duration storm for non-discharge TSFs using water balance modelling combined with operational and emergency response considerations.
- Undertake sensitivity analyses to explore the influence of tailings properties and climatic conditions.
- Propose a practical method for assessing and selecting the critical duration that can be used to inform TSF design and operational planning.

There are many uncertainties inherent in TSF water management, and the way these are addressed varies significantly between jurisdictions and site settings. This paper is not intended to challenge existing guidance or regulatory requirements, where present, but rather to propose a general framework that practitioners can adapt, expand upon and apply to their specific context.

Background

TSFs are complex systems that must safely manage variable inflows from tailings deposition, runoff and direct rainfall, while maintaining sufficient freeboard to mitigate the risk of overtopping and run-on stability problems. To add further complexity, TSF structures are typically constructed gradually (i.e., raised in stages), resulting in a permanent landform that must function safely in perpetuity under a changing climate.

Water is typically removed from TSFs via operational discharge infrastructure (pumped decant or gravity penstock), which – in flood scenarios – can be (and for design purposes is generally assumed to be) rendered inoperable. Thus, it is good practice to include a spillway to passively pass significant design floods in emergency scenarios. However, spillways can be complex and costly to construct and can inherently introduce additional risks, particularly for facilities raised in multiple stages or those lacking a viable spillway location.

As a result, in many situations it is considered more cost and/or risk effective to design non-discharge TSFs, relying on the impoundment's basin storage capacity to contain floodwater. This is particularly common in Western Australia (WA) and similar semi-arid to arid regions, where evaporation can exceed rainfall by an order of magnitude, and flat terrain lends itself to large, paddock-style TSFs with limited catchment areas. TSF ponds can remain well below operating limits, and design storm ponds remain distant from the embankment by hundreds of metres. Similarly, in-pit TSFs are commonly designed as 'non-discharge facilities' as the risk of overtopping or instability inducing a catastrophic failure can be negligible. This is acknowledged in WA regulatory guidance (DMP 2015), which states that *'the use of spillways is not encouraged, particularly for paddock or ring-dyke type facilities with perimeter retaining structures constructed using tailings.'*

In contrast, guidance from ICOLD (2025) and ANCOLD (2019) recommend that an emergency spillway or controlled overflow pathway should always be considered as a fail-safe. Therefore, the decision to exclude a spillway must be a well-justified, risk-based decision that considers the risks associated with storing additional water.

For TSFs with spillways, the critical duration of the design flood can be readily determined by routing the inflow hydrograph through the basin and identifying the duration that produces the maximum outflow and/or water level. However, for non-discharge TSFs where all floodwater must be retained, the concept of a critical storm duration is more nuanced. Under storm conditions, active discharge systems are assumed to be unavailable due to power outages, access constraints or operational risk controls. As such, the longer the storm duration, the greater the accumulation of water in the impoundment. The critical duration is governed by a balance between increasing inflow, limited passive losses and decreasing storage availability over time. If a reliable and proven emergency response plan is in place, the critical duration can be bounded by the period over which the plan can be enacted.

Most industry guidance and standards, such as the Global Industry Standard on Tailings Management (GISTM) (GTR 2020), refer to inflow design floods without prescribing a specific duration for non-discharge TSFs. In practice, designers frequently adopt 24-hour or 72-hour events as a default. However, there is limited justification for these choices in the context of non-discharge TSFs where all floodwater must be retained.

Methods

The approach presented in this paper is based on simple water balance modelling to account for inflows from longer duration, multi-day storms and passive outflows. This can be readily expanded to account for uncertainties and superimposed with assumptions about operational status and emergency response during extreme events, forming a framework to identify the storm durations that govern maximum pond levels in non-discharge facilities.

The hydrological inflow to the model is based on rainfall time series that are representative of the local climate. The rainfall input should be representative of a range of storm durations associated with the design annual exceedance probability (AEP), selected considering the tolerable risk level. It is noted that 'long' duration events are typically comprised of several embedded short duration rainfall bursts, thus a long duration design storm implicitly accounts for the probability of sequential events.

Practically, this involves constructing a series of synthetic design hyetographs of different durations, consistent with design intensity–duration–frequency relationships and relevant climate change predictions. These design hyetographs (graphical representation of rainfall intensity over time) are then embedded within a longer continuous record or applied to representative antecedent moisture conditions and transformed to runoff over the contributing catchment. For extreme design events, runoff is typically represented using conservative loss assumptions (i.e., negligible or very low losses).

Model outflows are limited to passive losses from evaporation and infiltration. As with rainfall, evaporative losses are represented by time series that are characteristic of the local climate, noting that actual evaporation during storm events can be significantly lower than average conditions.

Infiltration into tailings is a complex process, as hydraulic behaviour varies and evolves over time with spatial variability due to beaching, consolidation, deposition history and desiccation. A fully coupled unsaturated flow model is not practical to incorporate into the proposed framework. Instead, infiltration is represented using simple physically based formulations, or by prescribing effective loss rates derived from available site data or representative parameter ranges.

The TSF storage characteristics are represented through a stage–storage relationship that reflects the geometry of the basin, including the tailings beach and supernatant pond area. This relationship may be developed from survey data or idealised design geometry and should reflect the expected operating configuration at the time the design event is assumed to occur, or the configuration that results in the most critical outcome. Where tailings are actively being deposited and beach geometry is continually evolving, a conservative representation of beach slope and pond area should be adopted.

To identify the critical storm duration, the model is run for a set of scenarios in which storms of varying duration, but common AEP, are applied. By comparing the predicted maximum pond levels across durations, the storm or sequence of storms that produces the highest pond level is identified as the critical duration for the modelled conditions and assumptions. The resulting maximum pond levels should then be assessed in the context of overall TSF performance and risk criteria, including freeboard, stability, erosion and other site-specific operational limits.

Emergency response plans should specify intended measures such as siphons, pumps or emergency excavated spillways. Where such measures are demonstrated to be reliable and are explicitly relied upon, their effect can be superimposed on the water balance model, potentially limiting the critical storm duration. This must consider both the influence of storm intensity on site access and the time required to initiate and implement the emergency response actions.

Monte Carlo simulations or sensitivity analyses can be used to account for, and explore, the influence of key parameters and assumptions on the model results and resulting critical duration. Key uncertainties may include tailings beach slope and the resulting stage–storage relationship, catchment size and runoff characteristics, infiltration and evaporative losses, climatic conditions, antecedent conditions and emergency response assumptions. By varying these parameters within plausible ranges, the robustness of the analysis and its dependence on site conditions can be assessed.

From a design perspective, it is not recommended to rely on infiltration and evaporation losses when calculating required storage capacity, as these losses are often negligible during the peak of the event and can be highly uncertain. However, incorporating realistic passive losses allows practitioners to identify a meaningful, physically justifiable critical duration, while still sizing storage allowances on a conservative basis.

Application

The proposed method was applied to a paddock-style TSF in the Goldfields region of WA. A simplified approach was adopted to inform the selection of appropriate design criteria at an early design stage, before the facility was constructed and in the absence of observation data. The facility is designed to have a downstream-raised embankment, a small supernatant pond (operationally discharged via a pump), no spillway, and 0.5% beach slopes. The climate is semi-arid, with low but highly variable rainfall dominated by infrequent, high-intensity short-duration storms and occasional multi-day events, and very high potential evaporation across most of the year.

A simplified water balance model was constructed in which a design storm is applied above the maximum operating level, assuming that both tailings deposition and reclaim pumping are ceased at the onset of the event, no controlled releases from the TSF occur, and pumping can only resume after a prescribed recovery period once weather conditions improve and access is restored. Infiltration into the tailings beach is assumed to decrease exponentially from an initial capacity of 1 mm/h to a constant minimum rate of 0.5 mm/h as the tailings becomes saturated over time. An average evaporation rate of 10 mm/day is applied, reducing to 40% of this during the storm event.

A 1% AEP design storm is selected and assessed for durations ranging from 24 to 168 hours (selected as required to reveal the critical duration). The design rainfall depth is obtained from the Australian Bureau of Meteorology and included climate change adjustments as recommended in Australian Rainfall and Runoff Guidelines. An example of the model results for a 24-hour storm is shown in Figure 1, illustrating a drain down period of approximately 18 days to return to the original pond level, relying only on passive outflows (infiltration and evaporation) and assuming no further rainfall occurs in the days following the design storm.

The model was then run for a set of scenarios in which storms of varying duration but common exceedance probability were applied to the TSF. Given the uncertainties inherent at the early design stage, alternative scenarios were also considered in which key assumptions were varied, including beach slope, evaporation and infiltration capacity. The results for the full range of durations assessed are shown in Figure 2. In this case, the infiltration capacity of the tailings beach both largely controls the outflows and represents a substantial uncertainty at the design stage (which could reasonably vary by an order of magnitude). A 1% AEP event with a duration of 120 hours was conservatively selected for design.

However, in this scenario the absolute difference between the design storms is relatively modest. The additional freeboard allowance required between a 72-hour and 120-hour 1% AEP event is in the order of 25 mm, which is within both the accuracy of the assessment and adopted design tolerances. Thus, for this facility, adopting a 'default' 72-hour storm duration for storage calculations would not have materially underestimated the risk of exceeding the available freeboard provision.

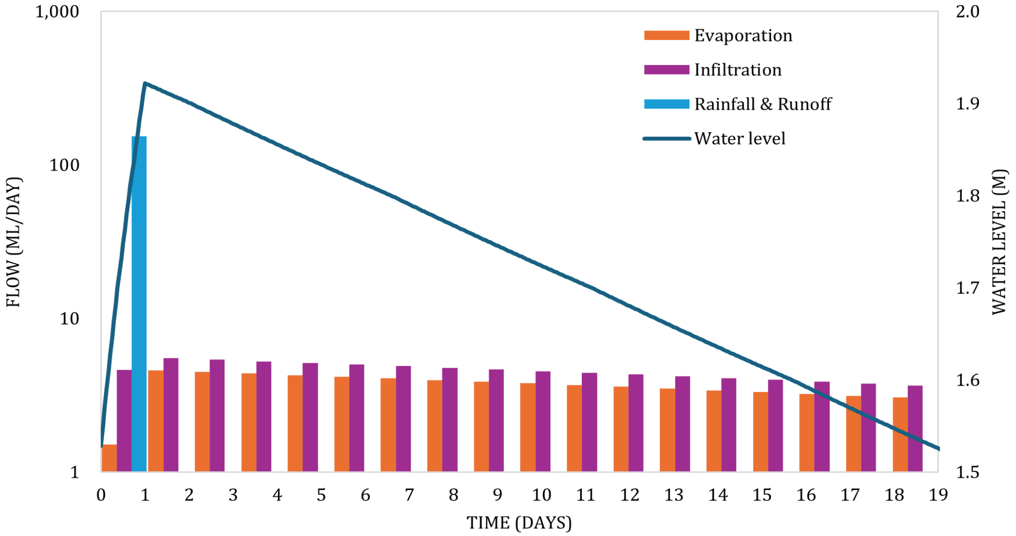

Figure 1 24-hour duration simplistic water balance result.

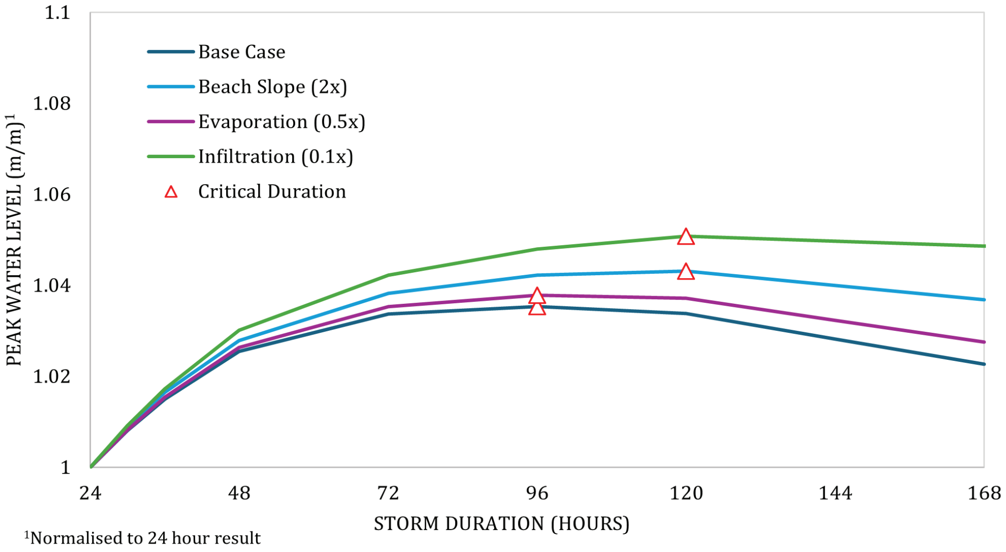

Figure 2 *Scenario analysis results.*

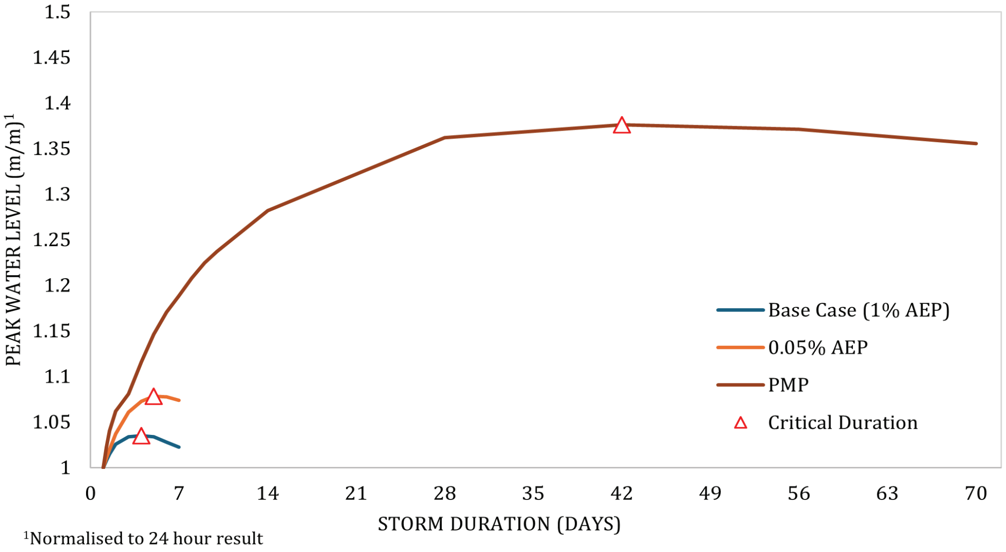

Figure 3 *Alternative AEP results.*

To enable stress testing and inform a risk assessment, the model was then run for a range of alternative AEPs. The results are shown in Figure 3. The results illustrate that the critical duration increases as the AEP decreases, which is expected given the relationship between inflow intensity and the rate-limited outflows, which are assumed constant. Accordingly, and in contrast to the base case (1% AEP) assessment above, adopting a default 72-hour storm duration for probable maximum precipitation (PMP) storage calculations would significantly underestimate the risk of exceeding the available freeboard, especially in closure designs which commonly adopt design storms from 0.01% AEP events up to the PMP.

Practical guidance for practitioners

For practitioners, the key is to embed critical storm duration assessment within routine TSF design and review, rather than relying on default 24–72 hour events for non-discharge TSFs. A practical workflow is to:

1. select the design AEP (or AEPs) consistent with risk tolerance, best practice and regulatory criteria
2. construct a simple but defensible water balance model that represents a range of realistic operating conditions before, during and after a design storm event
3. apply a suite of design storms of varying duration for the chosen AEP
4. use sensitivity analysis to test uncertainties in critical parameters such as stage–storage relationships, infiltration capacity and evaporation
5. select the critical storm duration to be adopted for the chosen design event
6. if required, and where there is a demonstrably reliable plan, superimpose credible emergency response actions (for example, deployment of siphons or pumping to adjacent storages) to bound the critical duration.

The selected critical duration should then be used to assess storm storage requirements (generally ignoring all losses) and translated into operational freeboard criteria and trigger levels (e.g. maximum allowable pond volume prior to the wet season). The assessment should be clearly documented alongside the underlying assumptions so they can be revised as observation data and site conditions evolve.

It is acknowledged that determining design rainfall depths for long duration, rare events can be challenging. Where long duration estimates are required, practitioners may need to extrapolate beyond standard guidance or consider more complex analyses.

Conclusions

This paper presents a practical framework for identifying the critical storm duration for non-discharge TSFs using a simple water balance model. The example application demonstrates that relying on a default storm duration without justification can underestimate the risk of freeboard exceedance, particularly for design storms of increasing rarity.

The results emphasise that the critical duration is inherently site-specific. It is governed by the relationship between the intensity and duration of the design storm inflows and the rate-limited passive outflows (infiltration and evaporation). Because this balance changes with storm severity, the critical duration is not constant across different AEPs or storm intensities. In the example application, the difference between 72-hour and 120-hour storms at the 1% AEP was modest and within design tolerances, but for rarer events (e.g., 0.05% AEP and PMP) the critical durations increased significantly.

Finally, even where a non-discharge configuration is selected, the decision to not include a spillway should be made on a risk-informed basis. The example application shows that large paddock-style TSFs in highly evaporative climates can, in some cases, safely operate without a spillway, provided adequate storage capacity and freeboard provisions are in place. Nonetheless, a spillway or controlled overflow pathway remains an important fail-safe that should always be actively considered in design, consistent with contemporary TSF guidance and good practice.

References

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