Beyond the design storm: from compliance metrics to adaptive operations for consecutive minor events in dams

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Return water dams at mines are commonly assessed against single-event compliance criteria, typically the 1-in-50 year 24-hour storm, with probable maximum precipitation used as an upper check. Although useful for design verification, these criteria do not adequately represent the operational risk posed by sequences of smaller storms occurring over days to weeks. In practice, spills are often driven by cumulative inflow, antecedent wetness, reduced recovery time between storms, sedimentation and limitations in pumping and operational response.

This paper presents a sequence-based framework for assessing the performance of return water dams and linked tailings storage facilities under consecutive minor rainfall events. The framework uses continuous water balance simulation, rainfall sequencing, antecedent wetness response and climate stress testing to evaluate spill likelihood, time at risk for freeboard exceedance and recovery capacity. A case study based on observed rainfall at a South African mine site is used to illustrate the problem. During January 2026, 831 mm of rainfall was recorded over 11 days, equivalent to about 145% of the local mean annual precipitation. Within this sequence, daily events reached approximately the 5-year to 20-year range, while the 72-hour and 7-day accumulations approached the local 50-year design depths. The findings support a shift from a design storm philosophy towards a design sequence and adaptive operations approach.

INTRODUCTION

Return water dams (RWDs) and tailings storage facilities (TSFs) are often assessed against single-event storm criteria. For mine water systems, this usually means demonstrating adequate storage for a selected design storm, commonly the 1-in-50 year 24-hour event and checking more extreme conditions such as probable maximum precipitation (PMP). These criteria remain useful for benchmarking, but they do not always reflect the way spills occur in practice.

Exceedances are frequently associated with sequences of moderate storms rather than one exceptional event. In such systems, water level depends on cumulative runoff, direct rainfall, return flows from the TSF, pumping capacity, evaporation and the remaining effective storage after sedimentation. Spill risk therefore depends not only on storm magnitude, but also on antecedent wetness, event timing and recovery capacity between storms.

These issues are increasingly relevant under climate variability, where rainfall sequencing, clustering and wet-season timing may change even when long-term annual totals remain broadly similar (IPCC, 2023). This paper examines the limitations of the single design storm approach and proposes a more practical framework based on continuous simulation and adaptive operation.

LIMITATIONS OF SINGLE-EVENT COMPLIANCE

Single-event assessment assumes that the critical system response can be represented by one storm applied to one set of initial conditions. For storage-driven mine water systems, this assumption is limited for three reasons.

First, initial conditions are rarely neutral. Before a wet sequence begins, the catchment, TSF beach and dam may already be wet or partly full. Second, recovery between storms is constrained by pumping, transfer capacity, power supply and maintenance readiness. If storage is not restored, the next event arrives on an elevated level. Third, effective storage changes with time. Sedimentation and operating constraints reduce available live storage and freeboard, sometimes materially.

For these reasons, compliance with a single 24-hour storm criterion does not necessarily imply acceptable seasonal reliability.

METHODOLOGY

A continuous water balance framework was adopted to assess sequence-driven spill risk. The model includes:

- A return water dam with a level-storage relationship
- Direct rainfall and evaporation on ponded areas
- Runoff from mine catchments
- Lagged return inflows from the TSF
- Reclaim and transfer pumping
- Variable pump availability
- Reduction in effective storage due to sedimentation
- Drawdown trigger levels for operational response

At each time step, storage is updated through a standard mass balance:

$$S(t+1) = S(t) + Q_{in} - Q_{out} \qquad [1]$$

where Qin represents runoff, direct rainfall and return flows and Qout represents pumping, evaporation and other losses.

Continuous rainfall series are used rather than one synthetic design storm. Historical records or resampled sequences preserve event depth, seasonality and dry-period structure, allowing assessment of clustered storms and incomplete recovery. Antecedent wetness is represented through dynamic runoff response, while operational scenarios account for pump outages, delayed preparation, loss of standby capacity and reduced live storage.

Climate stress testing is used to assess the effect of altered storm sequencing, shorter dry periods and shifts in wet-season timing. The purpose is not to predict one future climate, but to test system robustness under plausible future sequences.

CASE STUDY: JANUARY 2026 CLUSTERED RAINFALL SEQUENCE

A case study was compiled from rainfall observations at a mine tailings area, supported by comparison with a nearby Department of Water and Sanitation station and a mine site record. Figure 1 shows the cumulative rainfall trends for the three datasets. These are broadly linear over time, indicating that the key hazard in this case is not a major change in long-term annual rainfall totals, but the concentration of rainfall into short-duration wet periods.

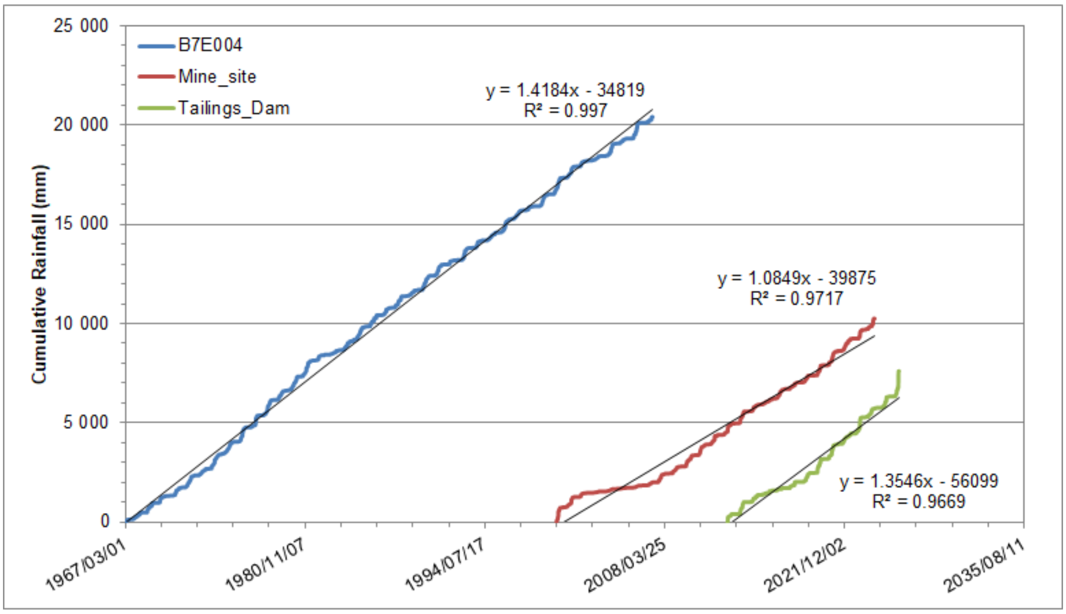

Figure 1. Cumulative rainfall trends for mine site

The derived mean annual precipitation (MAP) values were 510.66 mm for station B7E004, 439.55 mm for the Mine site and 574.28 mm for the Tailings Dam. Design rainfall depths derived for the tailings record are summarised in Table I, and the estimated 24-hour PMP was 522 mm.

Table I
Design rainfall depths for the Tailings Dam dataset

Design storms	LP3	LP3	LP3	LP3
2	79	92	106	138
5	104	144	180	268
10	123	184	236	367
20	137	230	306	503
50	153	299	418	730
100	164	359	521	948
200	175	427	642	1213
500	187	532	837	1655
1 000	196	623	1015	2072
2 475	206	780	1347	2902
5 000	213	901	1605	3546
10 000	221	1021	1859	4181

Rainfall totals from the start of the 2025/2026 hydrological year to the end of January 2026 were 84.5 mm in October, 213 mm in November, 135 mm in December and 831 mm in January, giving a cumulative total of 1263.5 mm by 31 January 2026. Notably, the full January total occurred within 11 days, from 9 to 19 January 2026, as shown in Table II and Figure 2. Figure 2 shows the daily rainfall and cumulative rainfall from 9 to 19 January 2026, compared with the local mean annual precipitation and the 7-day 20-year and 50-year design storm depths for the Tailings Dam dataset.

Table II
Observed daily rainfall during the principal January 2026 wet sequence

Date	Daily rainfall (mm)	Cumulative rainfall (mm)
2026/01/09	9	9
2026/01/10	70	79
2026/01/11	75	154
2026/01/12	100	254
2026/01/13	138	392
2026/01/14	135	527
2026/01/15	125	652
2026/01/16	40	692
2026/01/17	80	772
2026/01/18	50	822
2026/01/19	9	831

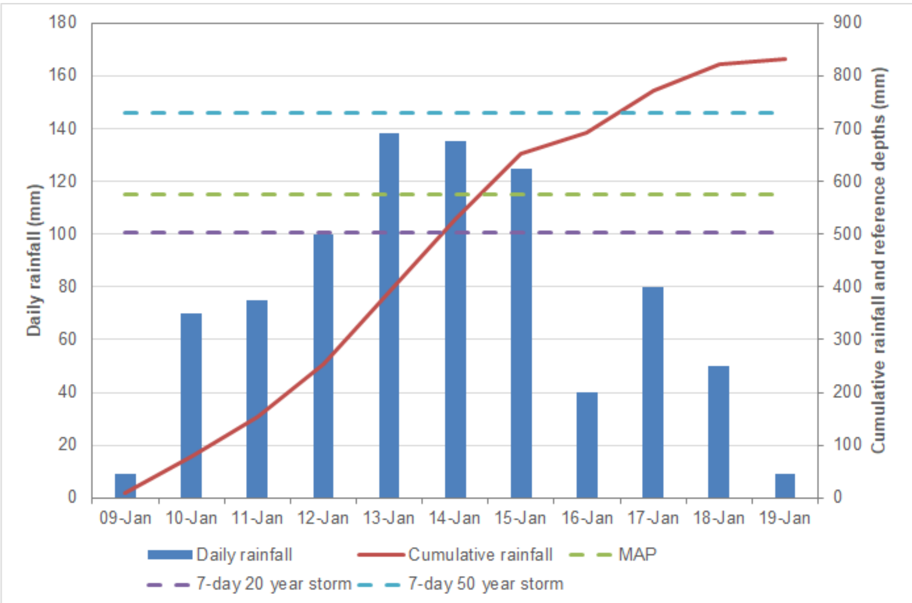

Figure 2. Rainfall comparison during the principal January 2026 wet sequence

The 11-day total of 831 mm is about 45% greater than the local MAP. Several daily totals were also hydrologically significant. The 100 mm recorded on 12 January was close to the 5-year 24-hour storm. The 138 mm on 13 January was approximately equal to the 20-year 24-hour storm. The 135 mm on 14 January fell between the 10-year and 20-year design depths, while 125 mm on 15 January was close to the 10-year 24-hour storm.

Multi-day totals were more severe. The 48-hour total for 13 to 14 January was 273 mm, between the 20-year and 50-year 48-hour design storms. The 72-hour total for 13 to 15 January was 398 mm, between the 20-year and 50-year 72-hour storms and close to the 50-year value of 418 mm. The 7-day totals for 10 to 16 January and 11 to 17 January were 683 mm and 693 mm respectively, both between the 20-year and 50-year 7-day design storms.

Figure 2 provides a practical illustration of the sequence hazard. The cumulative rainfall exceeded the 7-day 20-year design depth by 14 January, exceeded the local mean annual precipitation by 15 January and exceeded the 7-day 50-year design depth by 17 January. These comparisons are used as reference magnitudes rather than directly duration-equivalent thresholds, but they show how quickly the sequence escalated into a severe storage-loading condition. The significance is that the system was exposed to sustained inflow over multiple days with limited opportunity for drawdown, which is the principal mechanism by which return water dams may spill under clustered sub-design events.

DISCUSSION

The case study demonstrates a clear disconnect between single-event compliance metrics and actual operational exposure. The long-term cumulative records do not suggest a dramatic escalation in annual rainfall, yet the January 2026 sequence imposed an exceptional short-term storage demand. The relevant stress mechanism arose well below the 24-hour PMP. Instead, it was produced by repeated daily events in the approximate 5-year to 20-year range, which combined into multi-day totals approaching the local 50-year design depths.

This has practical implications. Adequate performance cannot be inferred solely from successful containment of a nominated 24-hour design storm. For storage-based mine water systems, reliability also depends on pre-wet-season drawdown, available pumping capacity, line condition, power reliability and preservation of live storage.

The case study therefore supports sequence-based planning, especially where RWDs and TSFs operate with limited freeboard, constrained pumping capacity or progressive sedimentation.

RECOMMENDED ADAPTIVE OPERATING FRAMEWORK

A practical adaptive framework for RWDs and TSF-linked water systems should include:

- Seasonal storage targets with lower wet-season operating levels;
- Assessment of pumping and transfer systems based on sustained recovery rate;
- Proactive sediment surveys and silt removal planning;
- Forecast-guided operating triggers for drawdown and storm preparation; and
- Continuous review of storage trends, pump status and near-miss events.

These measures improve reliability by preserving available buffer and recovery capability before and during clustered rainfall.

CONCLUSIONS

Conventional design criteria for return water dams remain useful for compliance and benchmarking, but they do not fully represent the operational risk associated with consecutive minor rainfall events. In many mine water systems, spill risk is controlled by cumulative inflow, antecedent wetness, loss of effective storage and limited recovery capacity between storms.

The case study presented here shows that 831 mm of rainfall was recorded over 11 days in January 2026, equivalent to about 145% of the local MAP. Several daily falls were in the approximate 5-year to 20-year range, while the 48-hour, 72-hour and 7-day accumulations approached the local 50-year design storm magnitudes. Under these conditions, event clustering, wet antecedent conditions and restricted inter-event recovery can be more important than the magnitude of any single storm.

A continuous sequence-based assessment therefore provides a more realistic view of system performance. It captures the effect of rainfall clustering, delayed drawdown, pump outages and sedimentation, all of which can cause freeboard exceedance even where the single-event design criterion is satisfied.

The findings support a shift from a design storm mindset to a design sequence and adaptive operations framework for mine water systems.

ACKNOWLEDGEMENTS

The authors acknowledge the support of colleagues at Knight Piésold involved in hydrology, mine water management and water balance modelling. The views expressed in this paper are those of the authors.

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