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Assessment of extreme multi-day flood events on tailings storage facilities

Évaluation des crues extrêmes plurijournalières sur les parcs à résidus miniers

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ABSTRACT: With a globally increasing focus on the safe operation and maintenance of Tailings Storage Facilities (TSFs) the management of water is core to the safety of these dams. One of the key considerations is to manage large and extreme floods. Careful consideration is required to ensure that extreme floods are contained within the basin of a TSF. Factors that need to be considered are climate change, multi-day storm events, freeboard requirements, and flood routing through outlet works. Previous practice for evaluating the flood management and freeboard of a TSF considers unrouted, 24-hour storm events with a minimum specified height to maintain satisfactory freeboard. This paper presents a broad approach for the determination and evaluation of extreme multi-day flood events onto a TSF catchment, considering the routed flood condition, with comparison to the unrouted flood condition. Multi-day storm events were quantified for various return periods using extreme value statistics, as well as the probable maximum precipitation (PMP). Stochastic modelling was performed using Monte Carlo simulations with pre-defined flood distributions to assess the expected flood depths for each storm. The paper shows that the standard practice and unrouted 24-hour events can provide reasonable proxies for shorter multi-day flood events with the most critical storm duration typically ranging between 7 and 10 days in Southern Africa

RÉSUMÉ : L'opération et l'entretien sécuritaire des parcs à résidus miniers (PAR) font l'objet d'une attention croissante dans le monde entier, par conséquent il est primordial d'évaluer soigneusement divers aspects afin d'établir la capacité de rétention des eaux des PAR. Ces aspects incluent les changements climatiques, des événements plurijournaliers, la revanche ainsi que l'acheminement de l'eau vers le PAR et son déversoir. La méthode standard considère les événements pluvieux de 24 heures ainsi qu'une hauteur d'eau minimale prédéterminée dans le PAR avec comme objectif de maintenir une revanche satisfaisante. Cet article présente une approche permettant de déterminer et d'évaluer l'impact des crues extrêmes plurijournalières pouvant affecter le bassin versant d'un PAR, et ce en considérant que celles-ci soient acheminées, en comparaison avec la méthode standard considérant une condition de crue non acheminée. Les événements de tempête plurijournaliers ont été déterminés pour diverses périodes de retour en utilisant des statistiques de valeurs extrêmes, ainsi que la précipitation maximale probable (PMP). La modélisation stochastique a été réalisée à l'aide de simulations de Monte-Carlo avec des distributions d'inondation prédéfinies pour évaluer les profondeurs d'eau attendues pour chaque tempête et en tenant compte de leur tracé. Cet article démontre que la méthode standard et l'utilisation d'événements de 24 heures non acheminés peuvent fournir des approximations raisonnables pour des événements d'inondation plurijournaliers avec une durée de la tempête la plus critique étant généralement comprise entre 7 et 10 jours.

KEYWORDS: rainfall, flood routing, tailings, risk management, climate change

1 INTRODUCTION

Upstream constructed tailings storage facilities (TSFs) are common in South Africa. One of the key management criteria for TSFs in South Africa is freeboard and stormwater management capacity. This is typically done by means of wall-building, as well as maintaining a small pond as far as possible from the outer shell of the TSF.

The legislated freeboard requirement for dams in South Africa state that water systems should be designed, constructed, operated, and maintained so that it is not likely for spillage to occur more than once in 50 years. Further to this, it states that tailings dams should have a minimum freeboard of 0.8 m above full supply level. (GN704 of the National Water Act, 1998) Prevalent practice is to impose the 1:50, 24-hour storm event level on top of the TSF pool with the added 0.8 m level on top of the 1:50 24-hour level to define the required freeboard. Figure 1 illustrates this methodology.

Other standards (GISTM 2019, ANCOLD 2020, and internal standards) require the consideration of larger storm events to determine the design floods. Local standards require contingency capacity of a dam to contain a 1:100 year storm with an additional 0.5 m to crest level (SABS 10286 1998). The probable maximum precipitation (PMP) is used to estimate the probable maximum flood (PMF) and is usually recommended to assess the freeboard and stormwater management capacity of a TSF.

Furthermore, global trends require consideration of climate change, as well as longer-duration storm events in consideration of TSF stormwater management.

This paper presents a case study on a TSF in South Africa, in the Limpopo bushveld where multi-day storm modelling was required to assess the freeboard capacity. The modelling included quantification of the rainfall depths for each return period and storm duration, as well as modelling of the storms onto the TSF catchment, accounting for active decanting structures – a flood routing exercise.

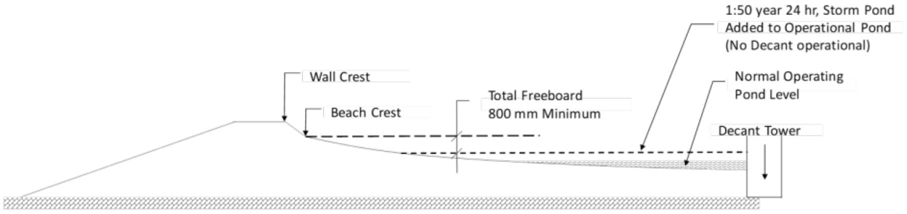

Figure 1. Definition of South African Legislation for determining the minimum required freeboard in South Africa.

The routed conditions were then compared to the baseline methods for defining the required freeboard for the TSF, which included the 1:50-year storm + 0.8 m, as well as simply imposing the 24-hour PMF volume onto the TSF basin. Both baselines are required to be lower than the beach crest level while assuming that no stormwater is decanted, i.e. the floods are not routed.

2 INFLOW AND OUTFLOW CONDITIONS

2.1 *Rainfall Depths*

The rainfall depths for relevant return periods from 20-years to 10,000-years were determined using the latest available daily rainfall data for the site, and Extreme Value (EV) statistical methods (SANRAL 2013). The method requires that the largest storm for a given duration is abstracted for each calendar year and an annual maximum series for the rainfall dataset prepared. Various statistical distributions are then fitted to the data to determine the most appropriate statistical distribution for the data. The log-normal distribution was found to be the most appropriate for this data set.

The PMP storm events for the various durations were determined using the Hershfield method as outlined in WMO (2009). The rainfall depths for the various return periods and durations are presented in Table 1.

Table 1. Storm depths for various durations and return periods

Return Period (years)	1-day (mm)	2-day (mm)	3-day (mm)	7-day (mm)	14-day (mm)	21-day (mm)	30-day (mm)
20	108	133	158	206	263	294	350
50	126	152	186	242	308	341	406
100	140	168	208	271	343	377	449
200	153	182	230	299	377	412	491
500	171	202	260	337	423	459	547
1 000	185	217	284	366	458	495	590
10 000	234	269	366	469	576	622	740
PMP	414	515	612	907	1 141	1 283	1 405

2.2 *Storm volume*

The TSF considered in this assessment is an upstream-constructed, ring-dyke impoundment facility. This means that the facility is enclosed on all sides, and no external catchments contribute to the storm volume that needs to be contained within the TSF. The storm catchment for the TSF is therefore equal to the top surface area of the TSF.

The total stormwater volume to be contained is determined using Equation 1:

$$V_{storm} = D_{rain} \cdot A_C \quad (1)$$

Where:
V_{storm} = Stormwater volume (m³)
D_{rain} = Rainfall depth (m)
A_C = Catchment area (m²)

2.3 *Inflow hydrograph and storm distribution over time*

Considering the relatively small catchment of this TSF (<30 km^2), it, can be reasonably simplified that the rainfall onto the catchment has an instantaneous effect at the point of outflow- the decant structure. The corollary of the small catchment is therefore that the rainfall distribution, the hyetograph of the storm, is essentially the same as the storm hydrograph.

Since the rainfall data for the site has a resolution of 1-day (or 24-hours), the hyetographs for the rainfall events at the site could not be determined. The soil conservation service (SCS) unit-hydrograph model (Natural Resources Conservation Service 1986) was therefore used as a proxy for a storm hydrograph on the TSF.

2.4 *Outflow hydrograph*

The outflow conditions for the facility are governed by the type of spillway and the pond depth at the spillway. The TSF in question uses 510 mm diameter vertical penstock towers and an outfall pipeline with an approximate capacity of 0.36m^3/s. The discharge rate at each water height was used to determine the pond volume at each timestep in the routing calculation.

The flow through a penstock tower can be described in three main categories with each flow regime being less efficient than the former:
1) Weir flow
2) Orifice flow
3) Pipe flow

3 STOCHASTIC MODELLING

3.1 *Rainfall distribution over storm duration*

To model a facility's reaction to multi-day flood events, a realistic flood must be generated first. The typical rainfall distribution parameters for various storm durations were derived from the rainfall database and are presented in Table 2.

This includes:
1) The probability of a given day receiving rainfall (*P(rain)*), i.e., the number of "wet" days out of the storm duration since a 30-day storm does not necessarily receive 30 days of continuous rain,
2) The mean fraction of rain that fell on a given rainy day ($\bar{x}$);
3) The standard deviation of the rainfall on rainy days (s).

Table 2. Statistical parameters for various duration rainfall events

Parameter	1-day	2-day	3-day	7-day	14-day	21-day	30-day
P(rain)	1.00	1.00	0.870	0.673	0.542	0.479	0.433
$\bar{x}$	1.00	0.500	0.383	0.213	0.132	0.099	0.077
s	-	0.309	0.268	0.205	0.138	0.113	0.086

For the purposes of explanation, the 14-day PMP/PMF event is used to present the approach taken:

The modelled distribution of a multi-day storm over the duration of the storm was generated as follows:
1) Each day was classified as "wet" or "dry" (rain or clear) by generating a uniformly distributed random number and checking if it fell below the relevant *P(rain)*.
2) For each "wet" day, a normally distributed random number is generated using the relevant distribution's $\bar{x}$ and s. This number is then multiplied by the total storm depth to convert the fraction into a rainfall depth for the given day.
3) Once the above steps are completed for each day of the storm duration, the storm is validated to ensure that any day or combination of days do not transgress the limits of the site's storm duration characteristics, for example:
   a) No one day may receive rainfall larger than the relevant 1-day storm.
   b) No three days may receive rainfall larger than the relevant 3-day storm, etc.

An example of a simulated 14-day PMP for the site is shown in Figure 2 with the cumulative rainfall of the simulation in

Figure 3. The inflow distribution from the SCS hydrograph method is presented in Figure 4.

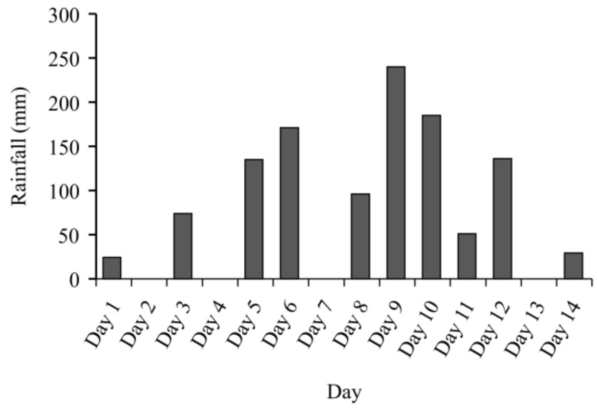

Figure 2. Rainfall distribution for a 14-day PMP storm.

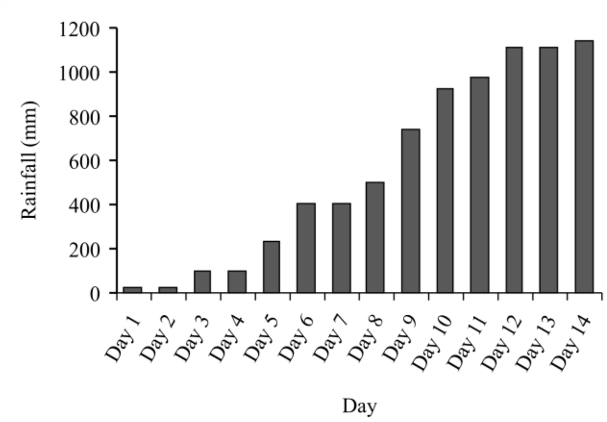

Figure 3. Cumulative rainfall for a 14-day PMP storm.

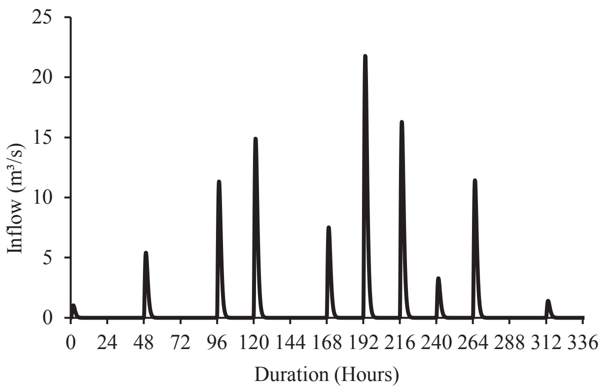

Figure 4. Inflow distribution for a 14-day PMF.

3.2 *Monte Carlo simulations*

One hundred storm events were simulated for each of the storm events and durations. Storm depths were assigned to each day and distributed with an inflow hydrograph. The pond depth over time was determined for each of the simulations, with the maximum achieved pond depth recorded for the assessment. The pond depth vs time for a 14-day PMF is illustrated in Figure 5.

Days that did not have consecutive rainfall events did in some cases allow the pool to drain back to the operating pool level (penstock level).

Additionally, to the 100 randomised simulations, two more user-defined distributions were evaluated:

1) The rainfall distribution for the historically highest event for a given duration.
2) A cumulative distribution of the PMF storm over the various days, where the 1-day PMP (414 mm) falls on day 1, the balance between the 1- and 2-day PMP (101 mm) falls on day 2, etc.

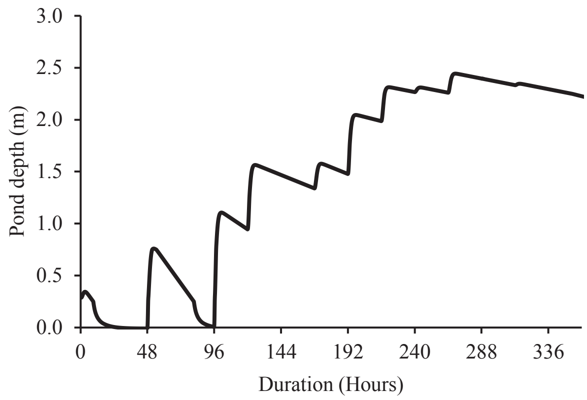

Figure 5. Pond depth over time for a 14-day PMF.

The distribution of the maximum pond depths for each of the storms was then defined, as shown in Figure 6. The maximum pond depths appear to follow a normal distribution.

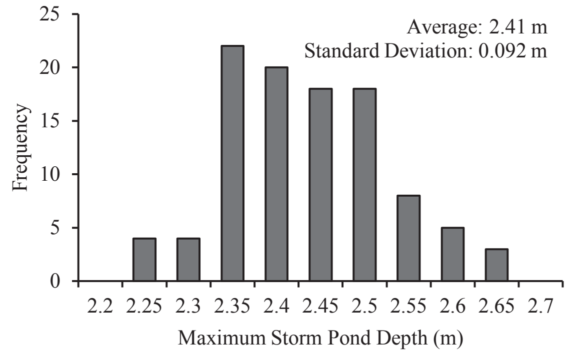

Figure 6. Statistical distribution of pond depths for 14-day PMFs.

4 RESULTS

The statistical parameters for a PMF event of various durations, as determined using the above methodology are presented in Table 3. The baseline assessments (1:50 + 0.8 m and unrouted 24-hour PMF) produced pond depths of 2.08 m and 2.11 m respectively.

The routed pond depths generally provided deeper ponds for the longer duration storms. The most critical storm durations were found to be between 7 and 14 days in length, with most of the critical rainfall occurring between 7 and 10 days of the longer duration events.

The average depth of the routed 7-day storm exceeded the 1:50 + 0.8 m flood depth by 17% (0.36 m) and the PMF flood depth by 16% (0.33 m). The baseline case, however, was found to provide reasonable proxies for the 2-day and, in some cases, the 3-day routed events. The facility in question at the time of analysis had available freeboard of 2.64 m equal to the absolute maximum height of a 14 day storm (Table 3).

Table 3. Statistical distributions for pond depths for various duration PMP storms

Storm Duration (Days)	Average Maximum Height (m)	Standard Deviation (m)	Absolute Maximum Height (m)
1	2.03	-	2.03
2	2.12	0.002	2.14
3	2.22	0.015	2.26
7	**2.44**	**0.050**	2.60
14	2.41	0.092	**2.64**
21	2.25	0.141	2.53
30	2.11	0.202	2.64

5 CONCLUSIONS

Each storm simulation was imposed onto the catchment of the TSF over time, with the total pond water volume and height calculated at each timestep. The statistical parameters from each storm in terms of the water height were determined from the 102 simulations performed. The results from the flood routing simulations were compared to the legislative South African practice (1:50-year, 24-hour storm + 0.8 m) as well as the unrouted 24-hour PMF height.

The unrouted 24h PMF and 1:50 + 0.8 m flood depths were generally found to be similar to the 2- to 3-day routed PMF storm events. The most critical storm duration was found to be between 7 and 14 days, depending on the return period assessed.

The approach to model storms with longer durations was presented and can be applied to other catchments and storms.

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