One breach or more? - Assessment of potential multiple flood overtopping dam breaches and sequencing

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Many quantified risk assessments finish the failure mode event tree at the estimated occurrence of an embankment breach leading to dam failure outflows and downstream consequences. In some situations, for dams with multiple embankments with potentially different consequences downstream of each embankment, the possibility for further breaches may be pertinent if there may potentially be higher consequences for a multiple breach scenario. The location of an initial breach and sequence of subsequent breaches could also result in different contributions to total risk.

This paper discusses a method applied to investigate the conditional probability of flood overtopping breaches for multiple earth-fill embankments with grass covered downstream slopes.

For the subject dam, preliminary modelling identified that for a flood overtopping breach of an embankment the breach's development may not be sufficient to reduce the lake level and sustained overtopping flow over the remaining embankment crests could lead to further embankment breaches.

A Monte Carlo dam breach simulation modelling approach was used with a large number of flood events. The simulation modelling considered erosion initiation for a grass slope due to the combination of velocity and duration of flow, and erosion continuing to breach based on duration of flow after erosion initiation. Potential uncertainty of erosion initiation and erosion continuing to breach were represented with probability distributions in the Monte Carlo modelling.

The results from the large number of dam breach simulations were then analysed with post processing to derive conditional probabilities for single or multiple breaches and breach sequence.

Keywords: *Flood hazard, Dam break, Breach, Conditional Probability, Stochastic, Prediction, Embankment*

Introduction

During a recent updated risk assessment for North Pine Dam, Seqwater identified that potential breach of more than one embankment due to flood overtopping should be considered in the risk assessment. At full supply level (FSL), North Pine Dam impounds 215,000 ML. The Extreme Consequence category dam is in an area experiencing sustained high growth in population. A significant portion of Population at Risk is within a short distance downstream of the main dam and saddle dams, which limits the available warning time in the event of a dam safety emergency.

The North Pine Dam main structure across the original river channel is a 39 m high mass concrete gravity dam. The concrete dam has spillway monoliths with piers supporting radial gates and adjacent non-overflow monoliths. The concrete dam is flanked by earth-fill embankments at the left and right abutments. There are three additional saddle dams located to the south of the main dam, refer **Figure 1**. Recent site survey identified that the two embankments each side of the concrete dam and three saddle dam embankments have varying dam crest levels at which overtopping flow may potentially occur.

The Authors identified that for a flood overtopping breach scenario of a saddle dam, the limited breach outflow could result in the lake level continuing to overtop the remaining embankment crests. It was further identified that termination of the risk analysis event tree with a single breach location and estimates of downstream consequences for one breach may not be adequate to assess the full quantum of total risk. It was also identified that downstream consequences could vary depending on the location of an initial breach. With the possibility of multiple breaches, the sequence of likely flood overtopping breaches at other embankments could also affect the magnitude of consequences and risk.

Initial modelling indicated that objective information to judge the likely location of an initial overtopping breach and likelihood of subsequent breaches at other embankment locations should be developed.

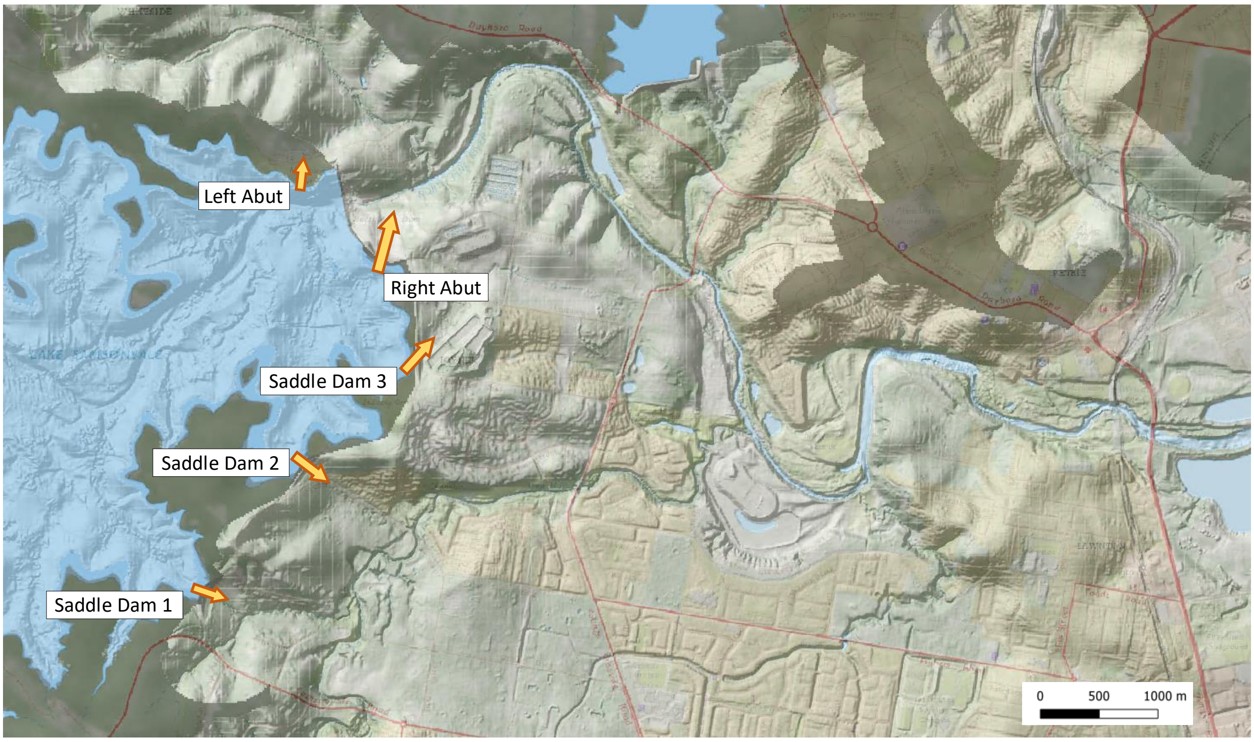


Figure 1: Locality Map at North Pine Dam

This paper describes a method to support the risk analysis judgement of conditional probabilities for flood overtopping breach. The method that was developed used Monte Carlo modelling with broad hydrologic loading and probability representation of steps leading to failure from flood overtopping of earth-fill embankments. This paper is limited to the method used to generate data to inform risk event tree probabilities for multiple breaches and potential sequence of further breaches. The risk assessment outcomes are not discussed.

Concept for potential flood overtopping breach of earth-fill embankments

Possibility of multiple breach, and likely location of initial breach, then subsequent breaches may be important for quantified risk assessment of dams with multiple embankments. The significance increases if there is a close downstream population at risk spread across multiple pathways downstream of the potential dam breach outflow locations, refer **Figure 1**.

Recorded data for breaches of dams with a long waterbody, low height saddle dam embankments and a large volume of impounded water at dam crest level is limited. Parametric breach estimation methods for a large volume of water to pass through a breach of a low height embankment indicate a relatively slow breach development time. When such parameters are simulated in modelling of breach outflow hydrographs, the predicted development time can result in a slow lake level fall the breach triggers which sustains flow overtopping other embankments. The duration of flood overtopping was identified as a key influence on breach probability.

There are some known precedents of floods overtopping earth-fill embankments such as Awoonga Dam in Central Queensland in 2013 and Enoggera Dam near Brisbane during the 1974 flood, where prolonged flood overtopping did not result in embankment breach.

The authors sought to establish a model to quantify duration of flood overtopping flow influence on the causal steps of flood overtopping leading to breach completion. A Monte Carlo dam breach simulation approach that represents duration of overtopping influencing multiple steps in sequence that leads to overtopping breach of an embankment dam was applied. Specifically, this assumed it is necessary for adequate duration of overtopping flows to initiate erosion and then erosive flow needs to be sustained for erosion to headcut upstream to breach the embankment.

A single breach model was expanded such that multiple breaches became possible due to continuing overtopping flow over other embankments. The timing and outflow influence on lake level for each breach location was simulated.

Conceptual steps leading to breach

Common practice in dam breach modelling typically triggers the start of breach development at a level typically at or just above the dam crest, depending on judgement of the overtopping depth required to initiate a breach.

The authors sought to improve dam breach modelling with conceptual steps of initiating erosion and continuing erosion leading to breach. A relationship between lake level and downstream batter or toe flow velocity for the embankment overtopping flow was modelled to dynamically respond to the flood hydrographs. A probabilistic relationship between velocity and duration defined resilience to erosion. A stochastically sampled criterion for the period of overtopping flow being sustained after erosion initiation defined whether or not a breach develops. The intent was to reduce the subjectivity in assuming a lake level results in a breach.

Figure 2 illustrates the concepts leading to a breach after flood overtopping. For North Pine Dam, the initiation of erosion at the toe or downstream batter, was assumed to be sufficient depth and duration of overtopping flow to generate velocities sufficient to exceed erosion resistance provided by the grass cover on the embankment. As erosion continues, it is becomes increasingly likely that it will be able to head-cut back to the dam crest and initiate a breach. The completion of this erosion phase was defined by a stochastically sufficient period following the initiation of erosion.

After commencement of a breach, the breach outflow is calculated dynamically as the breach dimensions increase. The lake volume and lake level adjusts to the breach outflow. The co-dependant influence between breach outflow and lake level allows the lake level response after breach to be calculated and possibility of other embankment breaches was able to be simulated.

Figure 2: Key phases in the erosion triggered embankment breach model

A multi-dam breach model was developed using the GoldSim software with the ability to model a non-linear dynamic flow routing model within a Monte Carlo simulation framework.

The conceptual methods within the GoldSim model comprised of routing lake inflow through a level-pool in two parallel scenario model outcomes. The two scenarios represented lake level response for flood overtopping only (non-failure) and with breach failure. The models included simulated outflow, dynamically driven by lake level for:

- flow via a gated primary spillway;
- flow overtopping the concrete dam monoliths; and,
- flow overtopping at five embankments and subsequent breach flow when embankments were breached.

The model resolves the interactive response relationship between lake level influencing outflow and breach formation. The model was setup to enable repeat (looped simulation) of 1680 unique flood events to allow each flood event to sample stochastic components of the method multiple times.

Approach to quantify erosion initiation

The initiation of erosion was simulated representing the co-dependence on the depth and duration of overtopping flow velocity. High velocity of overtopping flow could potentially initiate erosion within a short period, and conversely low velocity of overtopping flow may require a longer period to initiate erosion. For the application on North Pine Dam, this recognised that well established and maintained grass cover protects the surfaces of the downstream batter, toe, abutments, and downstream flow path. Engineering literature was available to quantify combinations of velocity and duration for erosion of a grass covered surface. The modelling utilised relationship tables for each embankment to derive relationships as follows:

- *develop and analyse a fine resolution two-dimensional supercritical flow model*. The analysis considered the shallow depths overtopping the dam crest to identify the location and magnitude of maximum downstream velocity (on the batter, dam toe, abutments or downstream flow path). The simulations were run with different depths of overtopping to develop a relationship between lake level and maximum downstream velocity. The same simulations were also used to develop a relationship between lake level and overtopping flow; and then,
- *define a relationship between combinations of velocity and duration of overtopping flow* across a grass surface to define probability of erosion.

Approach to simulate initiation of erosion

The model triggered initiation of erosion at each potential embankment breach location with the following steps in the simulation:

1. *estimate the downstream velocity for the current lake level* after overtopping the embankment crest at each model time-step;
2. *assess the duration that overtopping flow velocity* exceeds a range of threshold velocity values as overtopping progresses. An array of velocity and duration is tracked. For each combination of velocity and duration, an estimate of the erosion probability is calculated using a relationship adapted from engineering literature for erosion from flow over grass cover (refer **Figure 3**). At any given time, the probability of erosion is adopted as the maximum value across the array combinations of velocity and duration;
3. *initiation of erosion is simulated to occur* when probability of erosion from step two is greater than a random number between 0 and 1 sampled from a uniform probability distribution. The probabilistic nature of this step is considered important due to uncertainty in knowledge of erosion of grass and potential variability in quality of grass cover and erosion resistance.

Erosion probability lookup table

A key input was definition of an erosion probability table (refer **Figure 3**) for grass cover based on the co-dependency of velocity and duration that velocity is exceeded. This is used in the model as a two-dimensional lookup table of velocity and duration pairs, from which the model interpolates the probability of erosion.

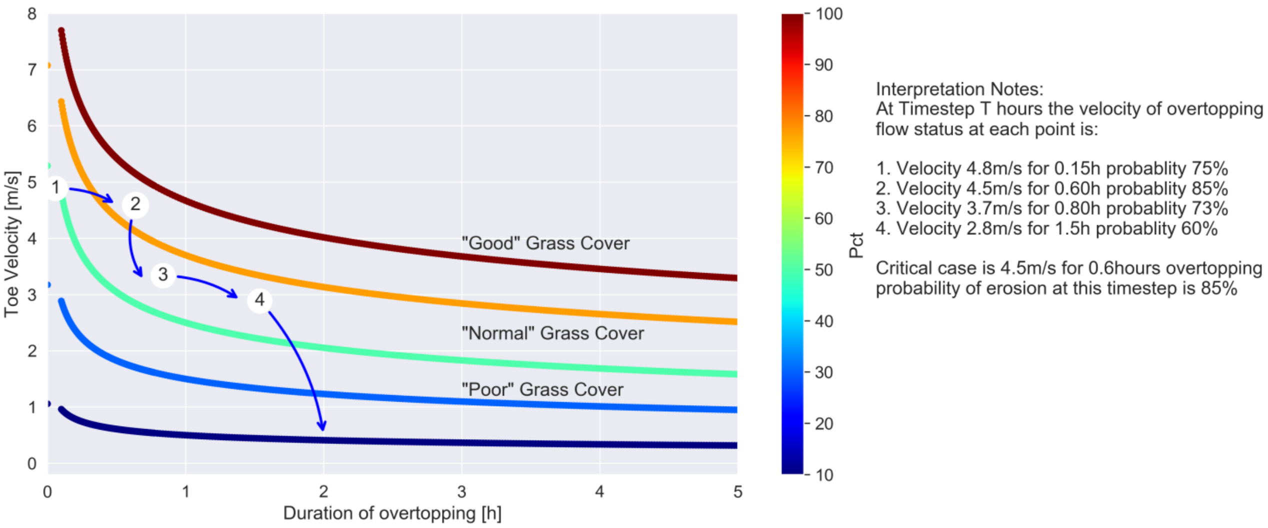


Figure 3: duration exceeding velocity thresholds to define probability of erosion

The derivation of the two dimensional lookup table was from a collection of curves originally reported in two *Construction Industry Research and Information Association* [CIRIA] documents, Technical Note TN71 (Whitehead et al, 1976) and CIRIA Report R116 (Hewlett et al, 1987).

Morris (2010) and others note that CIRIA Report 116 has safety factors for design that flatten the curvature of the relationship. Young (2005) published a relationship [Equation 3.3 'PC RING'] between grass cover quality (f_g) and velocity to the data in TN71.

$$u_c = f_g\, 3.8 \;/\; (1 + 0.8\; {}^{10}\log t_e)$$

where:

f_g varies from 0.7 to 1.4

Equation 3.3 in Young, 2005

where u_c = velocity; f_g = grass factor 0.7 poor, 1.0 normal, 1.4 good; t_e = duration of erosion

The downstream batters at North Pine Dam embankments have grass cover considered to be in good condition and well maintained. The velocity-duration curve for good, well-maintained grass cover was conservatively assumed to define 100% erosion probability threshold. The area under this this curves was integrated and apportioned to find intermediate erosion probability values. From these three curves, others were fitted to find areas for 75%, 50%, 25% and 5% probability.

Embankment overtopping hydraulic assessment

A hydrodynamic two-dimensional model was constructed for the embankments to define the relationships between overtopping flow, lake headwater level and overtopping flow downstream velocities. Terrain data for the two-dimensional model was sourced from detailed survey and defined in a one metre grid digital elevation model. The hydraulic model results were post-processed to define a tabular relationships required for the dam breach Monte Carlo model. A series of embankment locations were used to track toe velocity for increasing overtopping flow. The maximum envelope of toe velocity defined a relationship back to lake level, as shown on **Figure 4**.

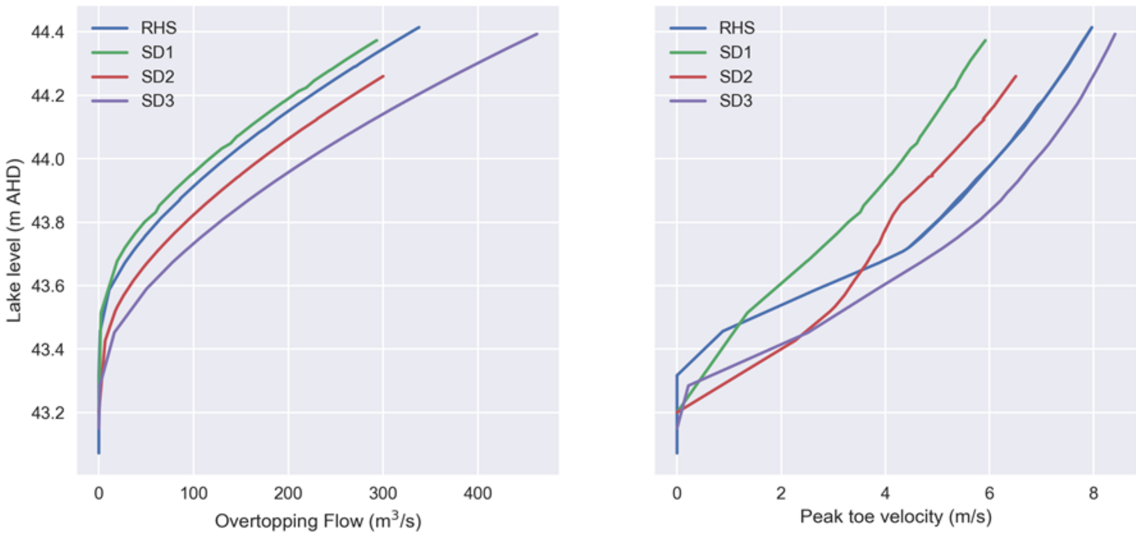


Figure 4: Relationship of flow to stage and toe velocity

Approach to assess erosion's continuation

After erosion initiates, a period of continuing erosion must occur where adequate time exists for erosion to headcut back to the dam crest to start a breach of the embankment. The duration for continuing erosion depends on the:

- evolving form and shape of the headcut erosion;
- corresponding volume of embankment material removed; and,
- rate of headcut erosion, which would depend on the:

a. erosion resistance of the underlying embankment material properties; and,
b. dynamic relationship between the morphing shape of the headcut and its influence on flow hydraulics.

In considering the complexities and inter-dependencies above, it was considered there was insufficient data to rationalise a deterministic process in the dam breach model. A simple approach based on engineering judgement defined the continuing erosion phase in the dam breach model as any sustained overtopping flow for a range of one hour to six hours (represented in the Monte Carlo model with a uniform probability distribution) is sufficient to headcut to the dam crest and then start a breach of the embankment. A breach was only triggered if the overtopping flow was sustained for the erosion continuation period. The Monte Carlo approach and multiple breach capability of the model meant that some floods events could result in a breach not developing, even after initiation of erosion, if a breach at another embankment causes the overtopping flow to cease before that embankment's trigger duration had not elapsed.

Simulation of breach development

The breach development was represented with the sine-growth development approach described in TD 39 (Brunner, 2014). The breach size parameters (specified by user input for invert level, base width and side slopes) defined the completion of breach development. The preliminary parametric calculation of breach formation times at the saddle dams were considered slow at around 4 to 5 hours. The Froehlich (2008) dataset of 74 dam breaches are arranged as six plots in **Figure 5**, which allows mutual comparison of the multi-variate equations. The initially predicted parameters (blue squares) appeared to plot at the extremities of the recorded dataset. A breach formation time (BFT) of two hours was applied to the model input. The blue arrows indicate the resultant changes.

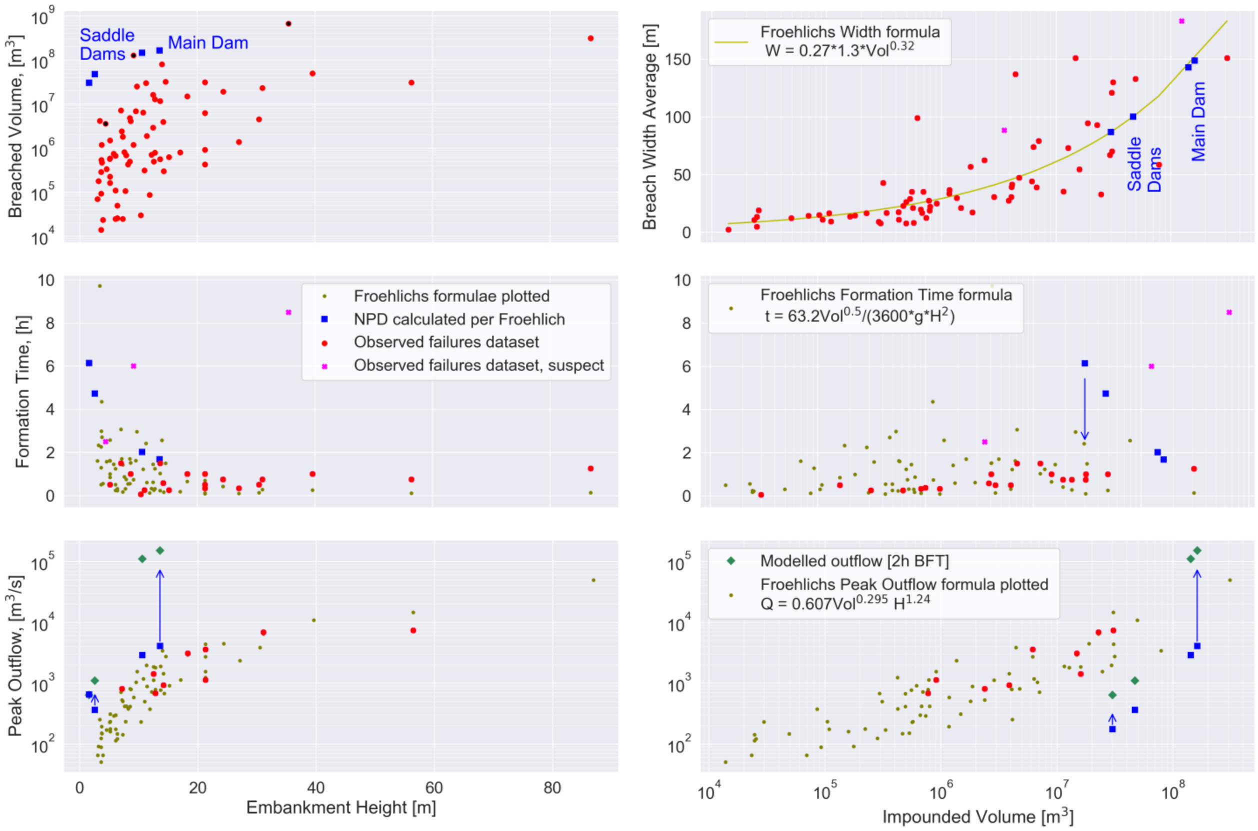


Figure 5: Froehlich's observed data and multivariate breach equations (Froehlich, 2008)

Model Simulation

The model was populated with a database of inflow floods generated from the design flood hydrology study for the dam which utilised the ensemble event approach outlined in *Australian Rainfall and Runoff 2016*. The range of design flood events covered; 14 rainfall storm Annual Exceedance Probabilities [AEP], 12 storm durations for each AEP, and for each storm duration 10 temporal patterns, providing a database of 1680 flood inflow events.

The Monte Carlo dam breach model repeated each flood event 60 times to allow sufficient sampling of the stochastic representation for erosion initiation probability and period for erosion continuation to breach. The results from the large number (100,800 per gate scenario) of dam breach simulations provided sufficient samples for post processing analyses to derive conditional probability estimates for the flood overtopping embankment failure mode in the subsequent risk assessment.

The number of repeat simulations and flood events was identified to be important to produce sufficient samples for events that overtop the dam embankments. This varied between fewest overtopping results for all spillway gates operational and the greatest number of overtopping results for a scenario of no spillway gates operational.

For each flood simulation, the model output tracked volume and peak outflow values at each location and phase of failure, time of peak flow, duration of overtopping, duration of erosion and duration of breach. Qualitative information was also captured such as the location and order of (including simultaneous) erosion and breach events. The breach model was paired to simulate the peak lake level that would occur with no embankment breach. This pairing was required for the post processing to produce fragility curves related to lake level.

Post-processing to derive conditional probability data

The likelihood of a dam embankment breach initiating after overtopping was considered to be dependent on the duration and depth that water flows over the crest. The duration of embankment overtopping was also dependent on the storm duration. From the design hydrology study for the dam, the critical rainfall burst duration event for peak level to exceed the embankment crest for all gate availability scenarios, is estimated to be in the order of 36 to 48 hours.

Filtering flood simulation results for post processing

The intent of the post-processing was to produce fragility curves for the probability of breach conditional upon lake level. For source data for the fragility curves the data mining of the Monte Carlo dam breach model results referenced the peak lake level result of each flood simulation representing a scenario with no breach, together with the breach outcomes from the same flood scenario that allowed breach to occur. This was important because the lake level partitions are aiming to identify the probability of breach outcomes, relative to lake level, assuming the dam has not breached at lower lake levels.

The fragility curves needed sufficient categorisation of the breach outcome of interest such as:

- separately identifying the probability of first breach and location of first breach; and then,
- defining the probability of subsequent breaches specific to other embankment locations.

A key step in the post-processing was to exclude potential bias being introduced by the very short duration rainfall burst flood events (well below critical duration) and very long duration rainfall burst floods (well above critical duration) on the conditional probability fragility curves. The inclusion of model results from too short/long duration storms dilute the fragility curve probabilities, as they increase the number of non-breaching samples. The rationale for this was that the subsequent quantified risk assessment is separately accounting for the flood loading probability based on the envelope of storm durations to define peak lake level probability. It is imperative that the fragility curves are based on flood simulations close to the critical duration for the flood level probability curves.

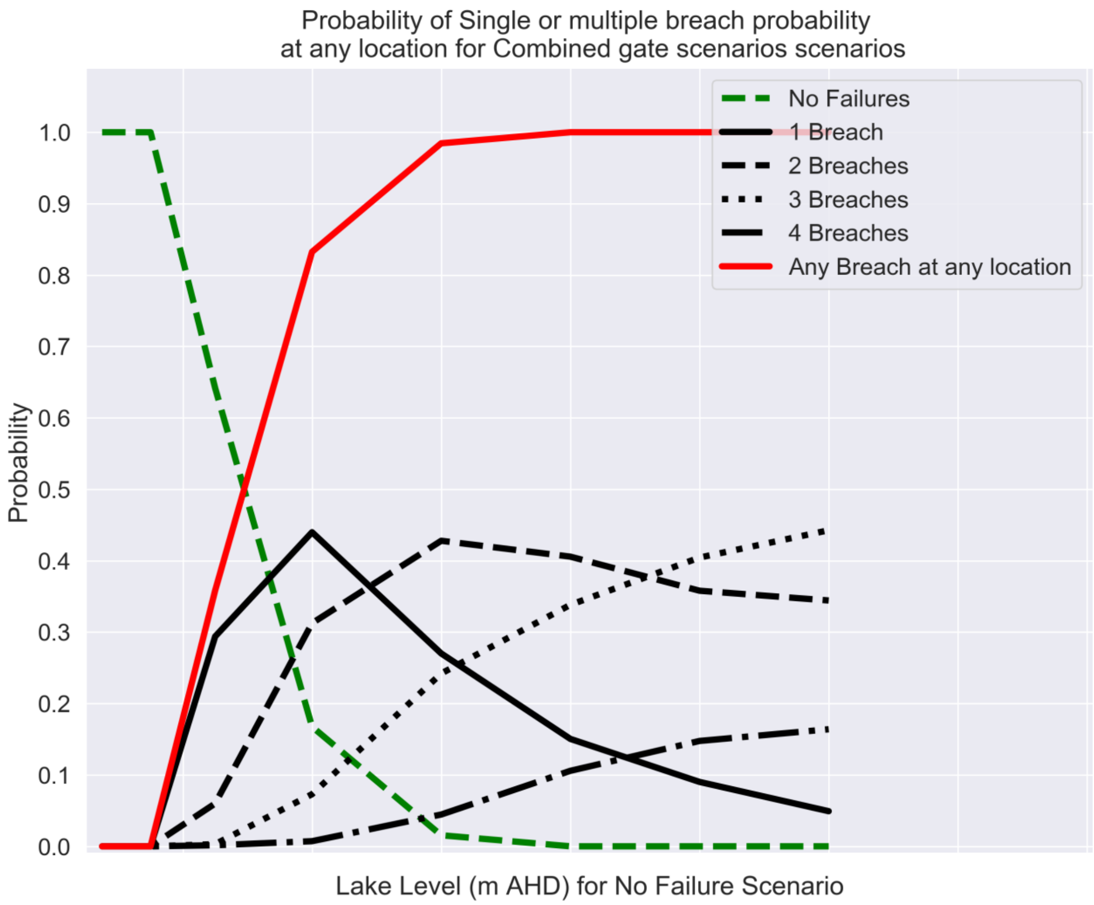
The results of frequency curves across a range of storm durations from the design flood hydrology identified that at levels near and overtopping the dam crest level, the 24 hour to 72 hour storm duration frequency curves for peak lake level are reasonably close. There was increased departure (significantly lower peak levels compared to the critical duration) for the frequency curves for storm duration less than 24 hours and greater than 72 hours. On this basis it was considered that the post processing of the Monte Carlo dam breach flood simulation results should be filtered to exclude floods caused by storm durations less than 24 and greater than 72 hours.

Categories of conditional breach probability

The post-processing was performed to derive conditional probability fragility curves for a range of specific conditions from a simple case of any breach at any location to more complex cases of specific location and sequence. These cases included:

- generalised probability of any breach at any location, refer **Figure 6** for example;
- generalised probability of single breach or multiple breaches at any location, not shown;
- probability of first breach at specific locations (with separate fragility curves derived for each embankment), refer **Figure 7**; and,
- conditional probability of subsequent breaches after a first breach at each specific location (with separate embankment fragility curves). Where the subsequent breach results in a second breach at a location and there are no further breaches, refer **Figure 8**.

For each of the above fragility curves, the probability of say no breach/any breach was also plotted to enable checking that total probability sums to 100%, refer **Figure 6**.



Notes: (a) 2 hour Breach Formation Time (b) flood events for 24 hour to 72 hour storm events

Figure 6: Example of total probability of breach at any location

Figure 7 illustrates the fragility curve that can be define probability values to assign to the risk event tree for the probability that an embankment is the first to breach at a lake level above dam crest.

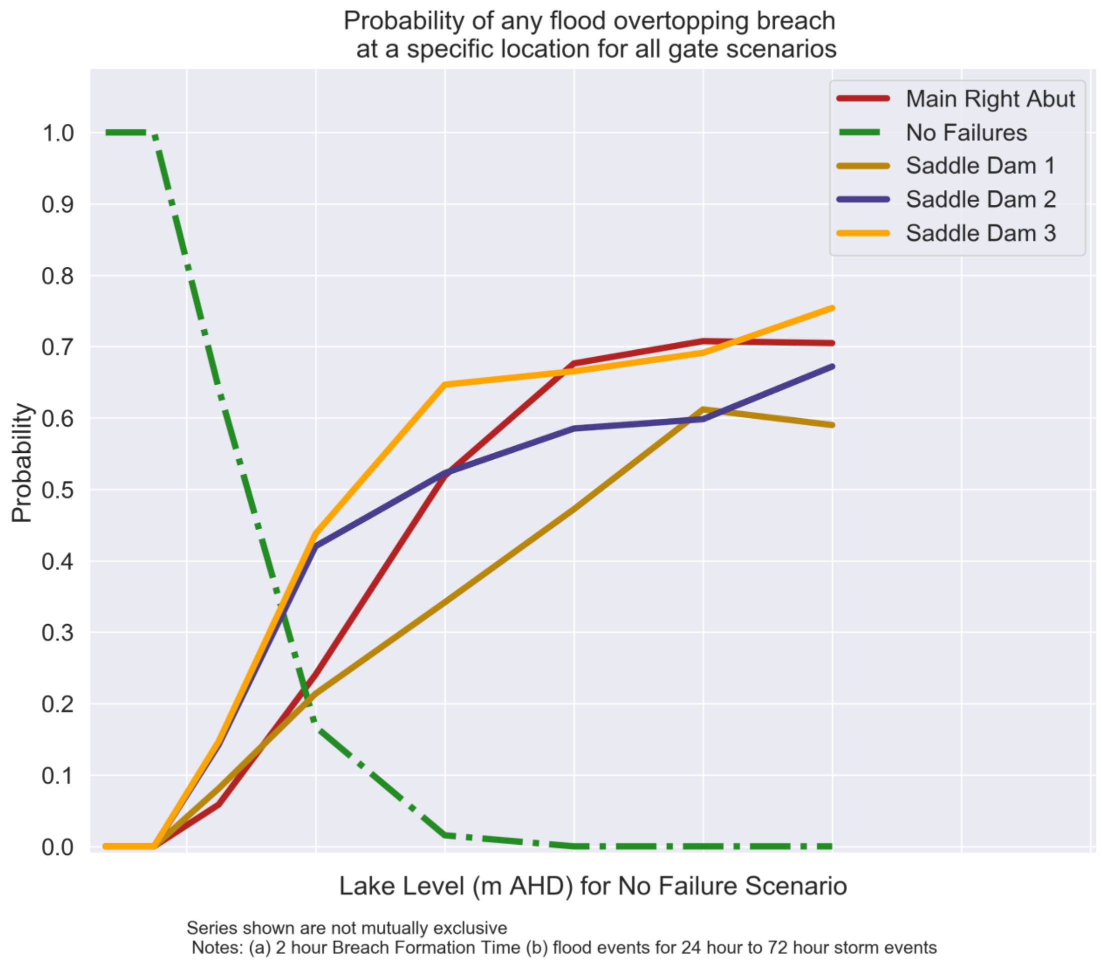


Figure 7: Example of fragility curve for first overtopping breach by location

A key output of this work was the determination of conditional probability of failures for specific conditions. This enables the risk assessment to quantify the conditional probability of no further breach, a single subsequent breach, or probability of three or four breaches. The intended sequence to build the risk analysis event tree could utilise the fragility curves, refer **Figure 8** in the following way. Use the first breach location fragility curves to define the probability that each specific embankment would have the first overtopping breach. Then once the location of the first breach is estimated, the risk assessment can determine the probability of subsequent breaches at the remaining locations using the fragility curve for multiple breaches dependant on the condition that a first breach has occurred at specific location. Each embankment fragility curve was labelled with the number of samples from the Monte Carlo simulation results that were available to define the fragility curve.

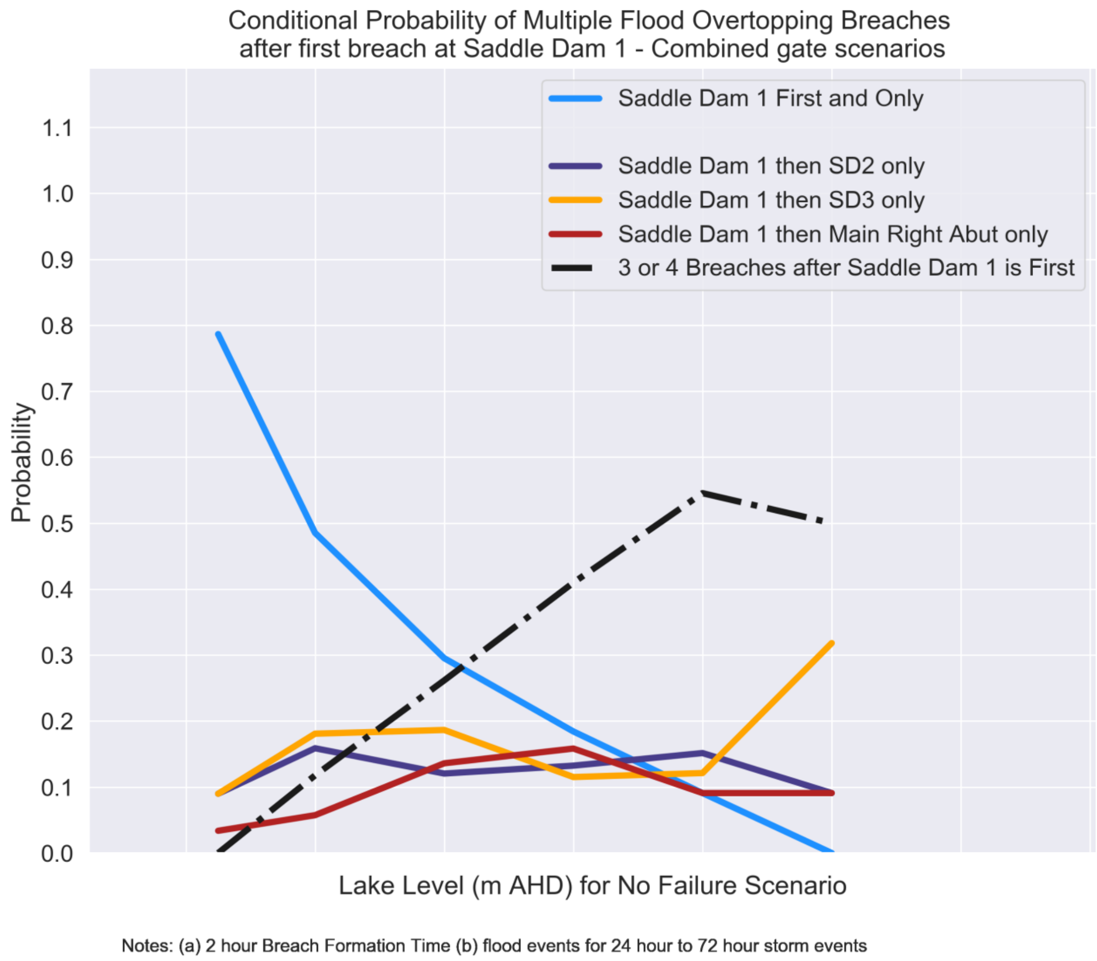


Figure 8: Example of conditional fragility curve of subsequent flood overtopping breaches after Saddle Dam 1 Abutment breach

Conclusion

A Monte Carlo modelling approach of the causal steps leading to failure from flood overtopping at earth-fill embankments can provide improvements over traditional dam breach modelling that simply applies subjective assumptions that a breach forms at a defined lake level or defined depth of overtopping. With modelling probabilistic (or stochastic) representation of the causal steps leading to a breach, together with the lake level response to breach and other outflows, the potential for multiple breaches can be simulated in a way that does not always assume the lowest or most vulnerable embankment is the first and only breach. Repeat simulations with a large number of flood events can produce a very large dataset of probabilistic dam breach scenarios that may provide sufficient data to inform conditional probability for use in risk event trees.

This paper has outlined a method to generate data to inform risk event tree probabilities for multiple breaches and potential sequence of further breaches. There are a number of uncertainties with any dam breach, but through use of parametric prediction, engineering judgement and stochastic methods, this paper has outlined an objective approach to consider possibility of multiple breaches in risk assessment.

In the case study for which the method was applied the modelling demonstrated that the breach development at saddle dams may not be fast enough to prevent a subsequent breach from occurring due to likelihood of sustained overtopping at other embankments. **Figure 8** shows at high lake levels, multiple breaches become the most likely outcome. The potential for multiple breach and possible sequenced breaching of dam embankments was considered sufficiently important to be represented in the risk assessment.

A large number of flood events are recommended to provide adequate and undiluted variation in overtopping flow. The simulation method with adequate number of flood simulation can objectively demonstrate the inferred expectation that higher depths of overtopping for short duration may not lead to breach and conversely lower depths of overtopping with long duration can be more critical for embankment breach.

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