A NEW WAY OF EXAMINING EMERGENCY RESPONSE TIME AND THE BENEFITS GAINED FROM MANAGEMENT MEASURES

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1. Abstract

Flooding on the Hawkesbury Nepean river system represents one of the largest evacuation challenges in Australia. The evolution that is occurring in flood estimation is providing new tools that allow us to better understand the variability of real floods and how to robustly plan large scale evacuations. The Monte Carlo approach allows design flood estimation inputs to be characterised probabilistically or using an ensemble instead of a single input. While these changes are being used to better estimate design flood levels they have significant benefit in understanding real flood behaviour by producing thousands of plausible synthetic events. The spatial and temporal variability in rainfall and the timing difference between the key tributaries is modelled. This approach allows impact of management measures to be assessed for all the variability seen in observed events and to properly understand what a mitigation strategy does to average and individual events. Emergency managers can use these events for evacuation planning and training. The true benefit from evacuation upgrades can also be assessed instead of assuming that a single design event is representative of real events.

For each scenario the equivalent of a 200,000 year flood record with 10,000 events of greater than a 20 year ARI rainfall is developed rather than the standard design events and run through hydrologic and hydraulic models. The following information was extracted and analysed from the model results to inform emergency management planning:

- Probability distribution of the time of inundation of key infrastructure or time to reach a key evacuation trigger height
- the change in number of times a trigger height is reached
- Variation in rate of rise and recession with event size

The method allows for a more detailed examination of flood damages and for agent based evacuation models to properly account for the variability in floods.

2. Introduction

The NSW state Government has commenced a detailed review of flood management for the Hawkesbury Nepean Valley. This review will consider a range of factors including the flood impacts of dam operations, impacts on evacuation and floodplain management options across the wider floodplain. A key input into this review is to update the flood modelling that has provided the basis for the assessment of flood management options considered in the past.

In the 1990's, a detailed flood study assessment of the Hawkesbury/Nepean system was undertaken as part of an overall Environmental Impact Statement (EIS) for the Warragamba Dam Flood Protection Program (Webb Mckeown and Associates, 1994). The study included the establishment and calibration of a comprehensive model of flood behaviour. A combination of hydrologic (RORB) and hydraulic (RUBICON) modelling was undertaken.

A key aim of the first stage was to update the design flood methods used in the 1996 flood study to more current and reliable techniques, so that broad scale flood management measures can be assessed. This work feeds into related projects that are assessing the economic and social effects of flooding and the most appropriate management measures to pursue in detail. An earlier stage of the project focused on updating the design rainfall data and flood frequency analysis with new information and techniques. The key aim of the current stage was to create a Monte Carlo framework to allow a more robust assessment of the short term operational changes proposed for Warragamba Dam.

3. Modelling Approach

In Stage 1 a traditional flood modelling design approach was adopted with a traditional hydrologic model and hydraulic model. The key purpose of the Stage 2 was to develop a more detailed modelling approach to better define the flood behaviour in the Hawkesbury Nepean Valley as a result of changes to the operation of Warragamba Dam.

To achieve this key purpose a modelling framework (refer to Figure 1) was developed that allowed the wide range of variability experienced in key inputs in a flood event to be incorporated. This includes rainfall patterns (spatial and temporally), timing of tributaries, dam storage levels preceding the event, and losses. Monte Carlo approaches allow for the observed variability in key inputs to be accounted for and attempts to mimic reality by randomly sampling from a range of possible inputs (for more detail refer to Nathan and Weinmann, 2013). When more than 2 variables need to be considered in a modelling analysis Monte Carlo modelling is generally the only practical approach.

This study considered variability in the following key design flood inputs:

- Rainfall frequency,
- Spatial Pattern of rainfall,
- Temporal Pattern of rainfall,
- Initial Loss,
- Pre burst rainfall,
- Dam drawdown and
- Relative timings of tributary inflows.

Outputs from the Monte Carlo modelling were then inputs to the traditional hydrologic model used in Stage 1. However instead of results for a handful of design events (eg. 10 year ARI and 100 year ARI) 2 sets of 10,000 hydrographs are produced. This was equal to 10,000 years of flood record and 200,000 years of events rarer than 20 year ARI.

The hydrographs are then routed through dam operations software. The dam operations assessed in this study are:

- Drawdown,
- Gate operations, and
- Pre-release strategies.

The dam outflow hydrographs along with inflow hydrographs at key locations are then applied to the hydraulic model. This produces 20,000 flood levels throughout the catchment. Figure 1 depicts the Stage 2 study approach.

The Monte Carlo approach allows:

- the behaviour of the dam under a range of flood conditions to be assessed,
- allows the rate of rise and timing for different evacuation triggers to be reached to be assessed for a range of flood conditions and
- allows flood damages to be produced using more data points.

Most of all it produces a range of inflow hydrographs that includes some plausible events that challenge any operation strategy including: double peaked inflows, very fast rising events and events with significant early downstream rainfall that has a very short evacuation window.

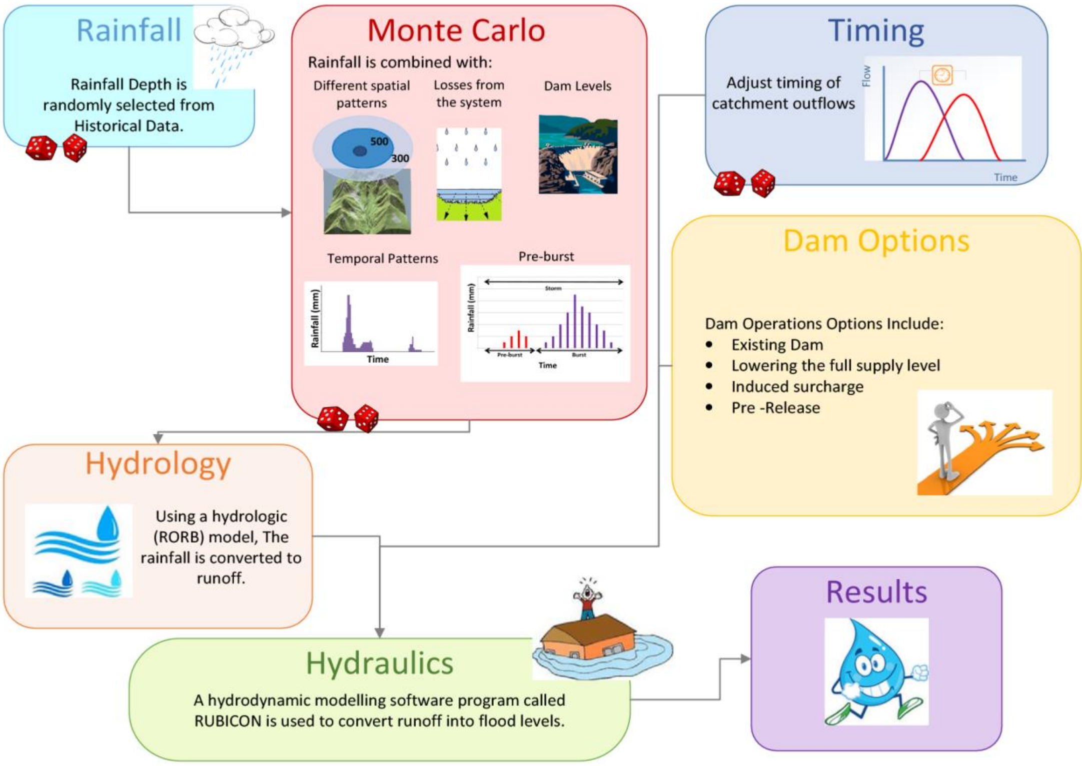

Figure 1: Modelling Framework

4. Monte Carlo analysis

4.1 Overview

Stage 1 of the Hawkesbury Nepean Flood Study (WMAwater, 2013) used a traditional flood modelling approach where a single design event is assumed to be representative of design flood behaviour. Real flood events exhibit an enormous degree of variability, most of which is determined by exactly when and where rainfall falls. Flood events are also influenced by how wet the catchment is and in the case of the Hawkesbury Nepean the flood levels in the dam. To overcome this limitation design flood estimation in Australia is moving from a single event per quantile (such as the 1% AEP) to Monte Carlo modelling where 1000's of events need to be run. In stage 2 of the Hawkesbury Nepean Flood Study, the variability in each of these key input variables has been estimated from observed events.

While most flood estimation is moving to Monte Carlo, dams are a particular case where it is important to test the observed variability in flood behaviour. Dam operations are designed to maximise flood mitigation but this optimisation needs to be developed and tested on a wide range of plausible events. Such a process ensures that the adopted operational strategy is robust.

This allows decision makers to make informed decisions on operational strategies and evacuation strategies. It is particularly good at identifying weaknesses in operational strategies. It is not uncommon for a proposed strategy to perform well against most events and have weaknesses against certain styles of events. Often a slight modification to a strategy will only slightly reduce the benefit at the same time reducing the adverse consequences for a small range of events. A good example of this is a multi-peaked event and events where normal dam operations cause outflows to coincide with other tributaries.

4.2 Inputs

The following sections describe how the inputs to the Monte Carlo analysis were determined. This study considered variability in the following key design flood inputs:

- Rainfall frequency,
- Spatial Pattern of rainfall,
- Temporal Pattern of rainfall,
- Initial Loss,
- Pre burst rainfall,
- Dam drawdown and
- Relative timings of tributary inflows.

Catchment average rainfall was used as the rainfall rather than the BoM 2013 IFD (which is only available at discrete quantiles). By using catchment average rainfall as a primary input it allows how rainfall falls spatially and temporally on the catchment to be defined separately. For each burst duration and rainfall events that was generated a random rainfall AEP was assigned.

The design temporal patterns were based on the BoM extreme storm database (Meighen and Kennedy, 1995). The number of temporal patterns available is dependent of the storm duration. For the 3 day duration 17 temporal patterns were available. Figure 2 depicts the 3 day temporal patterns as cumulative mass curves. Temporal patterns were selected randomly from the available patterns for the duration of interest. This means that the patterns are chosen multiple times. However, this approach is considered superior to the design event approach where only one temporal pattern is chosen.

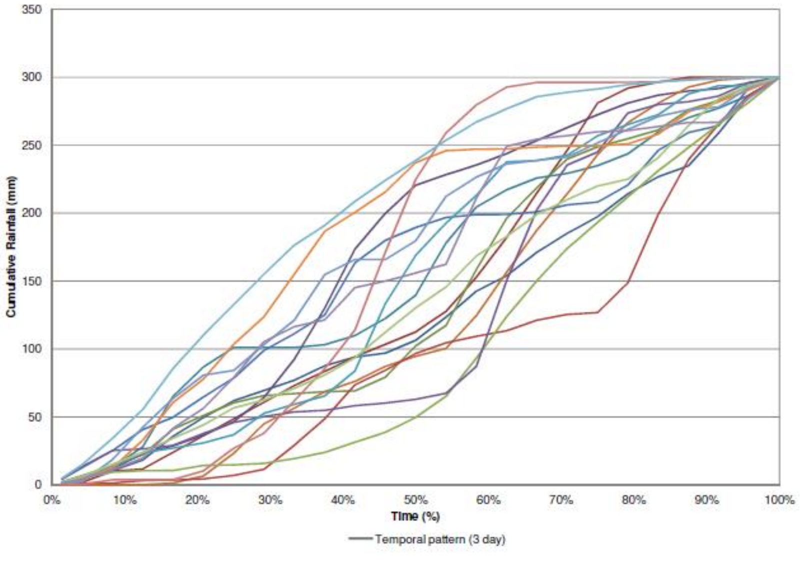

Figure 2: Temporal Pattern Distribution

A database of 125 observed spatial patterns of rainfall across the catchment was generated as part of the catchment average rainfall analysis. Figure 3 depicts the variation, for all 125 patterns, in the subarea rainfall to the entire catchment rainfall across the 4 major sub catchments. An example spatial pattern is plotted, which shows the majority of the rainfall falling on the Nepean Catchment. For each event a spatial pattern was selected from the closest 20 ranked patterns by catchment average depths. The ranked approach adopted minuses the scaling of frequent event patterns.

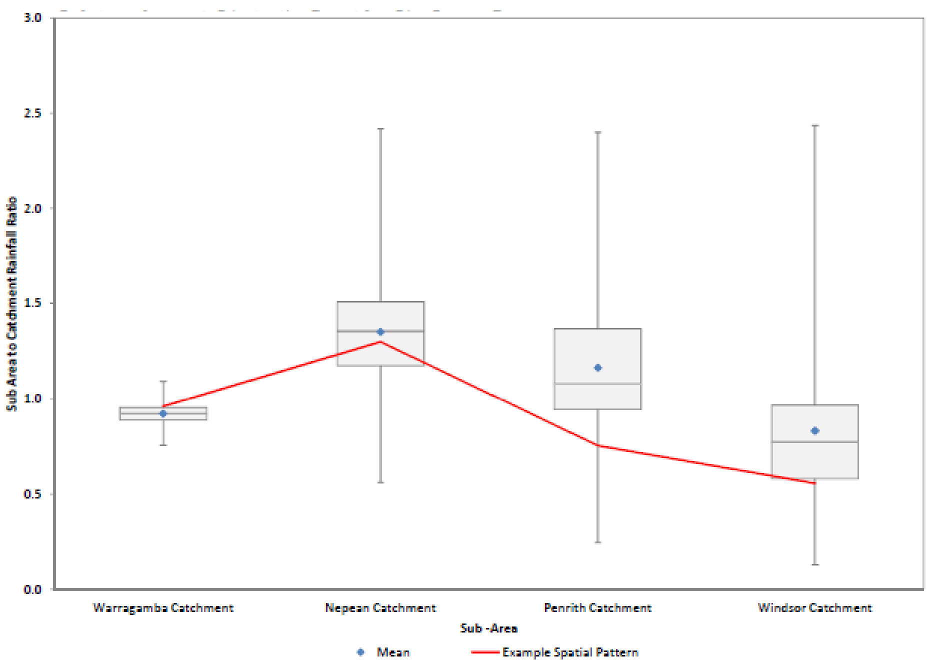

Figure 3: Spatial Pattern Distribution

A standardised initial loss curve was developed which ranged from 4.5 to 98 mm based on the methodology of Hill et al (2014). No correlation was enforced between the loss value and the dam level. This means that if the dam level was low (possibly during a drought) then it is likely that the soil would have low moisture content and that the losses to the soil would be high. Conversely when the dam level is high it is likely to be a wet period and the soil may be saturated meaning there would be low losses. However, the model is not constrained by this and therefore it is possible to have a high initial loss when the dam is full.

Continuing loss was used as a calibration parameter. While it is possible to also vary other inputs such as ocean levels the above inputs were selected for this study.

The design event approach uses a peak rainfall burst with no accounting for rainfall that occurs prior to the most intense burst of the storm (pre burst rainfall) starting rather than a complete storm. For this study a burst approach was used where pre burst rainfall was added to the start of the event. This allows dam operation scenarios such as pre-release to be fairly assessed. The distribution of possible pre burst rainfall was determined by calculating the ratio of the pre burst rainfall and each 3 day rainfall burst using the spatial catchment rainfall analysis.

The coincidence timing of tributary inflows can exacerbate flooding. This is of particular importance when designing a dam operation strategy to ensure that the timing of dam outflows and rain falling downstream of the dam don’t coincide. It is also of importance in evacuation planning.

The timing of tributary inflows were calculated for the following catchments compared to the Warragamba River timing:

- Nepean River
- Grose River
- Colo River

The timing of the tributaries is important for evacuation planning particularly in the Richmond/Windsor area where interactions of local flows can significantly reduce evacuation timings. Catchment average rainfall for 3 day storm events were calculated for the catchments listed above. A total of 125 observed events were used. The time at which 50% of the rainfall mass occurs was calculated. For each catchment the difference between the time of the 50% of the rainfall mass and the time for it to occur on the Warragamba Catchment was calculated. Figure 4 depicts the calculated timing differences.

This could be extended to include the timing of the catchments upstream of Warragamba Dam (Wollondilly, Cox/Kowmung system and the direct catchment area of the Dam).

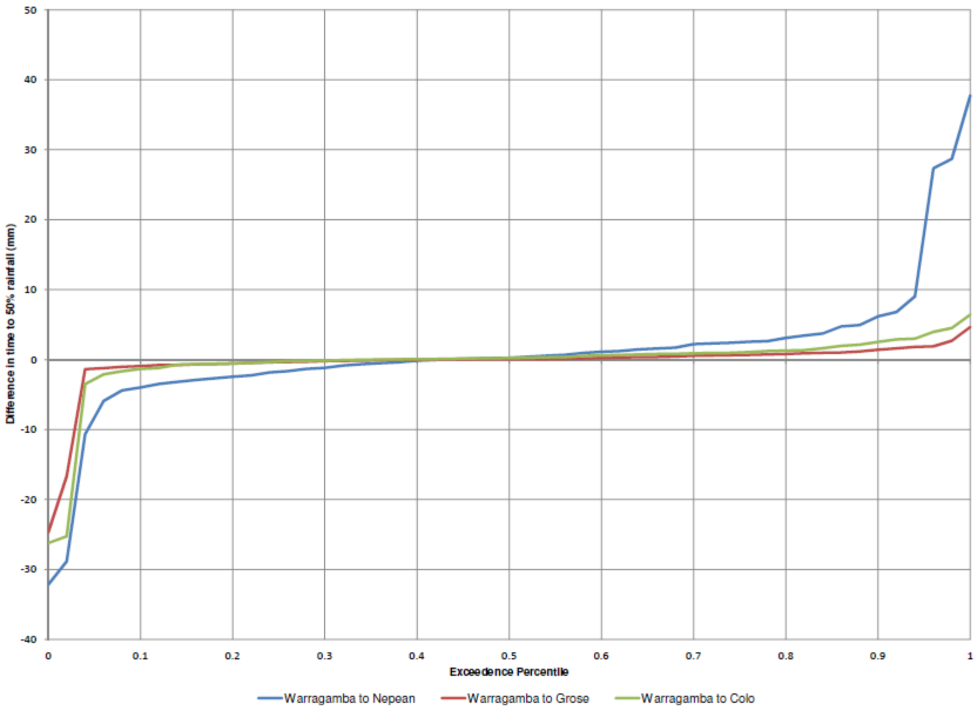

Figure 4: Timing Distribution

4.3 Sampling Strategy

A sampling strategy (method to combine the sets of 10,000 events) needs to be selected to properly explore events where:

- operational strategies are likely to have a significant effect on flood behaviour,
- key evacuation timing becomes crucial, and
- major flood plain damages occur.

For these reasons a strategy was adopted that focuses on the critical 20 year to 500 year ARI range, as while smaller floods cause significant community disruption they do not pose a significant threat to life or property.

Two sets of 10,000 events were run, one which contained 10,000 randomly selected events between a no flood event and the PMF (which is equal to a 10,000 year historical sample) and one which contains 10,000 events greater than a 20 year ARI (which represents a 200,000 year historical sample of events of >20 year rainfall). The two sets were merged on the basis of the underlying rainfall probabilities where a sample with the equivalent length of 200,000 years was produced by combining 10,000 above 20 year ARI rainfall and 9500 events from the crude sampling case below 20 year ARI rainfall. This process essentially assumes over a 200,000 year period each of the events above 20 year ARI rainfall is unique and each of the more frequent events occurs 20 times. This results in 90% of the greater than 20 year ARI sample being between the 20 year and 2000 year ARI which is critical for dam operations in the Hawkesbury Nepean.

5. Hydrologic model

The hydrologic RORB model established as part of the 1996 study was modified so that it could run in a Monte Carlo environment. The randomly selected rainfall, spatial patterns, temporal patterns, preburst and losses were applied to the hydrologic model to determine flows for the design events.

6. Hydraulic model

As part of the 1996 Studies a detailed one dimensional (1D) hydraulic model (RUBICON) was developed. The model covered the area Warragamba Dam to the Ocean and upstream on the Nepean to Bents Basin (200 km of river, Figure 5). The RUBICON hydrodynamic model software was used to quantify the hydraulic aspects of the flood behaviour (e.g. flood levels and velocities).

Two dimensional models are becoming the tool of choice for flood modelling in Australia. However, due to the size of the catchment and the nature of the flood problem it is only just becoming practical to model the floodplain using a two dimensional (2D) model. In order to accurately represent the channel cross section in a 2D fixed grid model 5 grid cells are required. As the channel can be quite narrow in parts a smaller grid cell would be required. This would increase model run times. The channel could be modelled in 1D with a 2D overbank. Due to the duration of historic flood events run times would be over a week which inhibits the calibration process. The use of a flexible mesh 2D model is likely to result in runs 4 times longer with some models having limited ability to model structures. Given current computer processing power a conventional 2D model of the Hawkesbury River would be either too slow to run practically or too coarse to model the conveyance of the channel accurately. For this study it was decided that a fast 1D hydraulic model that could be run for all 10,000 events within a practical timeframe would be adopted (a 7 day event runs in 5 seconds).

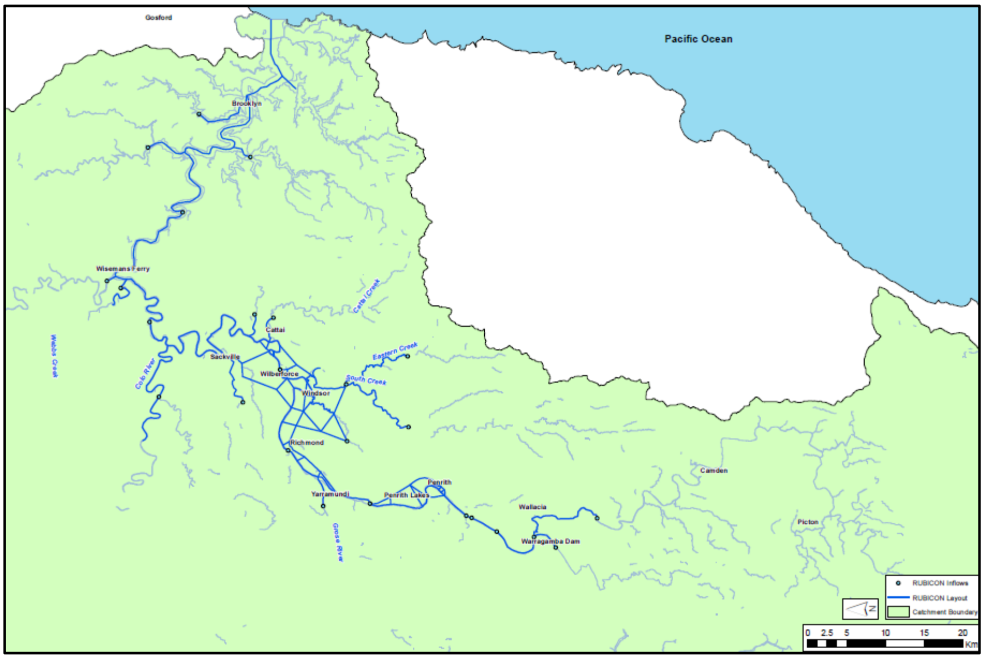

Figure 5: Hydraulic Model (RUBICON) layout

7. Flood extent mapping

Flood DEM mapping capabilities were developed as part of the EIS work. This mapping was revised and developed into software for the NSW SES as part of a flood prediction project. The development of the Digital Elevation Model (DEM) included careful consideration of break lines, overflow paths and backwater areas of the Hawkesbury Nepean floodplain. This software allows flood surfaces to be readily developed from RUBICON results. The flood mapping core software has been modified for use on other catchments (such as the Hunter River) and with other hydraulic models such as MIKE-11.

The mapping software was extended to use Monte Carlo sampled results at all 350 calculation points. For each option the combined equivalent 200,000 year sample was ranked and sampled at every calculation for a range of design quantiles (10% AEP and 1% AEP).

Using the ALS the flood extents, heights and depths were spatially mapped at variable resolutions.

8. Emergency Management Outputs

An important measure of the effectiveness of any mitigation measure on the Hawkesbury Nepean Valley is the impact on warning time and evacuations.

The Hawkesbury Nepean Flood Emergency Sub Plan (NSW SES, 2013) lists key triggers for warnings and evacuations within the catchment. For each of the 20,000 Monte Carlo events the time at which the trigger is reached was recorded. This was then ranked and plotted as probability vs time. Figure 6 depicts the probability vs time to reach the trigger. The start of the event is the start of the 3 day rainfall event that starts the flood. The probability on the x axis is the probability of the timing occurring not the probability of the flood event itself.

Figure 7 shows the ranked time to reach trigger data plotted against event probability for the existing conditions. Figure 7 clearly shows that an event of a certain water level probability can have a range of timings and that the magnitude of the event is a relatively crude indicator of timing. Some of the worst timings occur in the events in the order of 100-200yrs. The range of times to reach 13.5mAHD at McGraths Hill ranges from 20 to 65 hours after the event starts for the 1% AEP. One event of approximately 1 in 5000 AEP takes only 16hrs to reach 13.4mAHD at McGraths Hill. This allows the ability of an option to reduce the need to evacuate to be calculated.

The time of inundation of the key evacuation bridges and routes can also be analysed (Yarramundi 5 mAHD are shown on Figure 8. Similarly rate of rise and recession were extracted for each event (Figure 9 and Figure 10 respectively). Rates of rise up to 0.8m/hr occur. Rate of recession exhibits less variability than rate of rise as expected. These can be binned by AEP and box plots of the rate of rise produced (Figure 11) as well as the probability of a rate of rise occurring (Figure 12).

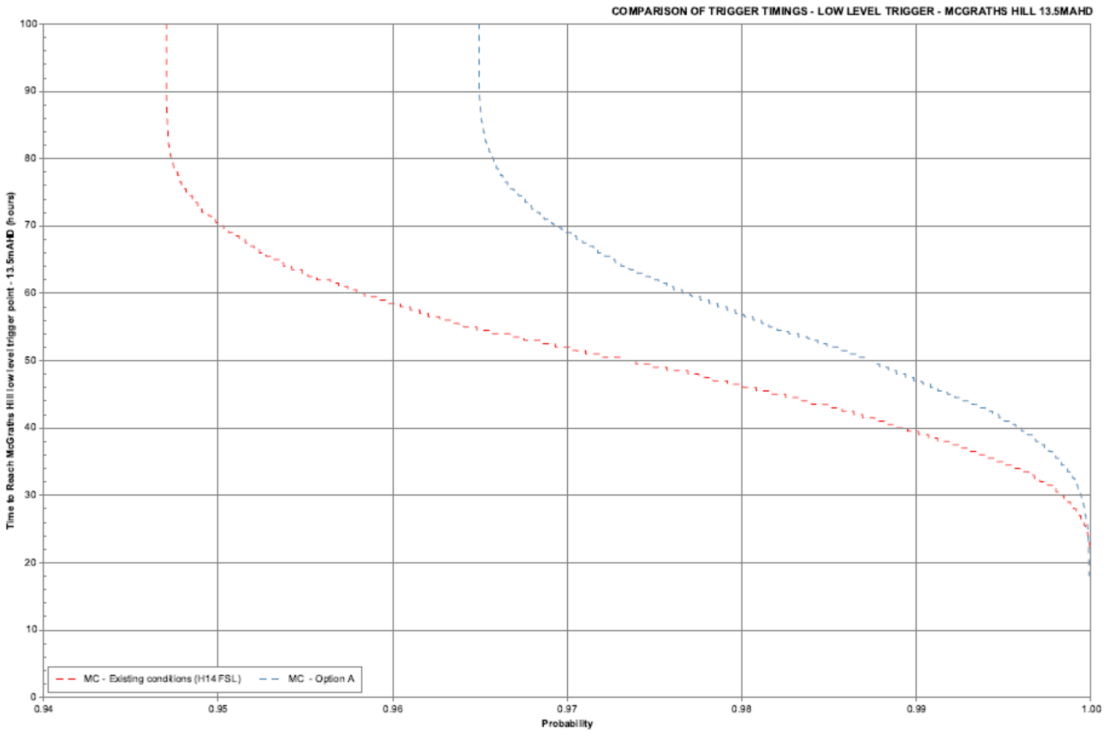

Figure 6: Time to reach a trigger vs probability

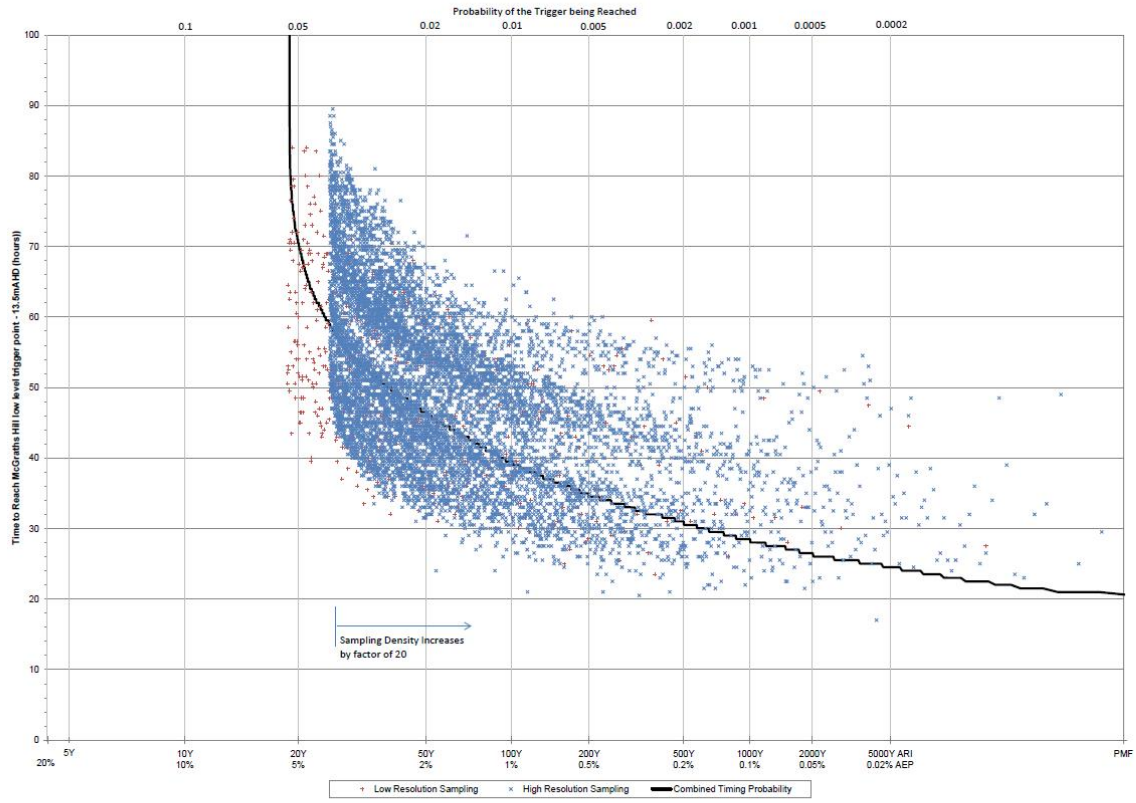

Figure 7: Time to Reach Trigger vs Event Probability - Existing conditions

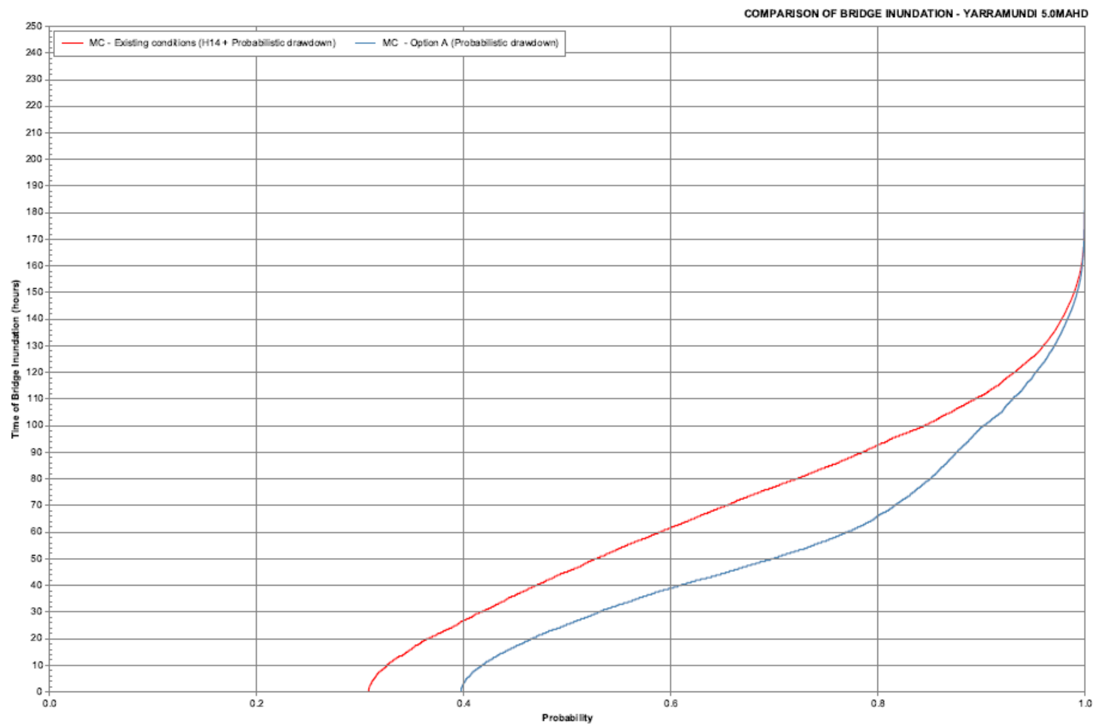

Figure 8: Time of Inundation - Yarramundi Bridge

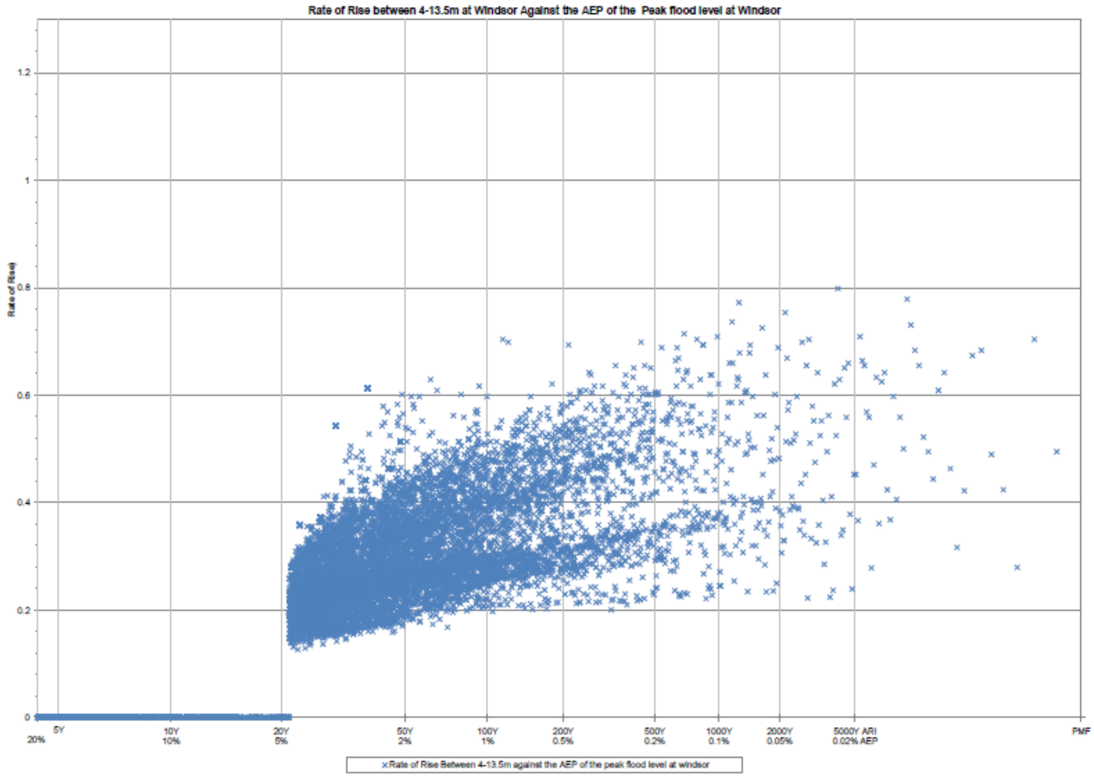

Figure 9: Rate of Rise vs AEP

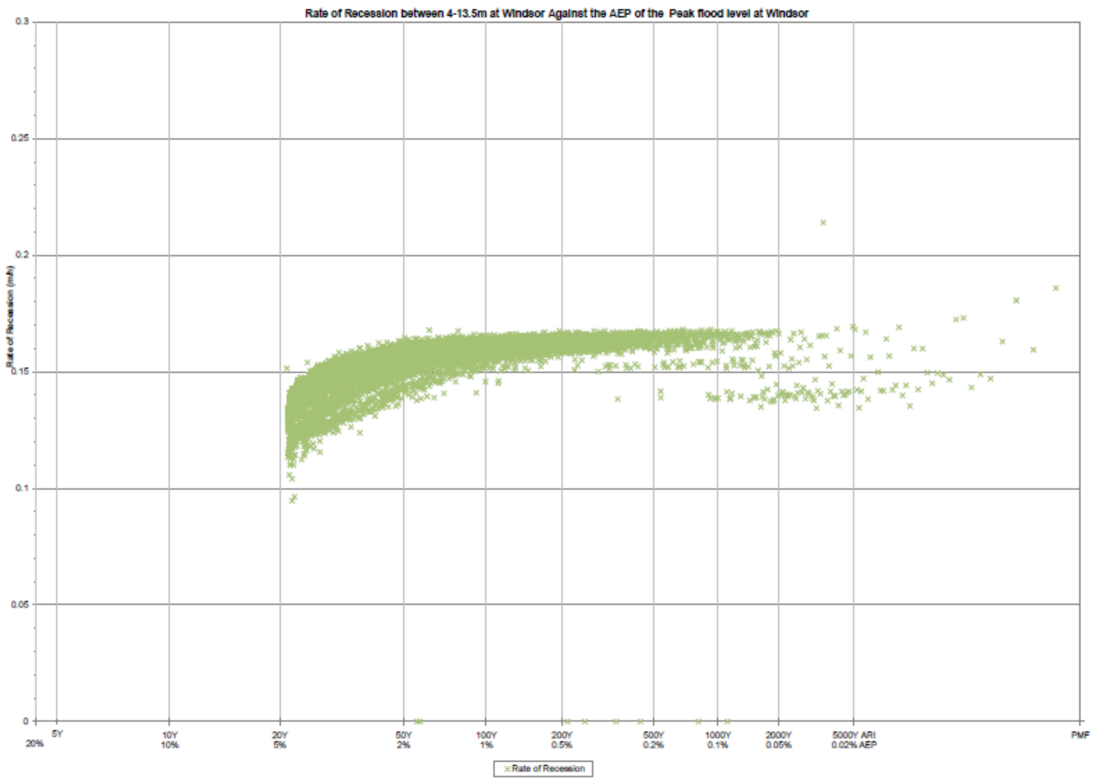

Figure 10: Rate of Recession vs AEP

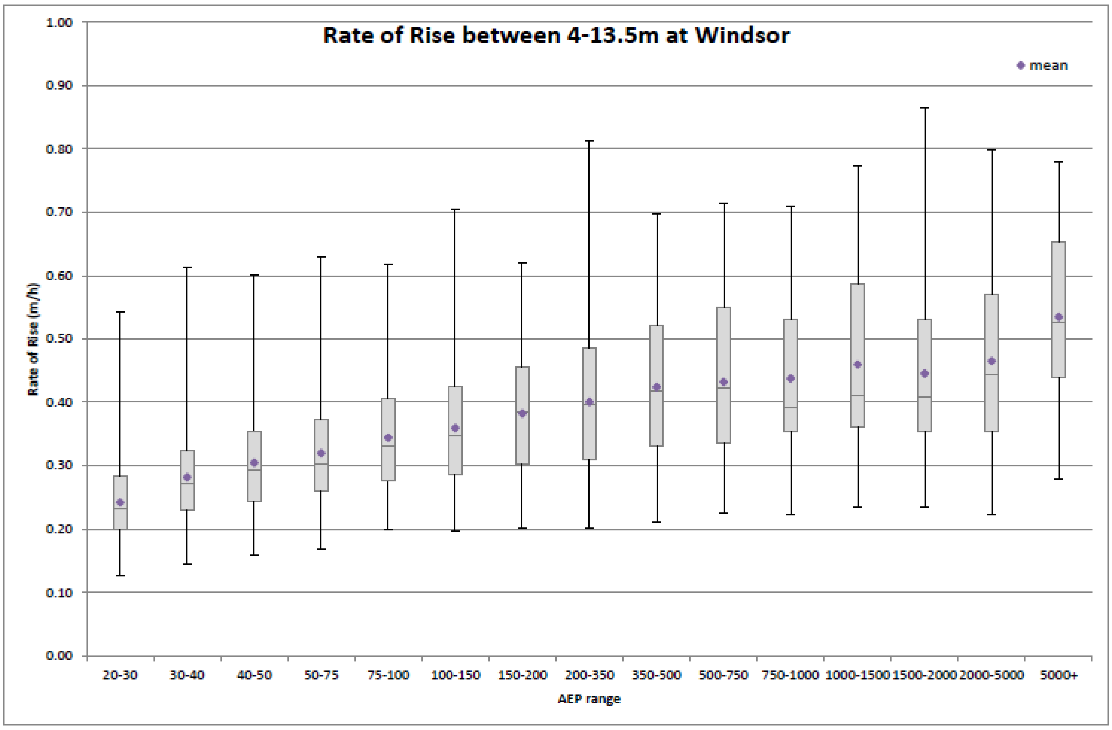

Figure 11: Box Plot Rate of Rise

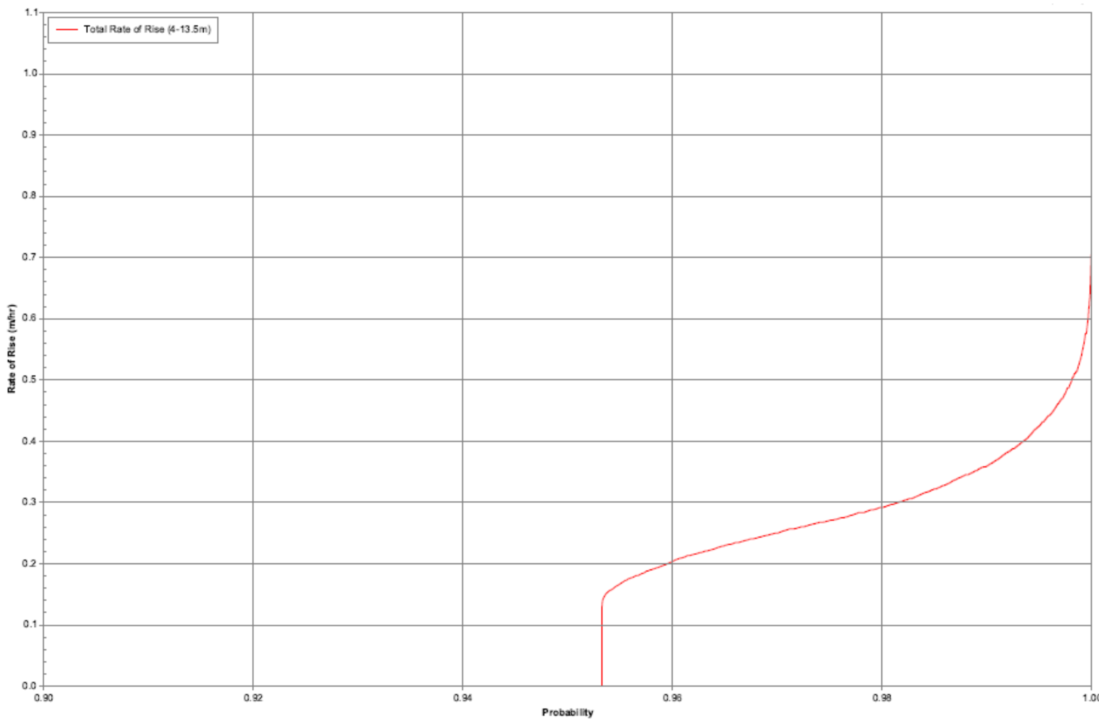

Figure 12: Probability of Rate of Rise

9. Flood Damages

Average Annual Damages is the area under the damage probability curve. It is simplified by working out the area using Simpsons rule. With Monte Carlo modelling it is possible to calculate damages for every single event and more accurately determine AAD. Figure 13 shows and example damages curve. Not the estimate between the 1 in 5000 AEP and PMF if the Monte Carlo approach is used rather than the design event approach. For this assessment a common starting level was used for the damages rather than a fixed probability to more accurately reflect AAD and avoid boundary effects.

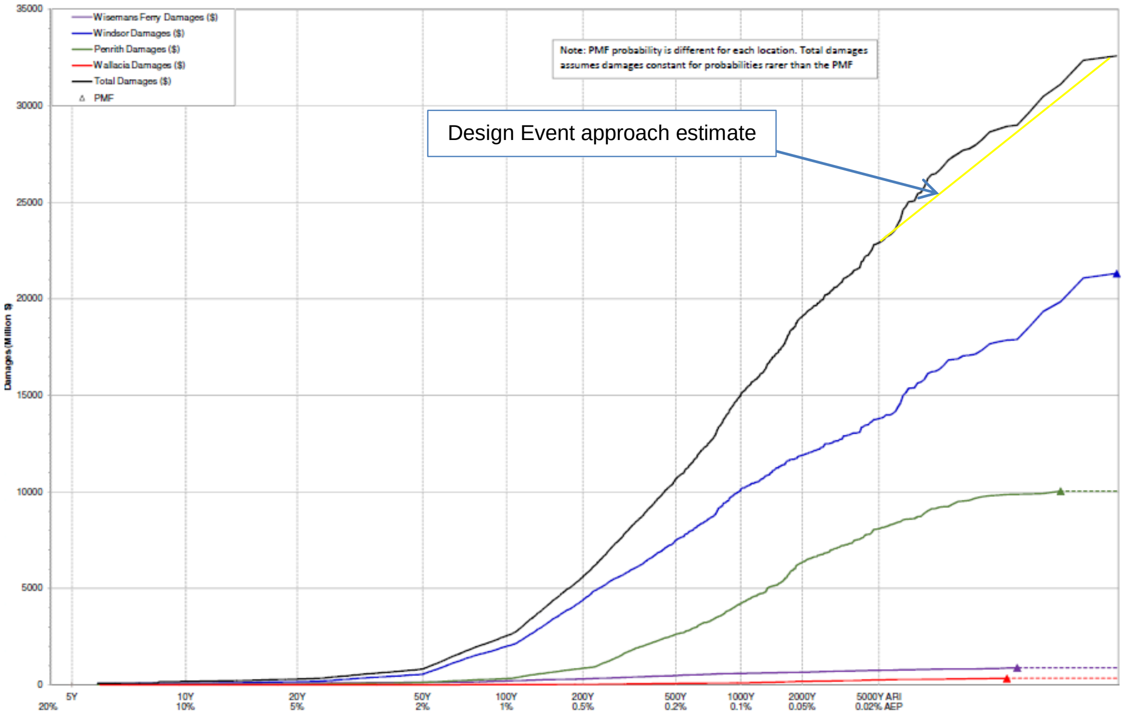

Figure 13: Damages

10. Evacuation Modelling

The outputs of the Monte Carlo modelling can be used in an agent based evacuation model to look probabilistically at the evacuation.

11. Conclusions

Design flood estimation practice is moving towards Monte Carlo modelling to improved flood estimates. Additional benefits from a Monte Carlo modelling framework include the assessment of different operation strategies, stress tests operations, allowing Emergency Managers to better plan for events and assisting in describing event variability to the community.

12. Acknowledgments

This project was funded by Sydney Catchment Authority. The Monte Carlo framework used in this study builds upon that developed by Melanie Loveridge as part of the PhD with Dr Ataur Rahman at University of Western Sydney.

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