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Brisbane River Catchment Flood Study Monte Carlo Hydraulic Analysis

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The Brisbane River catchment is large (~15,000 km^2), of which roughly half flows into Wivenhoe Dam. Rainfall across the catchment is temporally and spatially highly variable and antecedent conditions and initial dam levels significantly vary year-to-year. The influence of Wivenhoe Dam and the joint probability complexities of flows from Lockyer Creek and Bremer River rule out conventional approaches for deriving AEP flood events. To capture this variability a calibrated 1D hydraulic flood model was used to simulate 11,340 Monte Carlo flood events from downstream of Wivenhoe Dam through to Brisbane to derive AEP flood levels. An innovative process was developed to extract a representative set of 60 events grouped into 11 ensembles for the 11 AEPs from the 1 in 2 to 1 in 100,000.

1. INTRODUCTION

Completed in February 2017, the Brisbane River Catchment Flood Study (BRCFS) (BMT WBM, 2017) (Aurecon, 2015) assessed the flood behaviour of the Brisbane River below Wivenhoe Dam, including the lower sections of major tributaries Lockyer Creek and the Bremer River (refer Figure 1). The study represents one of the most comprehensive hydrologic and hydraulic modelling assessments undertaken in Australia to date. The BRCFS's major objective: The estimation of probabilistic riverine flood information for eleven Annual Exceedance Probabilities (AEPs), ranging from the 1 in 2 to the 1 in 100,000 AEP. Outputs of the study include flood exceedance statistics, reporting, mapping and digital data to inform the development (currently in progress by BMT WBM) of a comprehensive floodplain management plan. Likewise, the study provides an important flood database for future risk studies.

The Brisbane River catchment has a wide range of complexities that make it interesting and challenging to model both from a hydrologic and hydraulic perspective. Approximately half of the total catchment area drains into Wivenhoe Dam, which located on the Brisbane River has a significant influence on flooding. The catchment downstream of Wivenhoe Dam has three main branches, the main Brisbane River branch, and the tributaries of the Bremer River and Lockyer Creek. Catchment rainfall and antecedent soil conditions in each branch can exhibit high spatial and temporal variability, both of which are particularly important in determining the relative timing of flood flows.

The timing and magnitude of flood peaks in the three major branches strongly influence the peak magnitude of flooding in the urban centres of Ipswich and Brisbane. Major flooding can result from rainfall runoff in one-or-more branches. For example, in the Brisbane CBD, heavy rainfall in the upper

Brisbane catchment (above Wivenhoe Dam) accompanied with little-to-no rainfall in the combined Bremer and Lockyer catchments can cause a similar magnitude flood to an event where heavy rainfall occurs only in the Lockyer Creek or Bremer system. Flood peak magnitude can also be attenuated, mitigated or modulated by initial dam levels and operation, astronomical tide and storm tide levels, although notably during flooding the effect of the latter is confined to the lowermost reaches of the main Brisbane River branch.

These interactions and variations over temporal and spatial scales mean peak flooding cannot be represented using the traditional hydrologic approach. i.e. The application of a uniform temporal pattern of rainfall over the entire catchment. Due to these interactions a more comprehensive probabilistic approach for both hydrologic and hydraulic phases was required.

2. MODELLING FRAMEWORK

Monte Carlo Simulation (MCS) is a method for calculating probabilities in the field of numerical computing. Using MCS, the modeller can explicitly consider the natural variability of relevant physical processes that contribute to flood events. This allowed MCS to represent the complexity of the Brisbane River catchment through varying factors such as spatial and temporal rainfall; antecedent (wet to dry) catchment conditions; initial reservoir levels; dam operations; and storm surge and tidal conditions. The main challenge in the MCS approach is to generate realistic and representative potential flood events by considering the joint probabilities of the input variables contributing to flood flows. Practical disadvantages of the method are increased complexity of implementation, and that it requires longer or more simulation time. The generated events, of which can be tens of thousands, need to be simulated within a model both capable of representing the relevant physical processes, and efficient to allow the simulation of many events.

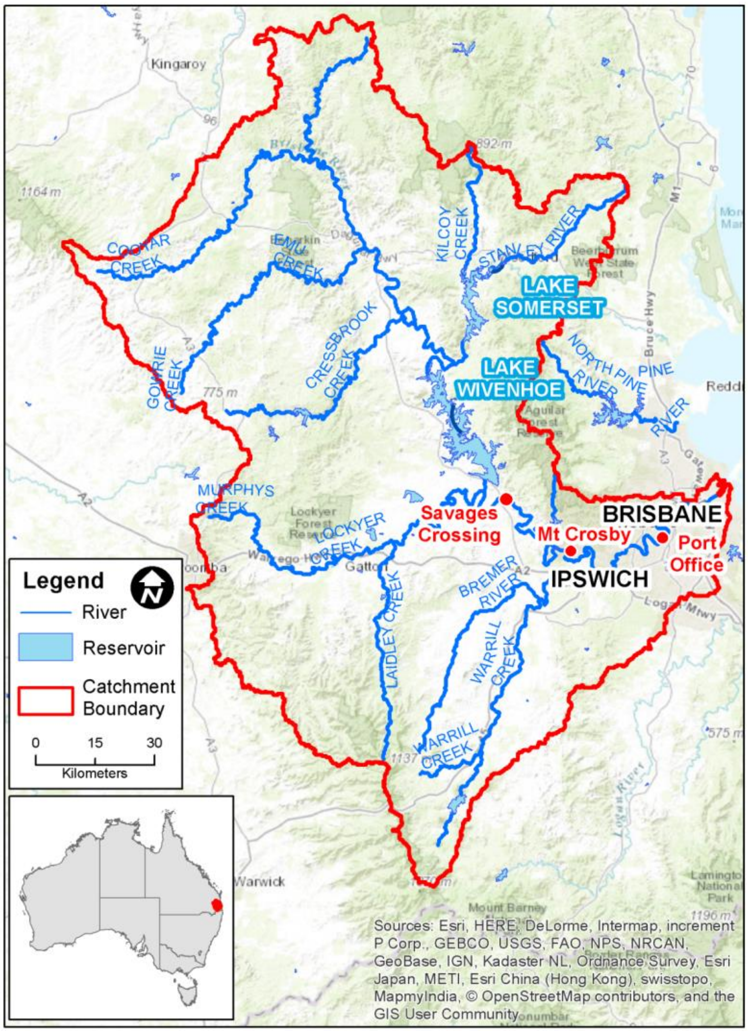

Figure 1 Study catchment area (source Nathan et. al., 2016)

2.1. Hydrologic Assessment

The BRCFS Hydrologic Assessment (Aurecon 2015) developed and applied consistent and robust hydrologic models using the rainfall-runoff-routing software URBS. The hydrologic MCS applied probability distributions to generate thousands of years of synthetic flood records. These events varied downstream tailwater levels, catchment infiltration losses, spatial and temporal rainfall; as well as emulating the operation of Wivenhoe Dam. Flow and volume exceedance statistics were calculated for the key sites downstream from Wivenhoe. The hydrographs and ocean tailwater resulting from 11,340 synthetic events from this analysis provided the boundary inputs for the subsequent hydraulic assessment.

2.2. Hydraulic Assessment

The BRCFS Hydraulic Assessment (BMT WBM, 2017) combined the strengths of two hydraulic models using the flood modelling software TUFLOW. Namely:

- The *Fast Model:* A one-dimensional only (1D) simplistic model designed for use in a MCS; and
- The *Detailed Model:* A 1D/2D model intended for high resolution, accurate calculation of flood behaviour both in-bank and within the floodplain (BMT WBM 2017).

2.2.1. Fast 1D Only Hydraulic Model

The *Fast Model* comprised over 2,300 channels using the well-established hydraulic modelling approach of combining a network of 1D channels and storage nodes, a process commonplace prior to the advent of 2D flood modelling. Channel hydraulic conveyance properties were based on cross-sections, which were extracted from digital elevation models of the catchment topography and where applicable, river bathymetry. Floodplain storage was extracted from available topography whist in-bank storage was calculated via channel cross sectional information. Main river structures such as bridges and floodplain structures such as underpasses or large culverts through embankments were represented in the model via 1D/2D linking and where applicable 2D only structures.

The *Fast Model* was calibrated and verified to tidal conditions, three minor floods (1996, 1999 and 2013) and two major floods (1974 and 2011). These floods varied substantially in their behaviour and size, and the *Fast Model* satisfactorily reproduced this wide range of events without needing to vary calibration parameters between events (Rodgers et al, 2017).

The Fast Model was designed to simulate a ten-day event within four to five minutes on an Intel i7 Skylake chipset (Ryan et al, 2015).

2.2.2. Detailed 1D/2D Hydraulic Model

The *Detailed Model* was the primary tool for producing required flood maps and 3D surfaces of flood levels, depths, velocities and hydraulic hazard for floods of varying AEP. The *Detailed Model* primarily uses the 2D form of the free-surface fluid flow equations, which are significantly more accurate in reproducing complex flow effects as occurs in the Brisbane River catchment than the 1D form. Although more accurate, these equations are numerous and the 2D solution takes significantly longer to compute with run-times of 2-3 days per event; or up to 500 times slower than the *Fast Model*. The development and calibration of the *Detailed Model* is further explored within Rodgers et al (2017).

2.2.3. The Fast and Detailed Modelling System

Although more accurate, the computation run time of the *Detailed Model* rendered it an inappropriate tool to simulate the many thousands of required MCS events. Conversely, while the *Fast Model* could run each event in 4-8 minutes it was unable to provide the required detail to provide high resolution mapping and information required for modern floodplain management. To solve this dilemma, an innovative methodology combining the strengths of the *Fast* and *Detailed Models* was utilised as follows:

- The 11,340 events (boundary conditions sourced from the hydrologic assessment) were simulated through the *Fast Model*.
- Peak water level and flow results were extracted for all events at 28 pre-defined ‘reporting locations’ distributed through the Lower Brisbane River, Bremer River and Lockyer Creek. Reporting locations were located at key gauging stations or sites deemed to represent flood level behaviour within their respective river reach. Extracted results were saved off to form a database available for further statistical analysis.
- Flood level frequency analysis was completed to assign AEPs to flood levels at each reporting location. The primary purpose of these simulations was to inform level frequency analysis focused on peak water levels to include the effects of backwater, hysteresis (rating curve looping) and the tide or storm tide, as the peak flow may not occur at the time of peak level. This process resulted in a series of tables identifying AEP levels for each reporting location.
- A sub-set of 60 *Fast Model* events were selected to be run through the *Detailed Model* to provide water level, depth, velocity and hydraulic hazard information for the 11 required AEPs ranging from the 1 in 2 to 1 in 100,000 AEP.

An overview of this workflow is provided in Figure 2 and each component is explored further hereinafter.

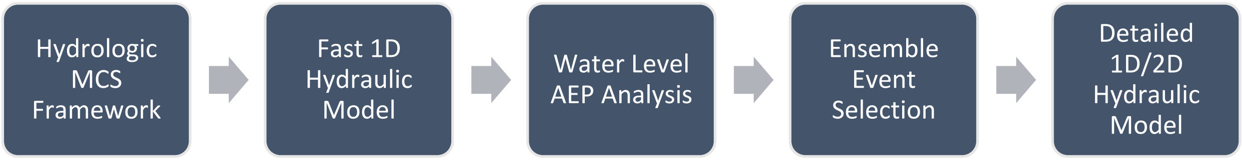

Figure 2 – Monte Carlo and Event Selection Workflow

3. FAST MODEL MONTE CARLO EVENT SIMULATION

Following the *Fast Model's* development and calibration, approximately 1.1 million hydrographs, including outflows from Wivenhoe Dam, were transferred from the hydrologic assessment's MCS to simulate 11,340 synthetic floods through the *Fast Model*. To ensure efficient simulation, events were run by using an automatic batching script to push each simulation to available CPU cores across a network of office computers with varying CPU specifications. Depending on the availability of CPU cores, the process would run all events within a time period of several days to a week.

The peak water levels and peak flows at each reporting location were tracked every computational timestep and written to a file at the completion of each simulation. In addition, time of peak, maximum change in level and flow over one timestep were tracked along with other hydraulic results to validate the model outputs. Fundamental checks such as checking the model mass error was within standard bounds were also carried out.

Peak water level and flow results for each (each event is represented by an individual dot) of the 11,340 events are presented in Figure 3 for David Trumpy Bridge (Bremer River at Ipswich) and Moggill (Brisbane River). Results are colour coded according to the average catchment rainfall AEP where blue is the most frequently occurring events and red the rarest events.

The analysis highlighted the many possible combinations contributing to peak water level and flow curves at each site, providing insight into the reliability of existing gaugings. At locations such as Moggill, where there is little backwater effect or hysteresis looping, a reliable relationship exists between peak level (H) and peak flow (Q). For sites such as David Trumpy Bridge at Ipswich there was greater spread due to the substantial backwater effects of the Brisbane River on the lower Bremer reaches, rendering it an unreliable site for a single QH relationship.

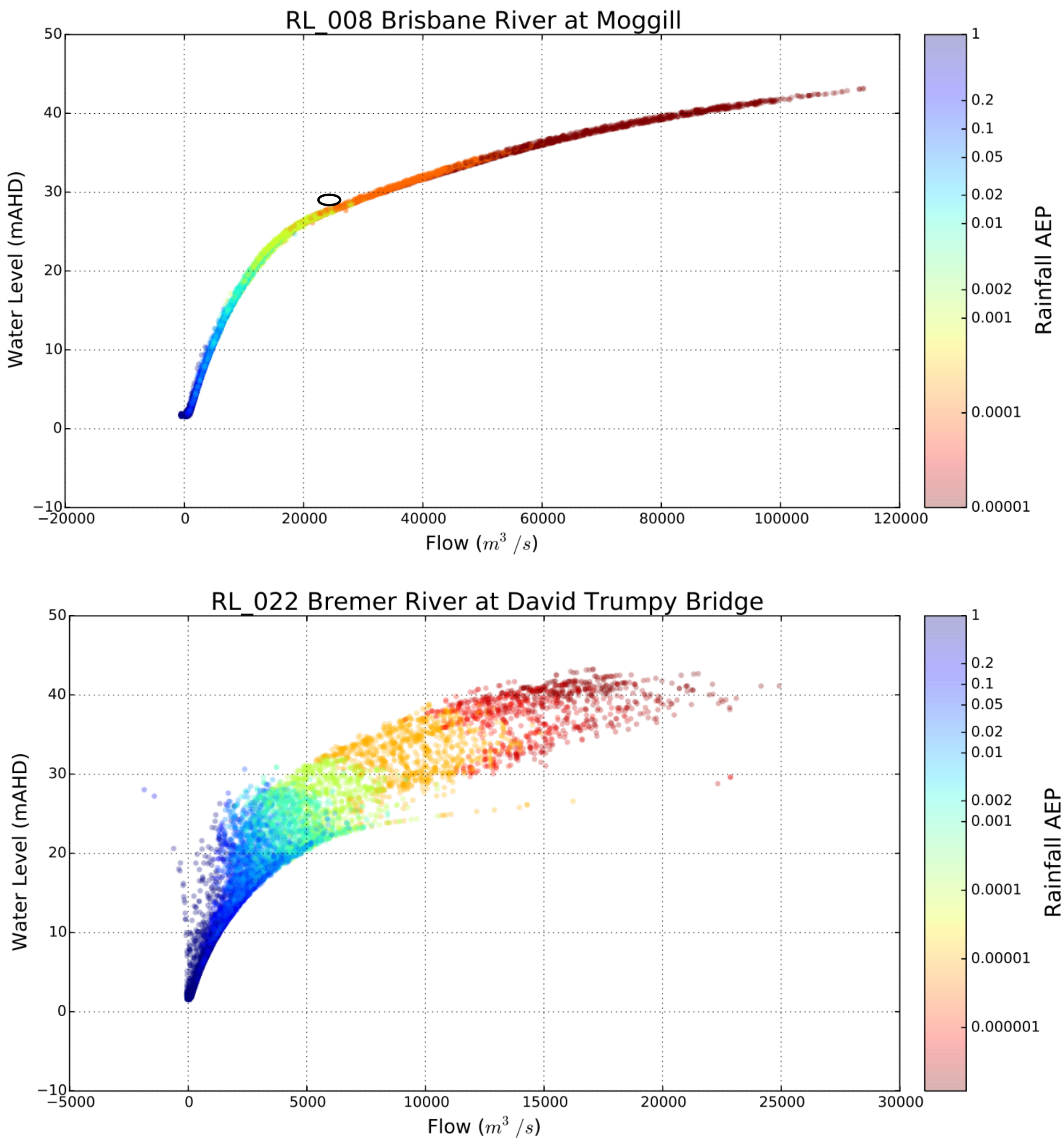

Figure 3 Peak Flow Rate vs. Peak Water Level at Moggill (top) and David Trumpy Bridge/Ipswich (bottom) (Extracts from Plot 5 and 6, Milestone Report 4, BMT WBM 2017)

4. MONTE CARLO AEP ANALYSIS

To derive level frequency relationships (i.e. the relationships between maximum flood level and AEP) the analysis utilised the database of peak water levels and flows generated by the *Fast Model*. The database consisted of 1,260 runs for 28 reporting sites for nine durations (12, 18, 24, 36, 48, 72, 96, 120, 168 hours), which represented the peak levels at 28 reporting locations from a total of 11,340 separate simulations.

The general approach adopted to estimate AEPs of peak flood levels was based on the Total Probability Theorem, first developed for this type of MCS scheme by Nathan and Weinmann (2002), and is described in detail within Nathan and Weinmann (2013). This approach assumes the characteristics of events that are most critical (velocity, hazard etc.) vary with event severity, thus it is necessary to consider the contribution of all flooding mechanisms over the whole probability domain of interest to estimate the magnitude of an event at any specific exceedance probability.

The analysis derived peak AEP levels at each of the 28 reporting locations. A graphical example of these results are shown below in Figure 4 for reporting locations on the Brisbane River. Importantly, it needs to be recognised that a longitudinal flood profile joining the AEP levels (i.e. a vertical section through the curves shown in Figure 4) represents the expected water level probability derived from a total probability analysis of many hundreds of events. Figure 4 also shows there is significant variation in flood level both between reporting locations and when transitioning from frequent to extreme events.

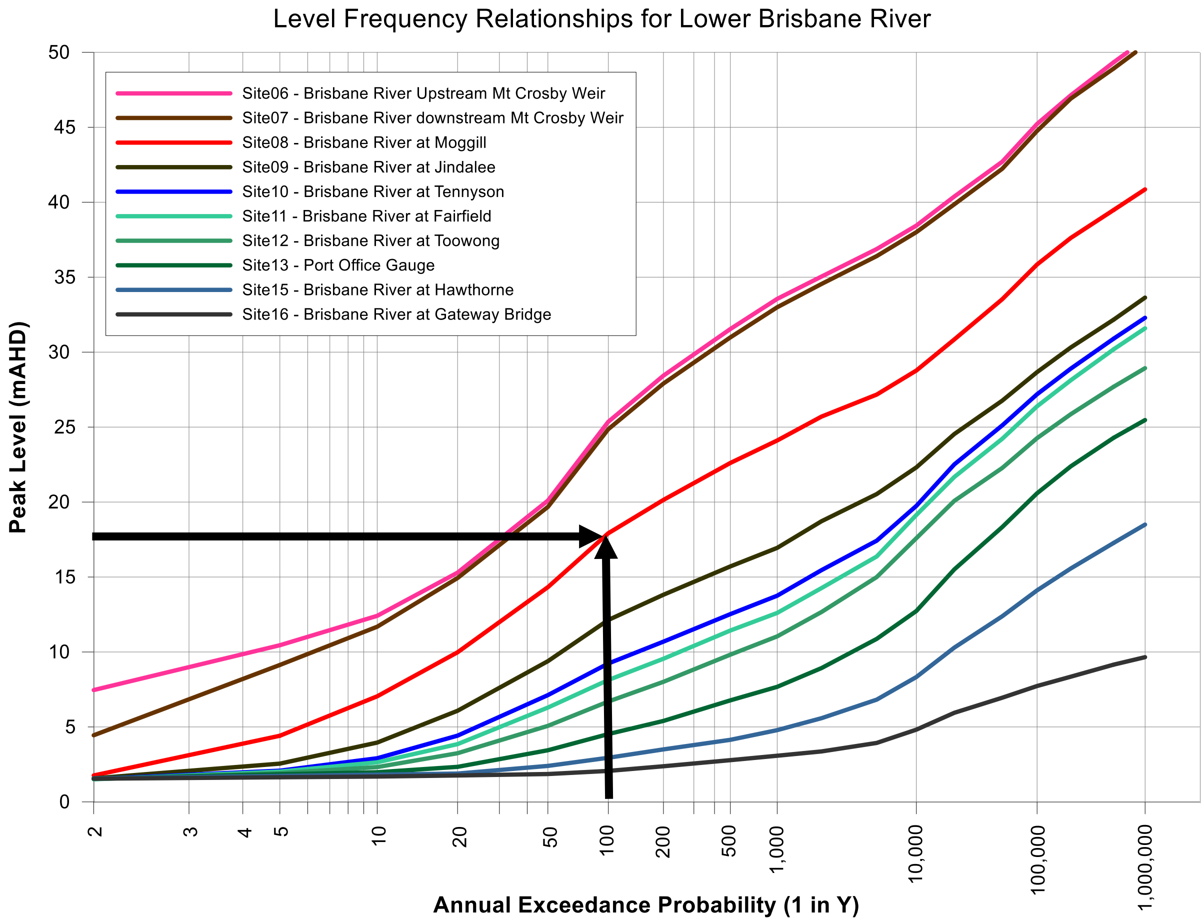

Figure 4 Level Frequency Relationships for Lower Brisbane River (Figure 4-4, Milestone Report 4, BMT WBM 2017)

5. ENSEMBLE EVENT SELECTION

The calculation of water level AEPs from thousands of events had implications when trying to isolate a manageable sub-set for re-simulation within the *Detailed Model*. For example, a peak flood level of 18 mAHD, approximately the 1 in 100 AEP level from the statistical analysis at Moggill (refer Figure 4) could be produced by hundreds of separate Monte Carlo events, as enclosed by the small black circle within Figure 3. If selecting any one of these events there was no guarantee that the same event would provide 1 in 100 AEP levels at any other reporting location. In fact, due to the inherent spatial and temporal variability applied to each Monte Carlo event, it was highly unlikely that any one event could match the 1 in 100 AEP levels at all sites. The same was true of the other AEPs considered.

The solution, an ensemble approach selecting a sub-set of the full Monte Carlo event set that gave similar flood levels to those estimated during the AEP analysis. This process was repeated at each reporting location for each of the eleven AEPs. The objective being the minimisation of the number of events required for re-simulation through the *Detailed Model*.

5.1. Event Selection Methodology

It was agreed through an exhaustive technical review process that for the ensemble of events to be functional, the AEP flood level surface would be calculated as the maximum of the ensemble's flood peaks, sometimes referred to as the maximum of the maximums. That is, the peak flood level at any given point is the highest peak water level of all the AEP ensemble's events. This ensured that there was a smooth transition in peak AEP water level throughout the hydraulic assessment study area. This ensemble approach can be viewed as analogous to the use of several durations to derive the AEP levels throughout a catchment because the critical duration varies within the catchment with short, more intense rainfall durations typically dominating the upper catchment, and longer duration, larger volume events prevailing in the lower areas.

To minimise the required *Detailed Model* runs, rather than trying to select an ensemble of events that perfectly matched derived AEPs at each reporting location, the project adopted the concept of Critical Event Tolerances (CETs). These varied with reporting location and allowed a Monte Carlo event to be selected if it was within a given tolerance of the AEP analysis level. Values for the CETs were agreed with key project stakeholders and ranged from ±0.15 in urban areas where topographic and bathymetric data quality was high to ±0.3-0.5m in rural areas. For each reporting location and AEP a 'critical event' was identified and selected assuming the following criteria:

- Criteria 1: The critical event at a reporting location must peak at or be within an acceptable tolerance of the AEP level, referred to as the Critical Event Tolerance (CET).
- Criteria 2: The critical event at a reporting location is the ensemble event that produces the highest water level yet remains within the AEP level plus CET range.
- Criteria 3: The critical event cannot exceed the AEP level at another reporting location (within the CET), otherwise the principle of taking the maximum of the maximums fails.

With the criteria applied, the approach for selecting the final ensemble events was completed using a series of stages as summarised in Figure 5 and detailed as follows:

- Stage 1: At each reporting location and AEP, independently of the other reporting locations, a list of preferred events was produced by rejecting all events that resulted in a higher level than the reporting location's AEP level plus the CET.
- Stage 2: If the event did not occur in the Stage 1 lists of all other reporting locations, the event was rejected. This removed events that had peaked above the AEP level plus CET at one or more other reporting locations, ensuring Criteria 3 was upheld The resulting list was referred to as the "Stage 2 List" and for all reporting locations the events were the same.
- Stage 3: Using the Stage 2 list the event that gave the best statistical match to the AEP levels at all reporting locations was selected.
- Stage 4: Where required, the overall AEP match was improved by grouping hydraulically similar reporting locations together and repeating Step 3 independently on the new group.

This methodology was incorporated into a Python scripting environment to ensure systematic and repeatable processing. The scripting environment also assisted in producing the many figures and tables required to visualise and review the various event selection stages.

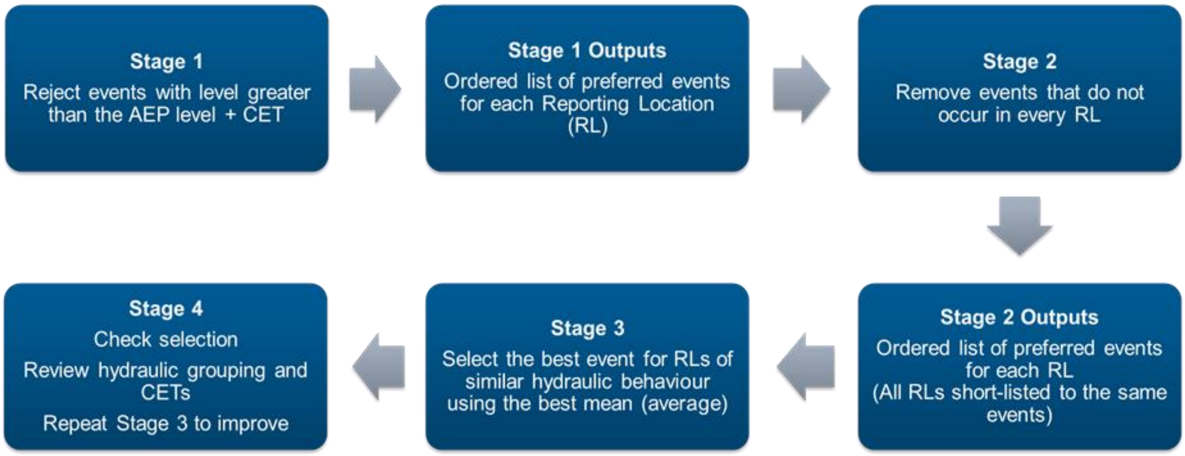

Figure 5 Event Selection Methodology

5.2. Event Ensemble Results

In total, sixty events were selected for simulation through the *Detailed Model* with ensembles ranging in number from four to seven individual events. The resulting peak flood surfaces for each AEP where combined using a maximum water surface envelope encompassing all events for that AEP. The resulting AEP surface was then carefully checked to ensure that water levels increased with decreasing probability of event.

Figure 6 6 shows an example of the 1 in 100 AEP which comprised five Monte Carlo events. At Moggill the event with ID ‘120_0776’ results in the highest water level (although two events give similar but slightly lower peak levels). At other locations within the Brisbane River catchment one of the five events provided the critical event.

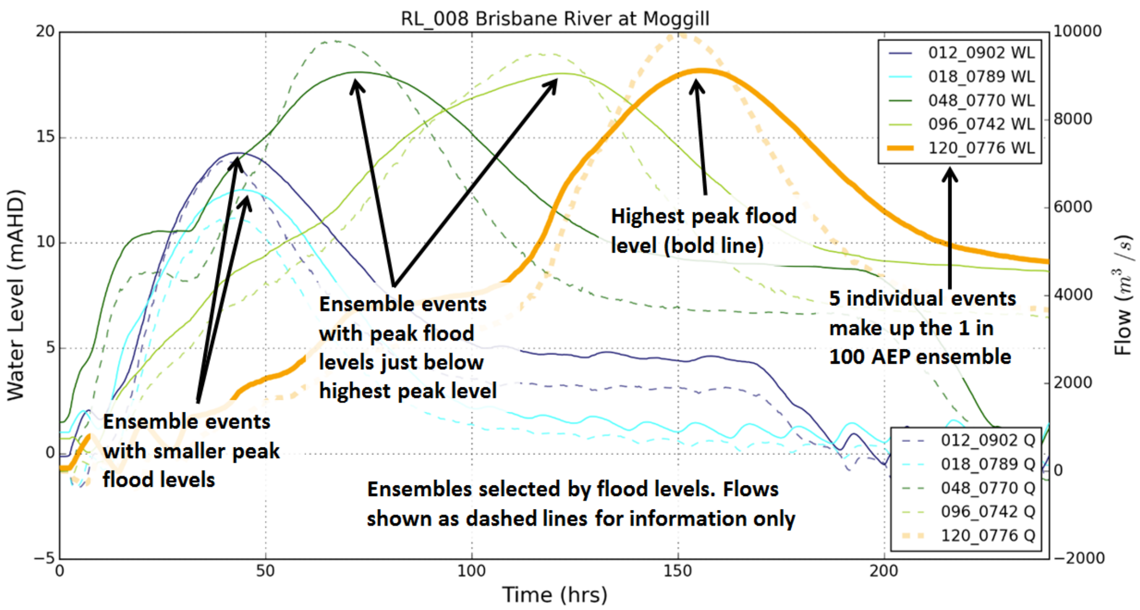

Figure 6 Example of an Ensemble (1 in 100 AEP at Moggill)
(Figure 6-11, Milestone Report 7, BMT WBM, 2017)

6. CONCLUSIONS

The Brisbane River catchment has a range of hydrologic and hydraulic complexities, interactions and variations over temporal and spatial scales that are difficult to accommodate using traditional AEP analyses. For the Brisbane River Catchment Flood Study these difficulties were overcome by utilising a Monte Carlo statistical analysis approach for both hydrologic and hydraulic phases.

For the hydraulic modelling phase, the requirement to model and manage 11,340 simulations presented a significant challenge that resulted in the development of new and innovative workflows to process and move model data, visualise, review and communicate results. The use of a calibrated, quick to simulate, 1D-only network model to run these events was key.

Results from the *Fast Model* were processed to provide a database of peak levels, flows and rainfall inputs that could be analysed to provide peak AEP levels throughout the catchment. This AEP analysis was completed using the Total Probability Theorem.

To match estimated AEP levels, a major challenge of the study was the selection of a sub-set of *Fast Model* runs to be re-simulated through a detailed floodplain-wide 1D/2D hydraulic model, known as the *Detailed Model*. A staged event selection process was developed that resulted in the selection of 60 total events for the eleven AEP ensembles considered. Ensembles ranged from four to seven events and provided the basis for riverine velocity, flood hazard, depth and water level mapping.

The study highlights the challenges and new methods that we may require as we increasingly move to ensemble and Monte Carlo approaches for hydrologic and hydraulic assessments.

7. ACKNOWLEDGMENTS

The authors wish to acknowledge the significant contribution made by the BRCFS Independent Panel of Experts, Technical Working Group, Steering Committee and Queensland Government Project Team. For a list of names, please refer to Appendix B of the Technical Summary Report (Milestone Report 7) available at https://publications.qld.gov.au/dataset/brisbane-river-catchment-flood-study.

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