BRISBANE RIVER CATCHMENT FLOOD STUDY: 1D MODELS ARE BACK! – MONTE CARLO HYDRAULIC MODEL ANALYSIS

Phillip Ryan[1], Bill Syme[1], Rory Nathan[2], Wai Tong Wong[3], Pushpa Onta[3]
[1]BMT WBM, Brisbane QLD
[2]Jacobs/University of Melbourne, Melbourne VIC
[3]Department of Natural Resources and Mines, Brisbane QLD

Introduction

The Brisbane River Catchment Flood Study (BRCFS) is one of the largest and most complex flood studies embarked upon in Australia. The Flood Study has been divided into three components: a) data collection; b) a comprehensive Hydrologic Assessment; and c) a comprehensive Hydraulic Assessment. Within the comprehensive hydraulic assessment a suite of models has been developed and calibrated. This paper focusses on the challenges of developing and calibrating a “Fast” (1D only) hydraulic model in a manner that facilitates the undertaking of 11,340 Monte Carlo simulations.

Background

The Brisbane River Valley has a wide range of hydraulic complexities that makes it a very interesting and challenging task to numerically model, both hydrologically and hydraulically. The Brisbane River has a catchment area over 13,600km^2, of which roughly half is upstream of Wivenhoe Dam. The rainfall variation across the catchment is highly variable from the wetter coastal hinterland ranges to the drier areas in the west of the catchment. Wivenhoe Dam offers substantial flood storage capacity and can significantly affect the shape and attenuation of the flood wave, and the severity of flooding downstream. The two major tributaries, Lockyer Creek with its large floodplains and the Bremer River, enter the Brisbane River downstream of Wivenhoe Dam, adding to the complexity in terms of timing and shape of the flood wave at Brisbane.

Conventional modelling approaches cannot account for the major variations in flood behaviour that can potentially occur due to the hydrologic/hydraulic complexity of the Brisbane River system. As such, a Monte Carlo approach was used to quantify the design flood events. The Hydrologic Assessment generated many thousands of synthesised flood events by selecting variables based on pre-determined statistical distributions. This enabled the hydrologic variability in key flood-influencing factors (such as rainfall patterns and antecedent conditions) to be considered in the synthesised Monte Carlo events (Aurecon et al 2014a; Aurecon et al., 2014b). The Monte Carlo events were simulated through a calibrated hydrologic model to produce frequency curves of flood peaks and volumes at key locations. However, to produce a flood *level* frequency analyses at locations downstream of Wivenhoe Dam, a hydraulic flood model was required to predict flood *levels*. The Hydraulic Assessment was responsible for developing a hydraulic model that was capable of reproducing the complex flood behaviour and yet able to run in a short period of time in order to simulate 11,340 Monte Carlo events. As the name suggests, the Fast Model was developed for speed, and satisfies these requirements.

1D “Fast” Model

The Fast Model is a 1D model developed using the 1D solver of the TUFLOW software, which solves the 2nd order solution of the full 1D St Venant equations using an explicit numerical solution. The Fast Model comprises more than 2,500 channels covering the Brisbane River and major tributaries below Wivenhoe. In order to simulate the thousands of Monte Carlo events, it was necessary for the Fast Model to have a simulation time of 15 minutes or less per flood event. At present, the Fast Model models a single 8-day flood in approximately 4 minutes.

The Fast Model is based on the well-established hydraulic modelling approach of using a network of 1D channels and storage nodes that was commonplace prior to 2D flood modelling. The network of channels gives a quasi 2D effect by conveying water through flowpaths representing both the rivers/creeks and floodplains. Spill channels connect the river/creek and floodplain flowpaths. The channels are hydraulically connected at nodes, which represent the storage of the system. Each node has a surface area versus height table defining the volume of water that a node can hold. For nodes connecting the in-bank river and creek channels, the storage is derived by multiplying the cross-section widths by half the in-bank channel lengths at varying heights. For nodes on the floodplain the storage is extracted from the DEM. Each overbank node is associated with a polygon that is used to extract the horizontal surface area from the DEM at different elevations. This approach ensures that the floodplain storage in the model is the same as that of the DEM. It is not an option to use the in-bank channel approach of multiplying cross-section width by channel length, as the floodplain storage can be grossly overestimated due to duplication or over-lapping of the calculated surface areas.

Development of the Fast Model schematisation was assisted by use of an existing 2D TUFLOW GPU model of the Brisbane River below Wivenhoe Dam. This 2D GPU model was developed as a Disaster Management Tool (DMT) (BCC, 2014a) for the purpose of producing broad-scale disaster management maps. While DMT model results are suitable for the production of such maps, model results are not of sufficient accuracy for more localised prediction of flood levels. The DMT model was also suitable for providing an indication of floodways for a range of events up to and including an estimated PMF. This was of great value in the development of the Fast Model as 1D models require the modeller to know the location and activation levels of floodways and to then manually insert each channel into the model. An example of the Fast Model schematisation and DMT results used to guide the 1D model creation are presented in Figure 1 below.

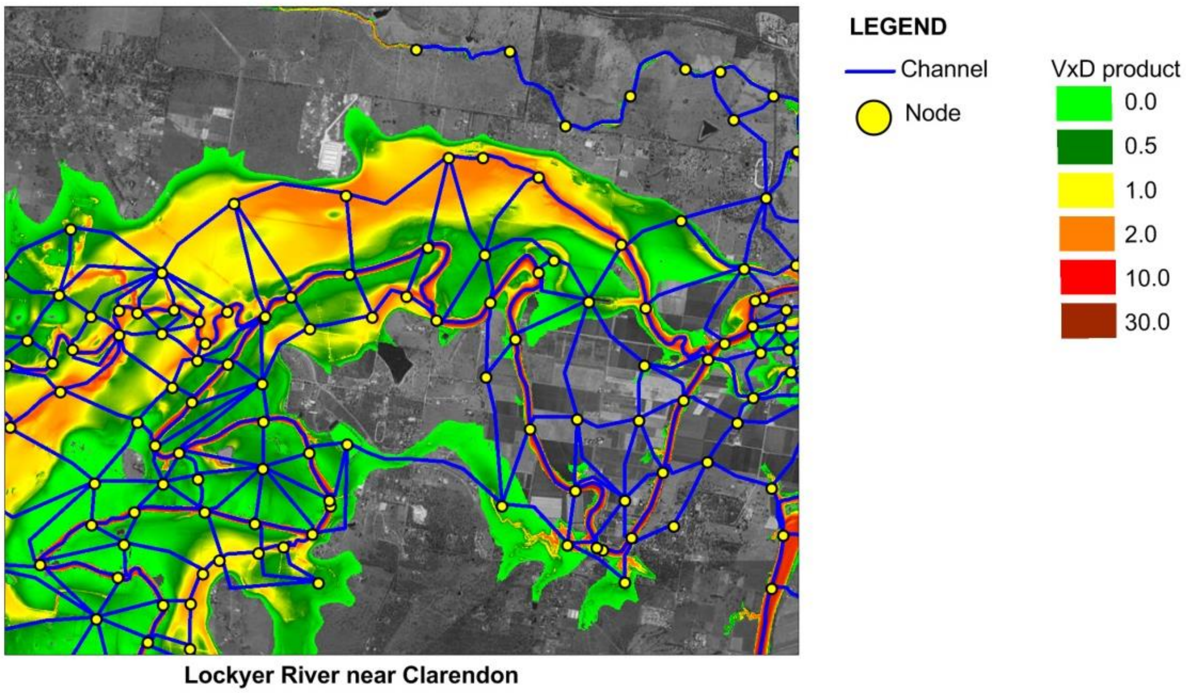

Figure 1 Example Fast Model Schematisation and DMT Model Results

The 2D DMT model was updated with a number of changes including new bathymetry in the Bremer and lower parts of the Brisbane River. This updated model was also produced as part of this study. A range of GIS tools was created by BMT WBM to automate the extraction of cross-sections, storage areas and channels into TUFLOW formats.

Model Calibration

Hydraulic models aim to realistically represent flow behaviour. In order to achieve this, models must be calibrated to historical events. The Fast Model calibration / verification process followed the sequence below:

1. Tidal Calibration: Calibration of the in-bank tidal waters Manning's n value
2. Calibration to "Steady State" Dam Releases: Calibration of the in-bank Manning's n values to the reasonably constant release from Wivenhoe Dam for 2011 and 2013 events.
3. Calibration to minor flood events: 2013 and1996 and verification to the minor flood event 1999
4. Calibration to the major 2011 flood event
5. Verification to the major 1974 flood event.

1D hydraulic models rely on the one-dimensional cross-sectional depth and width-averaged equations of fluid motion. A 1D scheme therefore cannot represent complexities of hydraulic behaviour that occur in two or three dimensions where rapid changes to velocity occur, such as eddies and torsional vortexes. As such, energy losses associated with such hydraulic behaviour need to be manually accounted for within the 1D model.

The Manning's n equation is the most common approach that can be utilised to represent losses due to surface roughness. A form loss coefficient can also be applied to the model to simulate the energy losses associated with hydraulic behaviour not able to be represented explicitly in the hydraulic model. The form loss is applied as an energy loss based on the dynamic head equation below where ζ_a is the form loss value.

$$\Delta h = \zeta_a \frac{V^2}{2g}$$

A Manning's n value of 0.022 was found to produce the best reproduction of tidal wave propagation in the Brisbane River in the tidal calibration phase. This value is consistent with the many other tidal calibrations carried out using 1D and 2D schemes and is within the acceptable range for tidal reaches (0.02 to 0.04) provided in Australian Rainfall and Runoff (Babister & Barton, 2012).

Records of post-flood "steady-state" discharges from Wivenhoe Dam following the 2011 and 2013 events provided an ideal opportunity to calibrate the in-bank roughness values. During these "steady-state" discharge periods, flow is relatively constant and mostly confined in-bank. To achieve calibration over these periods it was found that form losses (in addition to the Manning's n from the tidal calibration) were required to represent additional losses due to bends and channel formations. A small general form loss was applied in addition to targeted form losses at sharp, rock controlled, river bends and rock ledges (e.g. Dutton Park). The result of the 2011 calibration at Moggill using form losses and tidal Manning's n values as described is shown by the red (modelled) and blue (observed) lines in Figure 2.

It is interesting to note that in the absence of these additional form loss values, an in-bank Manning's n of 0.038 is required to approximately match the flood level at Moggill for the 2011 post-flood peak discharge of 3,500 m^3/s from Wivenhoe Dam – see green line (ST01A) on Figure 2 below. An in-bank n value of 0.041 is required to approximately match the peak flood level at Moggill for the 2011 event (orange line, ST01B below). In both cases (n=0.038 and n=0.041), the shape and timing of the hydrograph are poor when compared to the modelled (red) case using both a Manning's n and form loss approach. They also reduce the quality of the tidal calibration.

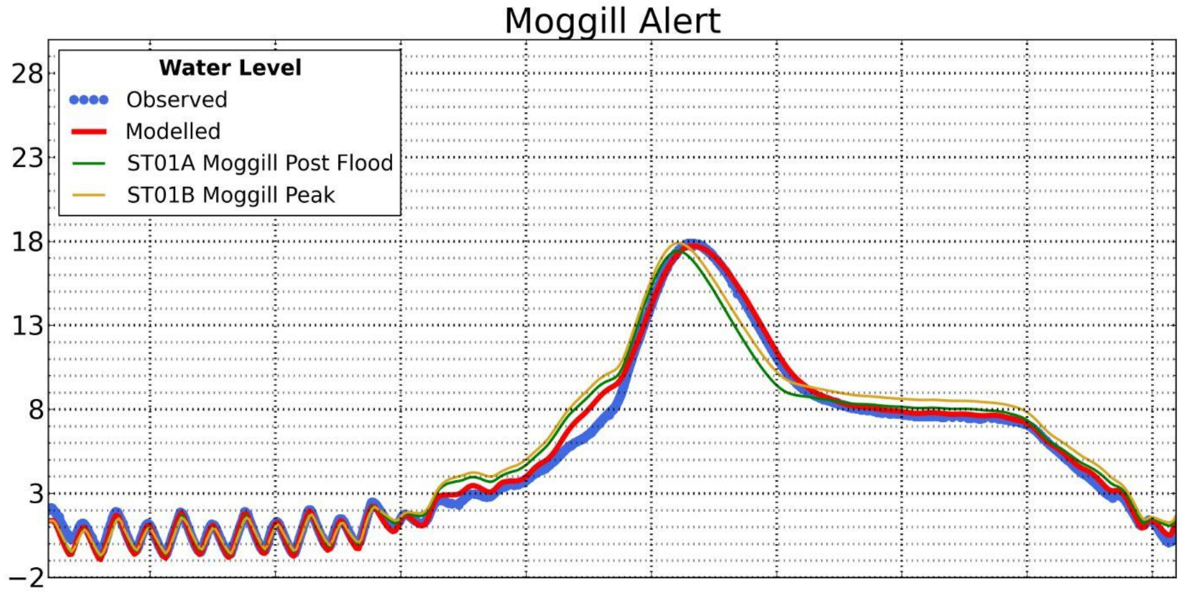

Figure 2 – Manning's and Form Loss Calibration 2011 Flood Event

The calibrated general form loss values for the Bremer River, Warrill Creek, Purga Creek, and Brisbane River from Mt Crosby to New Farm Park were 0.3/km. For the Lockyer Creek, Brisbane River from Wivenhoe Dam to Mt Crosby 0.2/km was required and Brisbane River from New Farm Park to the mouth, Oxley Creek, Breakfast Creek, Bulimba Creek, Norman Creek, Moggill Creek no general form loss was required. The presence or not of a general form loss can be correlated with the presence of minor rock ledges, and degree of irregularities along the river/creek bed.

For the targeted form loss, manual estimation considered geometry, bathymetry and recorded data. This allowed for similar bends to have a consistent value applied. For example a 180 degree bend was typically assigned a form-loss of 1.5, and a 90 degree bend a form loss value of 0.75. As part of the calibration process the values of form loss were varied to provide the most consistent match across the events. The targeted form losses were applied at approximately 90 locations.

The calibration exercise included calibration to a range of time series water level recordings, recorded flow data at Centenary Bridge and peak debris levels along the main rivers / creeks. An example time-series calibration is presented in Figure 3 below.

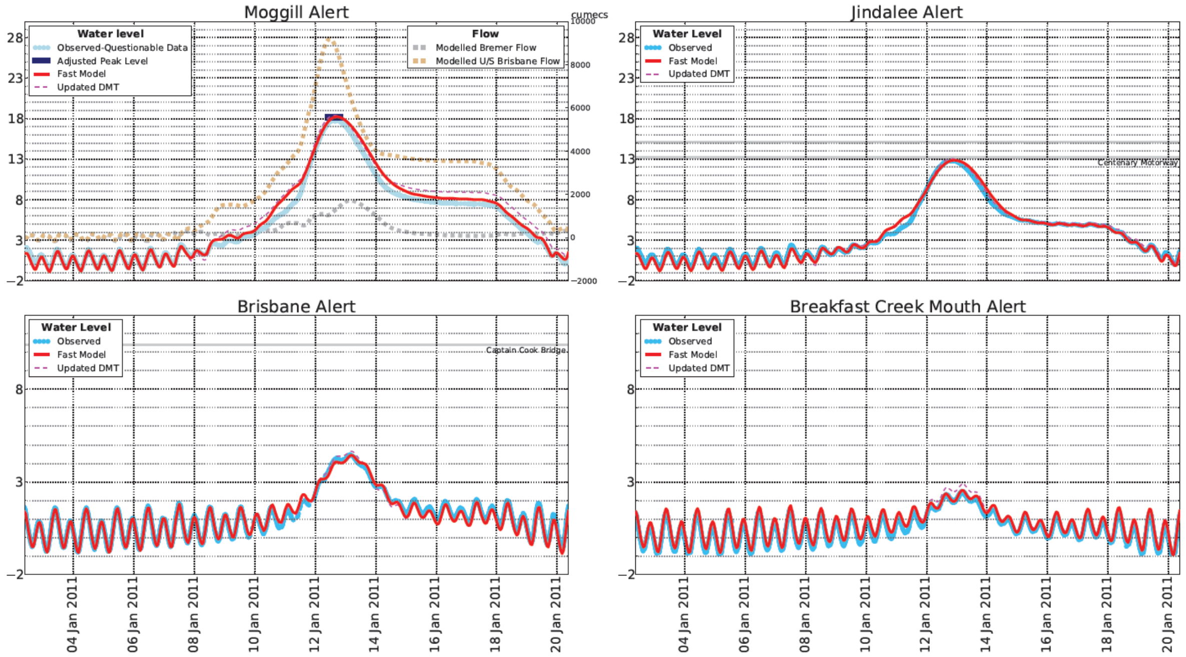

Figure 3 – Example Calibration Plot 2011

Extreme Event Testing

In 1893, Brisbane experienced two major flood events, both of which were greater in flow magnitude in Brisbane than any other recorded event, including 1974 and 2011. The 1893 events were not included in the Hydrologic Assessment to allow direct calibration, however an indicative assessment was made by multiplying the 1974 inflows by a factor of 1.5 to approximate an 1893 flood event.

The Fast Model was further tested to a number of hypothetical extreme events by comparing it to the 2D Updated DMT model to ensure it appropriately modelled the floodway channels. It was also critical that the Fast Model remained robust in extreme events, and such checks allowed this to be confirmed. Comparisons of the Fast Model and Updated DMT model were made for test scenarios of 2 x 1974, 5 x 1974 and 8 x 1974 flood inflows. New high-flow flowpaths predicted by the Updated DMT Model were incorporated into the Fast Model. An example of a high-flow flowpath that was subsequently added to the Fast Model to enable it to appropriately model the extreme events is shown in Figure 4. The circled flowpaths allow break out from the Brisbane River into Dutton Park / Woolloongabba to occur in an extreme 8 x 1974 flood event (greater than a PMF).

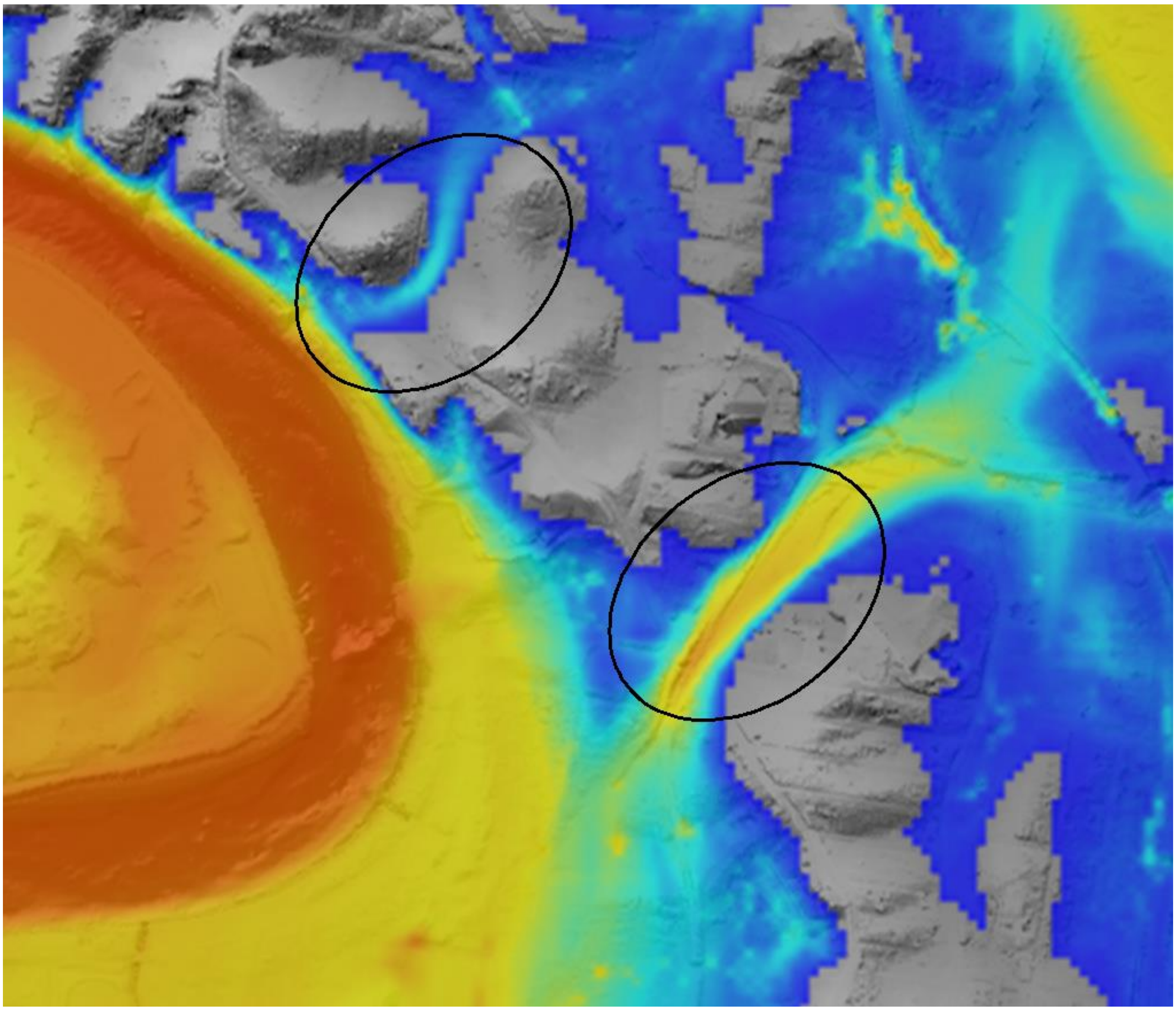
Figure 4 Example High Flowpaths for 8 x 1974 Extreme Flood Event

Monte Carlo Simulation

The primary purpose of the Fast Model is to simulate thousands of Monte Carlo events derived by the Hydrologic Assessment. Undertaking 11,340 simulations provides challenges in terms of model output, model runtimes and output quality control!

In order to undertake the large number of simulations in a practical timeframe, the simulations are distributed between a number of computers. This process was undertaken using the open source distributed computing software [HT Condor.](#) HTCondor is a software system that creates a High-Throughput Computing (HTC) environment. This allows for a "pool" of computers (each with differing numbers of CPU cores, CPU speeds and memory) to be managed from a centralised server queue. It effectively utilises the computing power of workstations that communicate over a network. HTCondor can manage a dedicated cluster of workstations. Its power comes from the ability to effectively harness non-dedicated, pre-existing resources under distributed ownership (UW-Madison, 2015). With our present setup (which we plan to expand), we have been able to run over 50 simulations concurrently. The software will also be used to merge the output files to a central location to allow for easier post-processing.

Modifications have been made to the TUFLOW engine to optimise the outputs from the Monte Carlo simulation, with particular focus on the 29 reporting locations of interest. Outputs for other areas are minimised but quality check outputs are enhanced. A range of checks are undertaken on a number of key model outputs, namely: peak water levels, time of peak water level, peak flows, time of peak flow and maximum change in water level to ensure the model is robust. A range of Python scripts has been developed to longitudinally plot these model outputs and identify discrepancies such as increasing water level in a downstream direction or time of peak that doesn't match surrounds. These can all be indications of the numerical model "bouncing" or failing to converge. It is necessary to automate this checking process due to the large number of Monte Carlo simulations undertaken and the impossibility of manually checking each one.

The peak flows and peak water levels from these thousands of runs will be used to carry out level and flow frequency analyses at 29 reporting locations within the assessment area. Results of these frequency analyses will be used to derive preliminary flood level AEPs at the reporting locations using the Total Probability Theorem framework developed by Nathan and Weinmann (2013). The information used to derive these frequency relationships will then be used to inform the selection of approximately 50 of the Monte Carlo events that will be used to represent 11 AEP design events. Each design event will be formed by an ensemble of Monte Carlo events with the number of events in each ensemble determined during the selection process. The Monte Carlo simulations and flow and level frequency analyses are currently being undertaken.

Conclusion

A Fast Model was created using a 1D modelling approach with the TUFLOW software. The 2D Updated DMT model was used to guide the schematisation of the 1D model, and the Fast Model was calibrated to a range of historic flood events. The primary calibration parameters were the Manning's n value and Form Loss coefficient which were tested and selected in order to provide the best match for tidal, minor and major flood events. A distributed computing framework was implemented to manage the 11,340 Monte Carlo events which are currently being simulated. Results from the Fast Model Monte Carlo simulations will be used to undertake flood level and peak flow frequency analyses. A sub-set of the Monte Carlo events will be selected to be simulated in the detailed 2D/1D TUFLOW hydraulic model, which is currently in calibration phase.

References

Aurecon et al (2013), Collection, Collation, Review and Storage of Existing Data – FINAL, Prepared for Department of State Development & Infrastructure by Aurecon, Royal Haskoning DHV, Hydrobiology, Deltares, Don Carroll PM as part of the Brisbane River Catchment Flood Study, April 2013.

Aurecon et al (2014a), Hydrologic Model Recalibration Report – Final Draft, Prepared for Department of State Development & Infrastructure by Aurecon, Royal Haskoning DHV, Hydrobiology, Deltares, Don Carroll PM as part of the Brisbane River Catchment Flood Study Comprehensive Hydrologic Assessment, 15 December 2014.

Aurecon et al (2014b), Monte Carlo Simulation Framework and Methodology – Draft Final, Prepared for Department of State Development & Infrastructure by Aurecon, Royal Haskoning DHV, Hydrobiology, Deltares, Don Carroll PM as part of the Brisbane River Catchment Flood Study Comprehensive Hydrologic Assessment, 18 December 2014.

Aurecon et al (2014c), Draft Final Hydrology Report, Prepared for Department of State Development & Infrastructure by Aurecon, Royal Haskoning DHV, Hydrobiology, Deltares, Don Carroll PM as part of the Brisbane River Catchment Flood Study Comprehensive Hydrologic Assessment, 15 December 2014.

Babister, M. & Barton, C. (2012), Australian Rainfall and Runoff Revision Project 15, Two Dimensional Modelling in Rural and Urban Floodplains, AR&R Report Number P15/S1/009, ISBN 978-085825-9850, 18 November 2012.

BCC (2014a), Brisbane River Catchment Disaster Management Tool Model Development and Calibration Outcomes Final Report, Prepared for Department of State Development Infrastructure and Planning by Flood Management Unit, City Projects Office, Brisbane Infrastructure Division, Brisbane City Council, 19 June 2014.

BCC (2014b), Brisbane River Catchment Flood Study Digital Terrain Model Development and Bed Level Sensitivity Analysis Final Report, Brisbane City Council, 268 pages.

BCC (2009a), Flood Study of Fernvale and Lowood, Prepared for Somerset Regional Council by Brisbane City Council, June 2009.

BCC (2009b), Brisbane River Hydraulic Model to Probable Maximum Flood, Final Report. Brisbane City Council, June 2009.

Nathan RJ and Weinmann, PE (2013): Monte Carlo Simulation Techniques. Australian Rainfall and Runoff Discussion Paper, Report D2. Engineers Australia, 41pp.

UW-Madison (2015) Website: http://research.cs.wisc.edu/htcondor/description.html accessed May 2015.