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Brisbane River Catchment Flood Study Calibration of Hydraulic Models

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Two hydraulic models were developed and calibrated for the Brisbane River Catchment Flood Study's Hydraulic Assessment. The Fast Model is a 1D model with a run time of 5 minutes. Its primary purpose is to simulate thousands of synthetic Monte Carlo (MC) events for flood frequency assessments. The Detailed Model is a 2D hydraulic model designed for simulating a sub-set of MC events to produce AEP flood maps and surfaces of flood levels, depths, velocities and hydraulic hazard.

The Fast and Detailed Models were calibrated to a considerable quantity of recorded water level and flow data from the floods of 1974, 1996, 1999, 2011 and 2013. Key observations from an exhaustive calibration exercise are presented with a focus on some of the more interesting outcomes. Discussion is provided on the need to include kinetic energy losses at sharp river bends, rock ledges and major confluences, in combination with industry standard Manning's n values, to achieve model calibration across all floods and tidal conditions using a common set of parameters.

1. INTRODUCTION

The lower Brisbane River, unlike most large east coast Australian rivers, has unusually few meanders formed by river migration, with many of the river's reaches contained within incised valleys. The hydraulic consequence is that very high velocities driven by steep gradients develop during a flood. The banks are often rock, bends can be a sharp 180º, and the entire flood flow is often solely confined between banks. In addition, the river meanders can change from gentle backwaters to high velocity, short-circuit flowpaths in large to extreme events.

The Brisbane River catchment has a total area of approximately 13,500 km^2 upstream of the Brisbane CBD. Approximately half of the catchment area is regulated by Wivenhoe Dam, which has a pronounced influence on flooding. Two major tributaries join the Brisbane River downstream of Wivenhoe Dam; the Lockyer Creek and the Bremer River. Figure 1 shows the total Brisbane River catchment including Lake Wivenhoe which forms behind the dam of the same name.

In January 2011, the lower Brisbane River and its tributaries along with many other catchments in Queensland experienced their largest flood events since 1974.

A key recommendation in the subsequent Queensland Floods Commission of Inquiry (QFCoI) (QFCOI, 2012), was that a flood study be undertaken of the Brisbane River catchment. The overarching objective of the study was to determine flood behaviour for floods of different probabilities.

In June 2014, BMT WBM Pty Ltd was commissioned to undertake the hydraulic assessment of the Brisbane River Catchment Flood Study (BRCFS) on behalf of the Queensland State Government. The study, including a significant hydrologic component was made public in May 2017 (BMT WBM 2017).

A major component of the hydraulic assessment was the development and calibration of two new hydraulic models; a 1D only model termed the 'Fast Model' and a predominantly 2D model termed the 'Detailed Model'. The purpose of the Fast Model was to be able to simulate thousands of synthetic Monte Carlo events, and hence there was a requirement that the model ran in a very short timeframe. The Detailed Model was used to run a subset of the Monte Carlo events with the subset determined from statistical analyses of the Fast Model results (Smith et al, 2017). The subset comprised events chosen to approximate peak flood levels of given annual exceedance probabilities (AEP). Both models represented the river and floodplain downstream of Wivenhoe Dam; the Fast Model using a network of 1D nodes and channels and the Detailed Model predominantly using a 2D grid of cells with embedded 1D elements where appropriate. The hydraulic assessment area for the models is shown in Figure 1.

The Fast and Detailed models needed to undergo a rigorous calibration exercise to ensure that a high degree of confidence could be placed in their results. Developing and calibrating an extensive 1D model and 2D model of the same catchment in near parallel provided a rare opportunity to compare and contrast the performance of the two models, albeit recognising the limits of 1D models and the slightly different purposes for which each model was being developed.

This paper discusses some key points of interest for the calibration of both hydraulic models and gives focus to how differences in results between both models were reconciled with the calibration data.

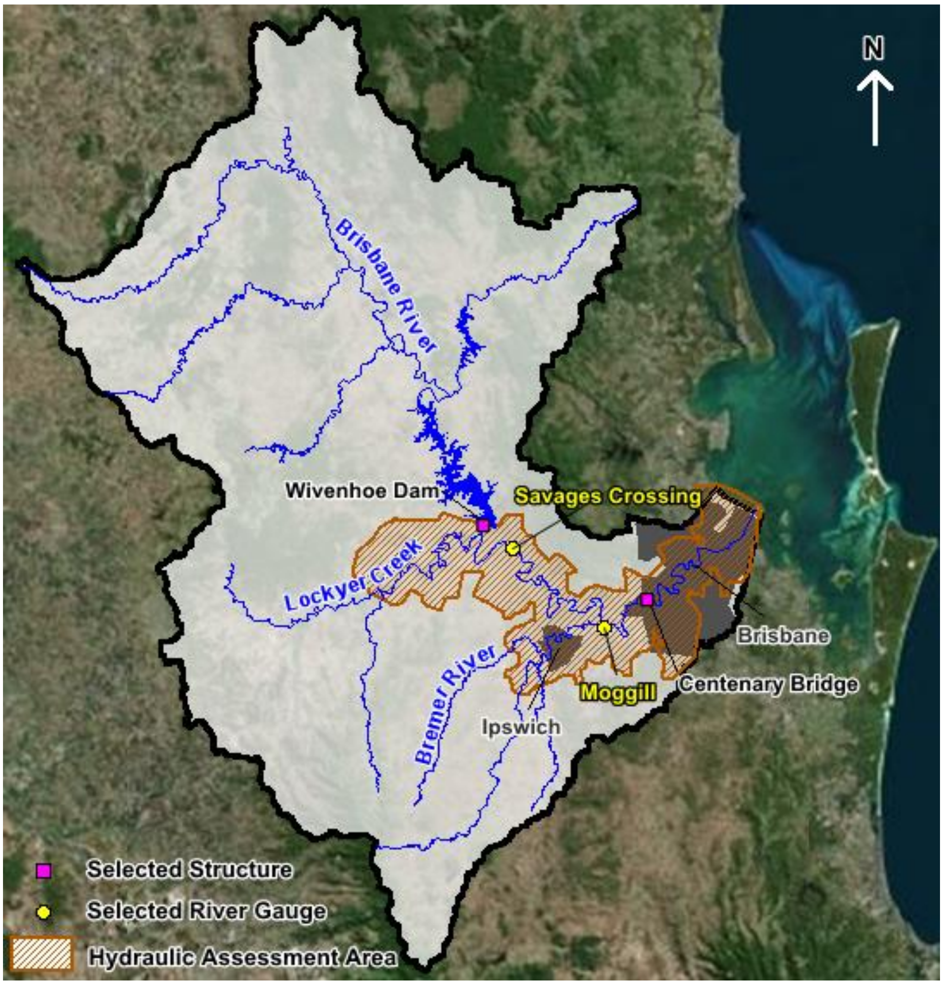

Figure 1 – Brisbane River Catchment, Hydraulic Assessment Area and Selected River Gauges

2. OVERVIEW OF THE MODELS

2.1. Software

Both the Fast Model and Detailed Model use the modelling package TUFLOW; an established hydraulic modelling software package, developed in Brisbane by BMT WBM and used extensively around the world for a wide range of applications for over 25 years (www.tuflow.com).

TUFLOW's implicit 2D solver, often now referred to as TUFLOW "Classic", is a 2nd order spatial finite difference solution of the full 2D hydrodynamic equations. The 2D scheme is dynamically linked with a 1D 2nd order solution of the full 1D equations. The solvers include the handling of upstream controlled flow regimes such as weir and supercritical flows.

For the Fast Model and nested 1D elements of the Detailed Model the TUFLOW 1D solver was utilised to solve the 1D equations of free-surface fluid flow often referred to as the St Venant equations. The full momentum equation (i.e. including inertia) is applied at the channels and the mass balance equation at the nodes. Open channels can automatically switch in and out of upstream controlled super-critical flow should this flow regime occur. For special channels, such as bridges, weirs and culverts, the momentum equation is replaced by equations representing the flow through the structure. These equations cater for the range of upstream and downstream controlled flow regimes that can occur specific to that structure.

2.2. 1D vs 2D Approach

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. It includes representation of both river and floodplain with connecting spill channels. Each floodplain 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, this 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 topographic digital elevation models.

Of note, a 1D solution does not inherently simulate losses due to change in velocity direction, i.e. the equations have no knowledge of a river bend. If these losses are present, additional bend (form) losses are required.

The Detailed Model is based on a fixed 2D grid of elements. The full 2D equations are significantly more accurate than the 1D equations in areas of complex flows characterised by high velocity and sudden changes in flow direction such as around a river bend. More complex flow phenomena such as superelevation (the surcharging of waters on the outside of a sharp bend), energy dissipation at major confluences and the complex interactions of in-bank and overbank flow paths are significantly better represented than with a solely 1D approach due to: the representation of momentum in two directions on a horizontal plane (cross-momentum) rather than in just one direction; and the inclusion of sub-grid scale turbulence effects (eddy viscosity).

Similar to the 1D solution, a 2D solution will not explicitly simulate all losses, but due to the inclusion of cross-momentum and eddy viscosity the 2D solution will simulate the majority of energy losses that occur in addition to bed friction (Manning's equation). For example: the effects of sub-grid scale features (e.g. bridge piers); and losses in the vertical (third-dimension) such as helicoidal flows around a sharp river bend, may not be fully represented by a 2D solution. Furthermore, one of the terms in the Smagorinski formulation is a function of the 2D cell surface area. As such, this term may change in magnitude with changes in cell size (Collecutt & Syme, 2017).

Therefore, whilst a 2D scheme may offer significant accuracy gains over a 1D scheme, there remains a need for model calibration wherever possible, to fine-tune the model's representation of those energy losses not well or fully represented by the equations being solved. Due to the characteristics of the 1D and 2D equations, the expectation was that the 1D Fast Model would require higher energy loss parameters than for the 2D Detailed Model, assuming Manning's n values are similar.

Both the 1D Fast Model and 2D Detailed Model are based on the same underlying topography and utilise the same land use datasets to determine surface roughness (Manning's n) values. Bridges and other hydraulic structures were built into the models using industry standard approaches and parameters. Both models were both calibrated and verified to the same events and as such, apply the same boundary conditions.

3. AVAILABLE DATA

The Brisbane River catchment benefits from a large amount of high quality historical calibration data in combination with catchment specific factors that significantly aid the calibration process.

Five events were considered for calibration and verification purposes, those being the major Brisbane river flood events of 1974 and 2011, and the smaller events of 1996, 1999 and 2013. The flood that occurred in January of 1974 pre-dates the construction of Wivenhoe Dam, whereas the remaining four events occurred post-Wivenhoe Dam, and as a consequence were heavily regulated by operation of the Wivenhoe Dam gates.

Data consisting of recorded stage hydrographs were available at multiple gauge sites within the catchment for each of the five events. For the events of 1974, 2011 and 2013 the gauge data is supplemented with recorded peak flood level marks. For the larger events of 1974 and 2011, the marks are numerous and are spread throughout the Hydraulic Assessment area. For the smaller 2013 flood, less marks are available and are largely confined to the creeks and rivers, except in Lockyer Creek where the flood was relatively moderate in scale.

Flow recordings (gaugings) on the Brisbane River were made during the flood events of 1974, 2011 and 2013 from Centenary Bridge (location shown on Figure 1). Flows were recorded near the peaks of the floods and during the recession of the flood events, and were a valuable dataset used in the calibration process as cross-check on the rate and volume of water being modelled.

In addition to the abundance of calibration data, there are several factors that benefit the calibration exercise:

- Wivenhoe Dam regulates flow from approximately half of the Brisbane River catchment and it forms the upstream boundary location of the hydraulic model. There is little uncertainty in the flow rate discharged through the dam's structures, and as such there is a high degree of confidence in the main inflow to the hydraulic models. Except for the 1974 flood, this negates the need to rely on a hydrological model, which are typically associated with a larger degree of uncertainty, to derive the inflow to the model at this location.

- During the flood events of 2011 and 2013 Wivenhoe Dam held back a significant volume of water. Both events resulted in a post-flood drain down operation of the dam following the passing of floodwaters in downstream creeks and rivers. The drain down period is typified by a near steady state (constant flow) release over an extended period lasting several days. This effectively results in in-bank steady state flow conditions on the lower Brisbane River, and for calibration purposes the exercise becomes solely one of conveyance as any uncertainties associated with model storage are effectively removed.

- During the 1996 event, Wivenhoe Dam retained all flow from the upstream catchment, making no releases until the flows on the downstream tributaries of the Lockyer Creek and Bremer Rivers had passed through the lower Brisbane River catchment. This was of benefit when calibrating flows on these downstream tributaries, which are often complicated due to the influence of backwater from the Brisbane River during flood events.

4. CALIBRATION AND VERIFICATION

4.1. Calibration Approach

For both the Fast and Detailed Model, calibration was undertaken using a staged approach as follows:

- Undertake a tidal calibration using the tidal signals in the lead up to the 2013 flood event.
- Calibrate to the minor flood of 2013.
- Verify the model against the minor floods of 1996 and 1999.
- Calibrate to the major flood of 2011.
- Verify against the major flood of 1974

The performance of the calibration was judged primarily against the gauged data (for timings and levels) and the peak flood level marks (for levels). For much of inner Brisbane the specified target was to be within +/-0.15 m of available peak level heights, albeit recognising there is a degree of uncertainty in these data. In addition, comparisons to: flow gaugings (1974, 2011 and 2013 floods); rating curves where available; and available flood extent mapping/imagery were performed.

Initially the calibration was attempted by varying the Manning's n values. However, it became necessary to introduce additional form (energy) losses in both 1D and 2D models to achieve an acceptable calibration. The Manning's n only approach, and Manning's n with form loss approach are described below.

4.2. Manning's n Calibration

Typically, hydraulic models are calibrated by adjusting the Manning's n values until a reasonable match between recorded and modelled water levels and timing is achieved.

A tidal (non-flood) period was used to carry out an initial calibration of the in-bank tidal waters Manning's n value. For both Fast (1D) and Detailed (2D) models, a Manning's n value of 0.022 was found to result in the best reproduction of tidal wave propagation.

The periods following the flood peaks of the 2011 and 2013 flood events provided a good opportunity to further calibrate the in-bank Manning's n values. During these periods, major flows on the downstream tributaries had subsided and reasonably constant releases over about four days were made from Wivenhoe Dam; around 1,700 to 1,800 m^3/s in 2013 and 3,500 m^3/s in 2011. These had the effects of producing near steady-state inflow conditions on the lower Brisbane River making the hydraulics solely a conveyance based problem where the effects of the tide are not pronounced.

During these periods of near steady state conditions, it was found that in bank Manning's n values of 0.031 and 0.038 were required within the Fast Model to approximate the respective water levels at the Moggill gauge for the 2013 and 2011 events respectively. Furthermore, to match the 2011 peak at this gauge, a higher still Manning's n value of 0.041 was required.

Figure 2 presents observed flood levels at the Moggill gauge for the 2011 event along with results from the Fast Model. Moggill is a key gauge on the Brisbane River as it is the first gauge located downstream of the Bremer River confluence (see Figure 1 for location), and therefore is the first gauge that covers the effect of all major contributing catchment flows.

The Fast Model results shown in Figure 2 include both the final calibration simulation (red dashed line) based on selected Manning's n and additional form loss values alongside results from two sensitivity tests; ST01A and ST01B. Both sensitivity tests did not apply any additional targeted form losses and instead selected in bank Manning's n values to achieve the following:

- ST01A (green line) – Attempted to achieve a match to the flood level during the post flood peak drain down period between 14 January and 18 January without significantly understating the flood peak. Used an in-bank tidal Manning's n of 0.038.

- ST01B (orange line) – Attempted to achieve a match to the peak flood level on 12 January. Used an in-bank tidal Manning's n of 0.041

The in-bank tidal Manning's n values applied in the sensitivity tests are all notably higher than the value of 0.022 determined from the tidal calibration and used in the final model run. Furthermore, these higher values are at the uppermost end of recommended values in the guideline Australian Rainfall and Runoff (Babister & Barton, 2012). It can be seen in Figure 2 that whilst the peak 2011 level at Moggill can be matched using a higher Manning's n value (test ST01B), both sensitivity tests result in hydrographs that arrive too early and overstate the near steady state flows between 14 January and 18 January. In addition, the higher in-bank Manning's n values result in an unacceptable dampening of the tidal signal, particularly for locations on the Bremer River. A similar pattern with Fast Model results was observed for other gauges on the lower Brisbane River.

Notably, using a Manning's only approach failed to reproduce the stair-step pattern in flood levels longitudinally down the Brisbane River caused by the sharp bends and rock ledges. The in-bank Manning's n values of 0.038 and 0.041 attempt to match the steady state and peak flood levels at the Moggill gauge but significantly overestimate peak flood levels, and fail to reproduce the stair-step profile, between Moggill and the river mouth as shown in Figure 3 for the most downstream 30km reach of the Brisbane River.

The Detailed Model experienced similar issues although the differences were not so notable as the 2D solution better represented the energy losses at the river bends.

In summary, the modelled peaks at many gauges on the lower Brisbane River could not be matched to observed levels without resorting to relatively high in-bank Manning's n values, which then had a compromising effect on the calibration elsewhere. It was apparent that use of a Manning's n only approach would not result in an acceptable calibration.

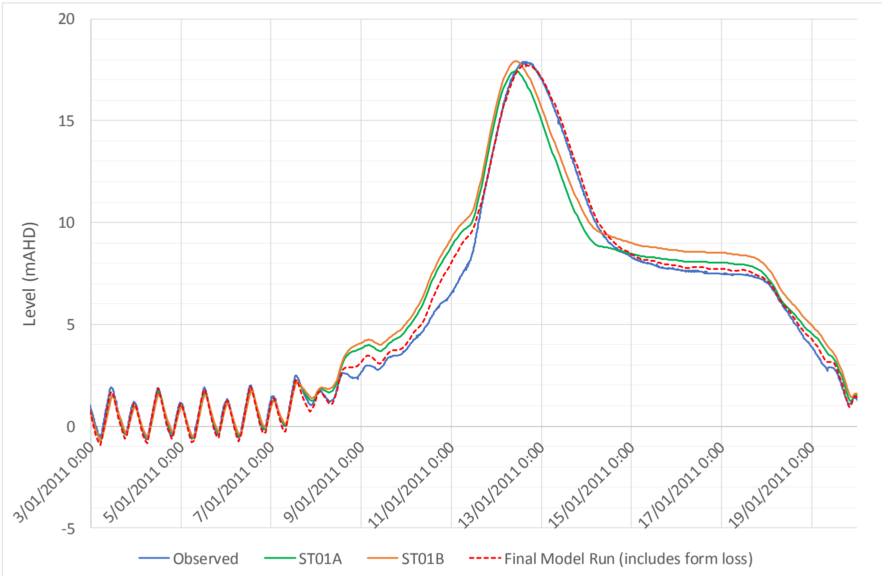

Figure 2 – Fast Model Calibration Testing of Manning's n Scenarios at Moggill (Based on Figure 4-4, Milestone Report 2, BRCFS, Ref: BMT WBM 2017)

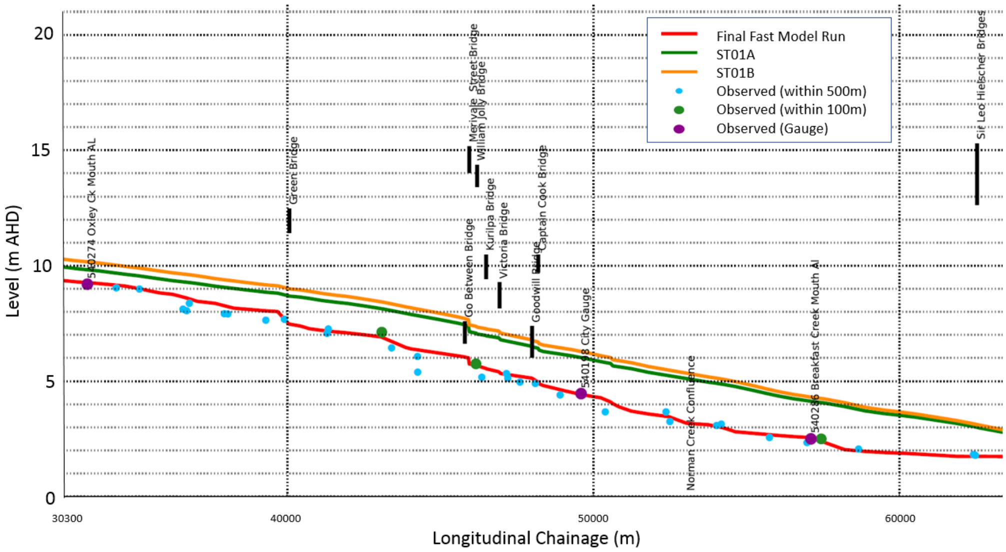

Figure 3 – Fast Model Calibration Testing of Manning's n Scenarios – Longitudinal Profiles (Extract from Plot 46, Milestone Report 2, BRCFS, Ref: BMT WBM 2017)

4.3. Supplemental Form Loss

It was demonstrated above that calibration to recorded flood levels could not be achieved solely by varying the Manning's n values; increasing values to raise water levels in order to match recorded levels served this purpose at specific locations but compromised the rest of the calibration by dampening and delaying the tidal signal and producing unacceptable longitudinal profile comparisons. To overcome these issues, the tidal Manning's n value of 0.022 was retained in both Fast and Detailed Models and additional form losses were introduced at sharp bends, rock ledges and other locations where significant energy losses occur.

Form loss, which can also be referred to as an energy loss, is a loss of available kinetic energy ($V^2/2g$) such as that which would occur due to water being forced around tight bends or from underwater obstructions such as rock ledges.

For the Fast Model, form losses were applied as both a constant (i.e. to all in-bank channels) and as targeted losses at river bends, known rock outcrops and major river confluences. For the Detailed Model, only targeted form losses were applied. The introduction of form losses generally had little effect on the tidal calibration with the tidal signal and range/amplification throughout the tidal reaches remaining well represented. However, it resulted in a significant improvement for the calibration to peak flood levels at gauges and flood marks.

5. FORM LOSS APPLICABILITY AND VALUES

5.1. Use of Additional Form Loss

As investigated in Sargent (1978), the Brisbane River is effectively a series of rock controlled steps/ledges with sharp bends and rock outcrops. As such there are many locations where complex three-dimensional flow patterns are likely to develop. These flow effects are enhanced by the resulting high velocities driven by steep gradients that develop during a flood.

It is the view of the authors that the energy losses which result from these obstructions to flow are more closely approximated by the energy (form) loss equation, rather than the Manning's equation, which represents the resistive force of the bed.

Justification and determination of values for additional form losses on the Brisbane River is supported by the high quality of available calibration data and the characteristics of the river flows during flood events. In particular, two elements of uncertainty that are commonly present when modelling catchments, but which were significantly reduced for the current calibration exercise were:

- Releases from Wivenhoe Dam, which regulates flow from approximately half the catchment, are known with a high degree of certainty thereby reducing the hydrological uncertainty.
- The near steady state releases during drain-down periods resulted in a near steady state flow condition for much of the lower Brisbane River, thereby reducing the hydraulic complexity to one of conveyance only.

Both of these factors, combined with the abundance and high quality of available calibration data, have provided a reasoned basis for applying additional form losses to both the 1D Fast Model and 2D Detailed Model, and have ultimately resulted in a much improved calibration.

5.2. Form Loss Values

The initial approach undertaken in determining appropriate values of targeted form loss was to consider the sinuosity index and the bend radius. However, it was found that a better outcome was obtained based on manual estimation. The estimation process allowed for similar bends to have a consistent value applied, for example in the 1D Fast Model a 180 degree bend was typically assigned a form loss of 1.5 and a 90 degree bend a form loss of 0.75.

When calibrating the Detailed Model it was found that 2D targeted form losses of around 20% of the coefficient value required by the 1D model gave the best results. These losses were applied on a unit length basis across a digitised plan area around the river bend. A 180 degree bend would therefore have an approximate total value of 0.3 and a 90 degree bend a value of 0.15. These values are approximate as each bend had varying hydraulic complexity due to factors such as tributary influences or rock outcrops.

As noted in Section 4.3, the Fast Model also applied a general form loss in addition to the targeted form losses at bends and other hydraulic features. General form loss values of 0.2/km and 0.3/km were applied depending on the reach under consideration.

6. OTHER CALIBRATION OBSERVATIONS

6.1. Catchment Changes

Flood events in 1999 and 2013 resulted in similar near steady state drain down releases from Wivenhoe Dam of between 1700 and 1800 m^3/s. However, the recorded flood level at the Savages Crossing gauge (see Figure 1 for location) was around 1 m higher in 1999 than in 2013 for these similar flow conditions. This was likely attributed to significant damage to channels and stripping of vegetation caused by the 2011 flood.

6.2. Superelevation

In hydraulics of river flows, superelevation is the term given to the phenomena of water piling up on the outside of a bend due to radial acceleration and associated centrifugal forces driving water to the outer bend. At various locations during the 2011 flood event peak level calibration data was available on both in inside and outside of river bends and indicated that superelevation had occurred.

Figure 4 illustrates the 2011 flood at Brisbane CBD where the river abruptly bends three times. At each bend, there are recorded flood marks on both sides of the river varying in height by up to 0.6m across the river. The Detailed Model is showing the same superelevation effects to those recorded highlighting the importance of using a full 2D equation solution where substantial superelevation effects occur. Figure 4 also shows the water surface contours highlighted in light grey in 0.1m increments illustrating how the water level can vary significantly from one side of the river to the other. The Fast Model does not reproduce this effect due to the 1D solution.

6.3. Energy Loss at Confluences

At the confluence of the Brisbane and Bremer Rivers, available peak level recorded flood marks show a 0.4m water surface drop in the Brisbane River between the confluence and the Moggill Alert Gauge. This occurs over a relatively short distance due to the two rivers converging and demonstrates the energy loss that occurs due to the two rivers combining.

The 2D Detailed Model slightly underpredicted the drop in water surface with no additional form loss applied. The 1D Fast model significantly under predicts the drop as it does not simulate the losses associated with 2D horizontal flow patterns generated at the confluence. The introduction of additional form losses across the confluence with coefficient values of 1.0 in the Fast model and 0.2 in the Detailed Model provided a good match to the recorded data, and was in general accordance with the rule of thumb by which the Detailed Model requires 20% of the Fast Model losses.

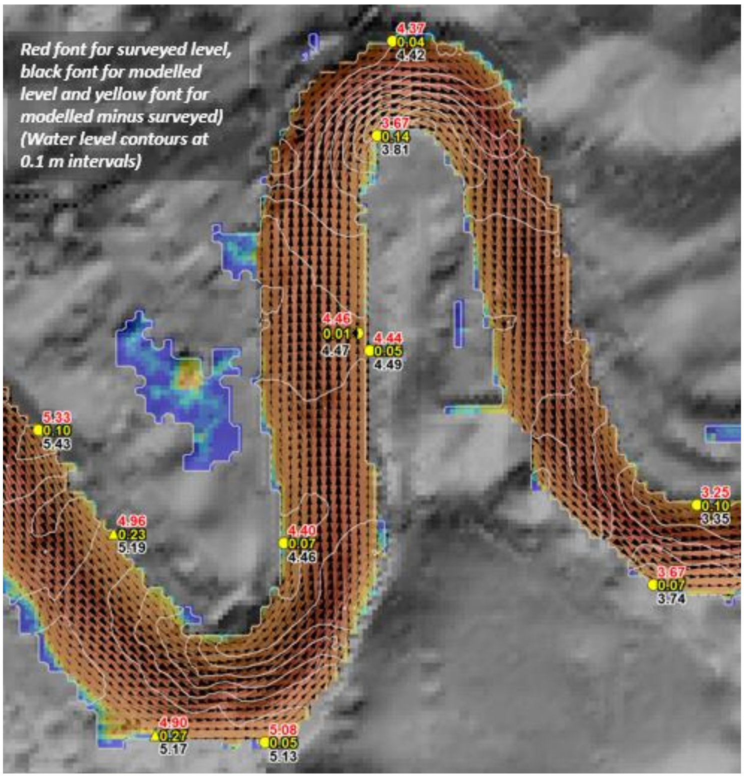

Figure 4 – Example of 2D model Reproduction of Superelevation at River Bends (Figure 4-1, Milestone Report 3, BRCFS, Ref: BMT WBM 2017)

7. CONCLUSIONS

Two hydraulic models were developed and calibrated for the Brisbane River Catchment Flood Study; a 1D 'Fast Model' and a predominantly 2D 'Detailed Model'. Whilst the models had different purposes for the study, they were developed using the same datasets and boundary conditions. Developing and calibrating the two models using a comprehensive and high quality calibration data, offered a rare opportunity to compare the two schematisations.

A key finding was that a satisfactory calibration based on adjustment of Manning's n values alone could not be achieved. Supplementary form (energy) losses introduced at locations where strong three-dimensional flow effects were likely such as at river bends, rock outcrops and major confluences was found to produce a significantly superior calibration.

An approximate rule of thumb based on model findings was that the additional form loss required in the 2D schematisation is around 20% of that required for the 1D schematisation.

The superiority of a 2D scheme over a 1D scheme is evident based on its ability to reproduce hydraulic effects such as superelevation, which a 1D scheme does not simulate. However, it was found that both models could be robustly calibrated to a wide range of events of differing magnitudes and characteristics using a combination of standard Manning's n values and form losses.

8. ACKNOWLEDGMENTS

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