

TUFLOW GPU – Best Practice Advice for Hydrologic and Hydraulic Model Simulations

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Graphics Processing Unit (GPU) computing represents a significant advancement in the continued evolution of flood modelling. BMT WBM the developers of TUFLOW are continually undertaking research work focusing on how best to use the software. This paper presents a range of GPU model validation results and summarises best practice recommendations on how to optimise execution to achieve fastest model simulation and most accurate results for hydrologic and hydraulic applications.

1. INTRODUCTION

Numerical modelling has been the industry standard assessment approach to estimating flood behavior for over 20 years. Despite their widespread use; data availability, computation overhead and hardware constraints have historically limited either the spatial coverage or resolution of modelling efforts. A range of factors have combined over the past five years to fuel major advances in two-dimensional (2D) flood modelling that largely remove these limitations. The factors are primarily:

- Computer hardware improvements, particularly the Graphics Processor Unit (GPU);
- GPU flood modelling software development; and
- Significant increases in data availability and accuracy.

The volume of computations possible within GPU hardware has advanced exponentially in the last decade primarily in response to the computer gaming market. TUFLOW users are now benefiting from these advances through the use of TUFLOW GPU. Testing has shown that TUFLOW GPU is between 20 to 100 times faster than its Computer Processor Unit (CPU) counterpart, TUFLOW Classic. This simulation speed-up equates to super computing power within a desktop computer!

Similar to GPU technology, parallel advances have also been made in remote sensing with digital three-dimensional (3D) topographic information now easily accessible for entire catchments. Combined with GPU hardware, catchment-wide data can now be used to its full potential for hydrologic and hydraulic applications.

Direct rainfall hydraulic modelling using TUFLOW GPU offers a new alternative to traditional hydrology modelling. The hydraulic model routes the flow based on the model topography and in doing so estimates the flood behavior across the entire catchment. It's a promising and relatively new assessment methodology. This paper presents real world direct rainfall model calibration results, provides guidance to practitioners using the approach and discusses potential future areas of research. This paper also provides guidance regarding how to best optimize GPU hardware performance.

1.1. TUFLOW GPU Overview

TUFLOW's GPU Module is a powerful solver built into the TUFLOW software suite. As its name implies it utilises the substantial computing ability of modern Graphics Processor Units. It is an explicit solver of the full 2D Shallow Water Equations including a sub-grid scale eddy viscosity model. The scheme is both volume and momentum conserving, is 1st or 2nd order in space, 4th order in time and can be run with either adaptive or fixed time stepping. TUFLOW GPU can be run on a single GPU or across multiple GPU cards in parallel.

Presently the solver runs 2D models only but thanks to the power of modern GPUs very large models (>100 million cells) with fine grids can now be run within a sensible timeframe. Refer to the TUFLOW manual for more detailed information: www.tuflow.com/Tuflow%20Documentation.aspx.

2. DIRECT RAINFALL MODEL VALIDATION

TUFLOW GPU has the promising potential for whole-of-catchment direct rainfall applications. Direct rainfall hydraulic modelling applies rainfall to every calculation cell within a 2D hydraulic model. The hydraulic model topography implicitly routes flow and in doing so calculates flow, water level, depth and velocity information across the entire catchment, as demonstrated in Figure 1.

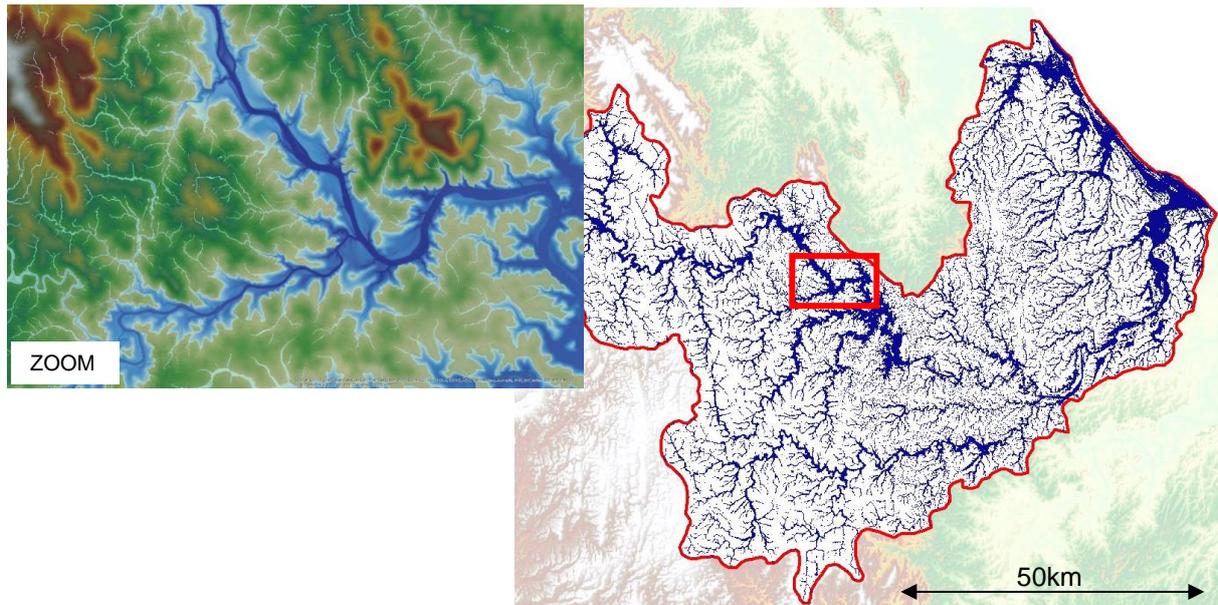


Figure 1 TUFLOW GPU Direct Rainfall Simulation Result Example

Although the direct rainfall approach is gaining momentum within the consulting industry, limited independent research has been undertaken assessing whether the fundamental calculation assumptions within 2D Shallow Water Equation based flood modelling software is valid using the direct rainfall approach. This work aims to initiate this discussion by presenting modelling results validated against real world recorded data.

2.1. Assessment Approach

The assessment approach for this study is summarized as follows:

- 1) Develop a 2D TUFLOW GPU model using industry standard model parameter values.
- 2) Calibrate the TUFLOW GPU model to recorded water level gauge data.
- 3) Verify the TUFLOW GPU model flow results against estimates derived using a calibrated URBS hydrology model.
- 4) Sensitivity test TUFLOW GPU model resolution assumptions to determine flow and water level result convergence.
- 5) Sensitivity test GPU hardware configurations to achieve the fastest possible simulation time.

2.2. Study Area

The Johnstone River catchment in far north Queensland, Australia has been selected for this calibration/validation exercise. It was selected due to:

- 1) Availability of model input data: Accurate LiDAR topography, river bathymetry data and high

- resolution areal imagery (provide by the Cassowary Coast Regional Council (CCRC)).
- 2) Availability of recorded calibration data for water level verification:
 - a. Good quality rainfall data coverage over the entire catchment;
 - b. Accurate river water level gauge calibration data;
- 3) Availability of a catchment wide calibrated hydrology model for secondary flow result comparison purposes.

The catchment covers an area of 1645km². It's upper and lower reaches are characterised by rural farmland. Grazing pastures dominate the upper catchment tablelands and sugar cane covers much of the lower catchment floodplain. The central region of the catchment is a National Park area covered in dense rainforest. Elevations vary from sea level (0mAHD) to over 1200mAHD within a distance less than 70km. The region is one of the wettest in Australia. The town of Tully, 40 km south holds Australia's annual rainfall record, 7.93 metres during 1950. Refer to the Reference list for links to past TUFLOW work in the catchment (BMT WBM, 2014).

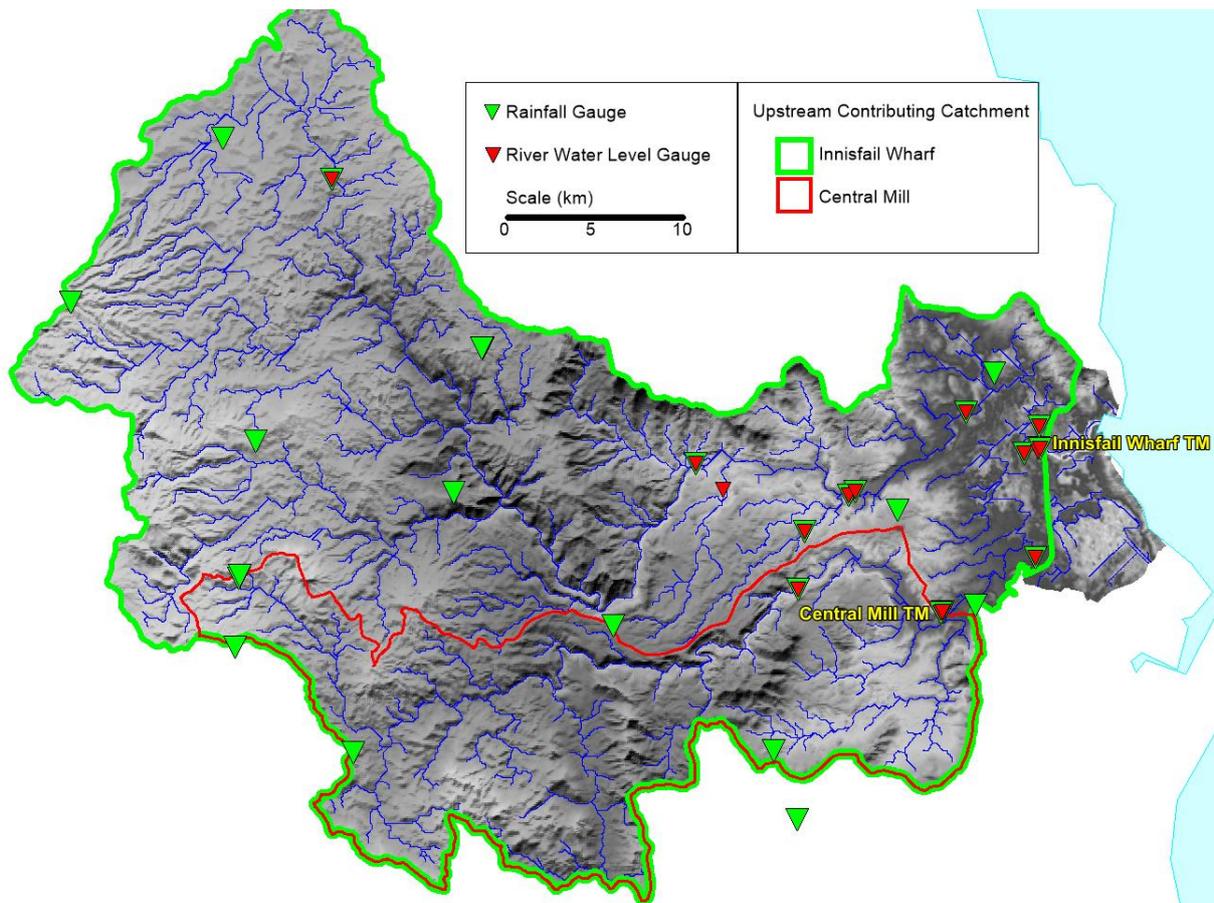


Figure 2 Johnstone River Catchment: Calibration Data Recorders

2.3. TUFLOW GPU Model Description

A brief description of the Johnstone River TUFLOW GPU model is summarised in Table 1.

Table 1. Johnstone River TUFLOW GPU Model Description

Hydraulic Model Feature	Description
Inflow Boundary Condition Specification	Direct rainfall method. Inflow rainfall is applied to every calculation cell within a 2D hydraulic model. The hydraulic model routes flow automatically based on the topographic relief.

	TUFLOW’s automated rainfall grid approach was used to distribute the recorded point pluviograph rainfall information across the entire catchment.
Calibration Event	February 2009. The event is a multi-peak flood which occurred over a 12 day period. It’s magnitude is comparable to a 20%AEP design flood event
Rainfall Loss Method	Infiltration
Downstream Ocean Boundary	Recorded water level data is not available at the river entrance. Water level time series data has been derived from astronomical constituent data.
Bed Resistance Approach	Depth varying Manning’s ‘n’
Model Topography Data	Airborne Laser Survey (ALS) was commissioned jointly by Emergency Management Queensland and CCRC in 2008/2009 for the lower (eastern) half of the catchment study area. This data was used as the primary topography dataset. The ALS data was supplemented with bathymetric data for in bank areas. Upstream (western) areas of the catchment were modelled using topographic data derived from the Shuttle Radar Topography Mission (SRTM), provided by Geoscience Australia
Cell Resolution	A 30m cell size was adopted. This provides sufficient resolution for approximately four (4) cells across the main river channel in the central region of the model. This discretization translates to ten (10) cells across the main channel in the lower catchment.

2.4. TUFLOW GPU Model Calibration Results

TUFLOW GPU direct rainfall hydraulic model results are presented in Figure 3 and 4 for a sample location in the middle and lower catchment (labeled in Figure 2).

- Central Mill is approximately 20km upstream of the ocean entrance, beyond the tidal limit.
- Innisfail Wharf is nearby the North and South Johnstone River confluence approximately 5km upstream of the ocean entrance and is tidally influenced.

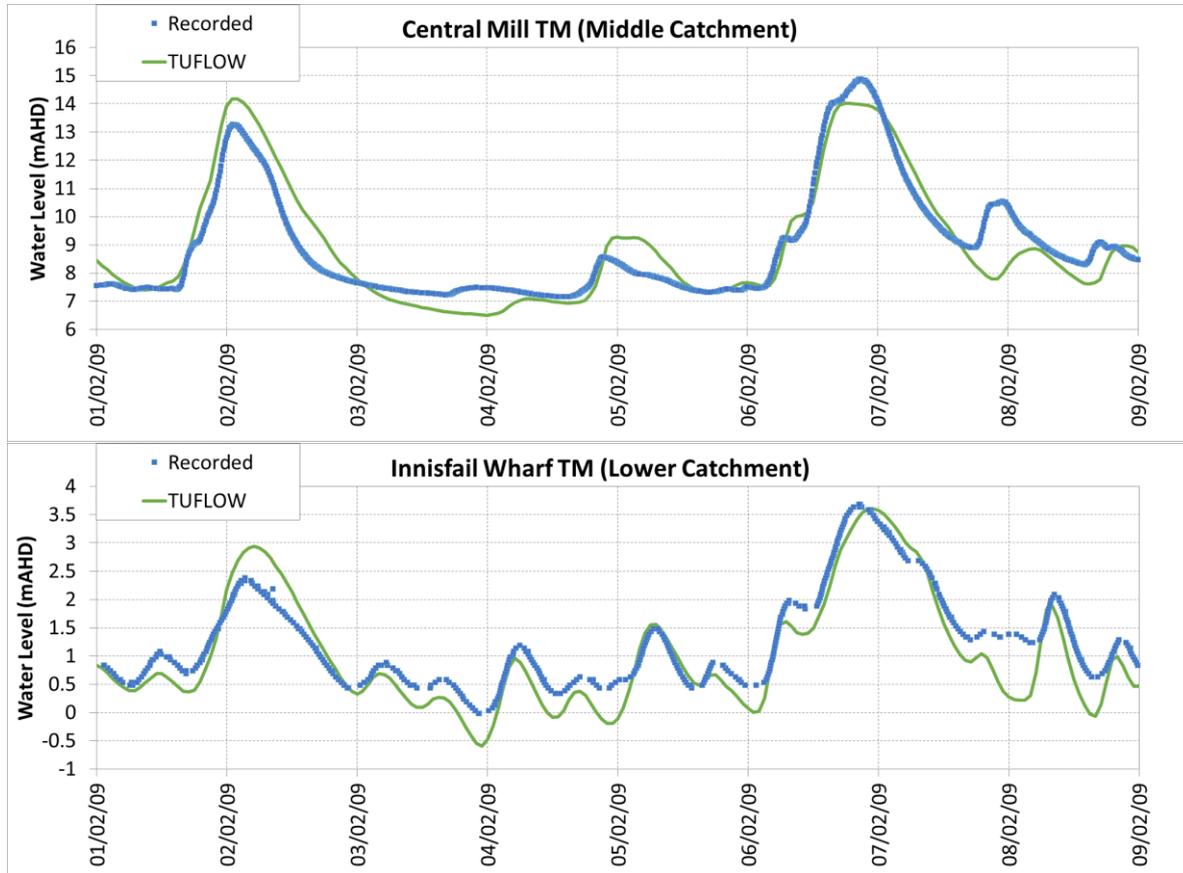


Figure 3 TUFLOW GPU Water Level Calibration Results (Lower Catchment)

The TUFLOW GPU direct rainfall model calibrated well to recorded data.

- The timing and level results compare well against the recorded dominant flood peaks on the 2nd and 7th of February at both water level recording locations.
- Result variance during the minor flood peaks proceeding and after the dominant flood periods at Central Mill can be attributed to special variability in catchment rainfall not adequately captured by the seven (7) available upstream rainfall recording stations.
- Slight under estimation of levels at Innisfail Wharf during the period of dominant tidal influence is expected. The TUFLOW GPU model downstream boundary is based on astronomical constituent data, and as such, doesn't include allowance for the ocean surge associated with the event. Elevated ocean levels were likely to have occurred during the event due to barometric and onshore wind setup. Unfortunately, recorded data doesn't exist to verify the ocean surge contribution.

The calibration effort required a number of iterations and resulted in several key learnings, as follows:

- 1) The upstream (western) model topography dataset was sourced from SRTM data. The coarseness of the dataset resulted in artificial depression storages in numerous upstream locations. To reduce these effects:
 - a. GIS pit filling of the SRTM data was used to remove the model storage artefact.
 - b. The GIS software "Stream Builder" was used to derive streamlines within the catchment. This breakline data was used within the model to ensure continuous channel flow paths for all minor tributaries.
 - c. Antecedent rainfall was simulated for a period of three days prior to the main event to fill any remaining artefacts not resolved by Items a and b.
- 2) Sensitivity testing was used to refine the initial and continuing infiltration loss assumptions. The final selected values were:
 - a. Initial Loss = 0mm
 - b. Continuing loss = 2mm/hour

2.5. TUFLOW GPU Hydraulic Model / URBS Hydrology Model Comparison

The Australian Bureau of Meteorology (BoM) have developed and calibrated an URBS runoff-routing hydrology model of the Johnstone River catchment for the purpose of flood forecasting. The URBS model has been calibrated to the following historic events: 1967, 1982, 1986, 1990, 1994, 1995, 1996, 1997, 1998, 1999 and 2009. TUFLOW GPU direct rainfall hydraulic model results have been compared against URBS hydrologic model results as a method to validate its flow estimate capacity. The comparison is provided in Figure 4.

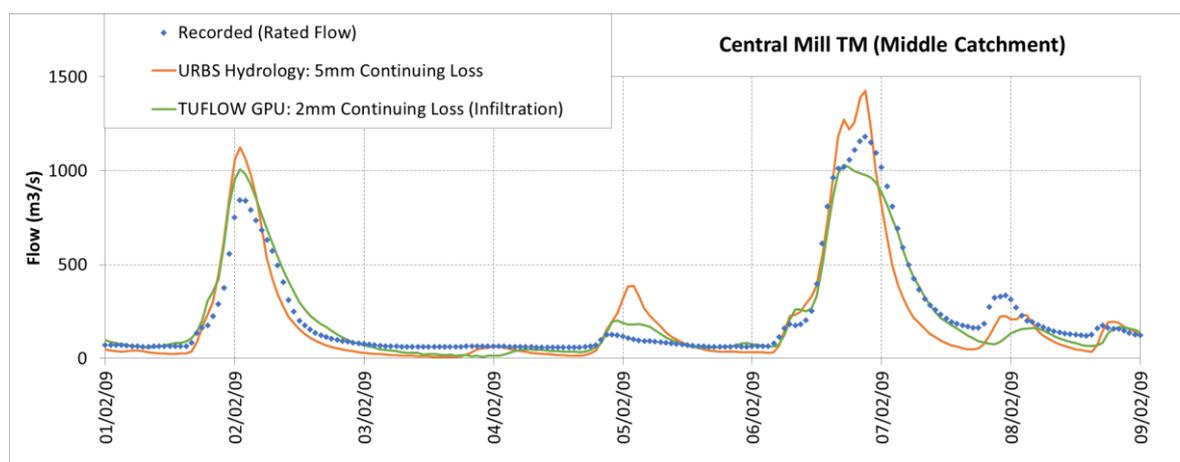


Figure 4 TUFLOW GPU / URBS Hydrology Model Flow Validation Results

The TUFLOW / URBS model result comparison in Figure 4 confirm the hydraulic model direct rainfall approach is a suitable alternative to commonly used runoff-routing hydrology modelling. Importantly however, this exercise highlights the need for caution by showing that model parameters used by runoff-routing hydrology models are not directly transferable to direct rainfall hydraulic models. The

TUFLOW GPU required a continue loss parameter of 2mm/hr to calibrate. In contrast, the Johnstone River URBS model required value of 5mm/hr. The difference in value can be explained by considering the different loss method used by both models:

- 1) TUFLOW uses an infiltration approach, removing water from wet cells within the model.
- 2) URBS uses a rainfall loss approach, removing water volume from the rainfall hyetograph before it is applied to a hydrology sub-catchment.

Large catchments with long catchment response times may be flooded for extended periods after rain has ceased. TUFLOW’s infiltration method will represent the ongoing losses during the period of no rain. By comparison the hydrology model rainfall loss approach cannot. As such, hydrology models using the rainfall loss approach (such as URBS) requires a greater continuing loss value to compensate for this limitation. This is demonstrated in Figure 5. The cumulative loss amount in both cases is approximately 500mm for the 12 day event duration.

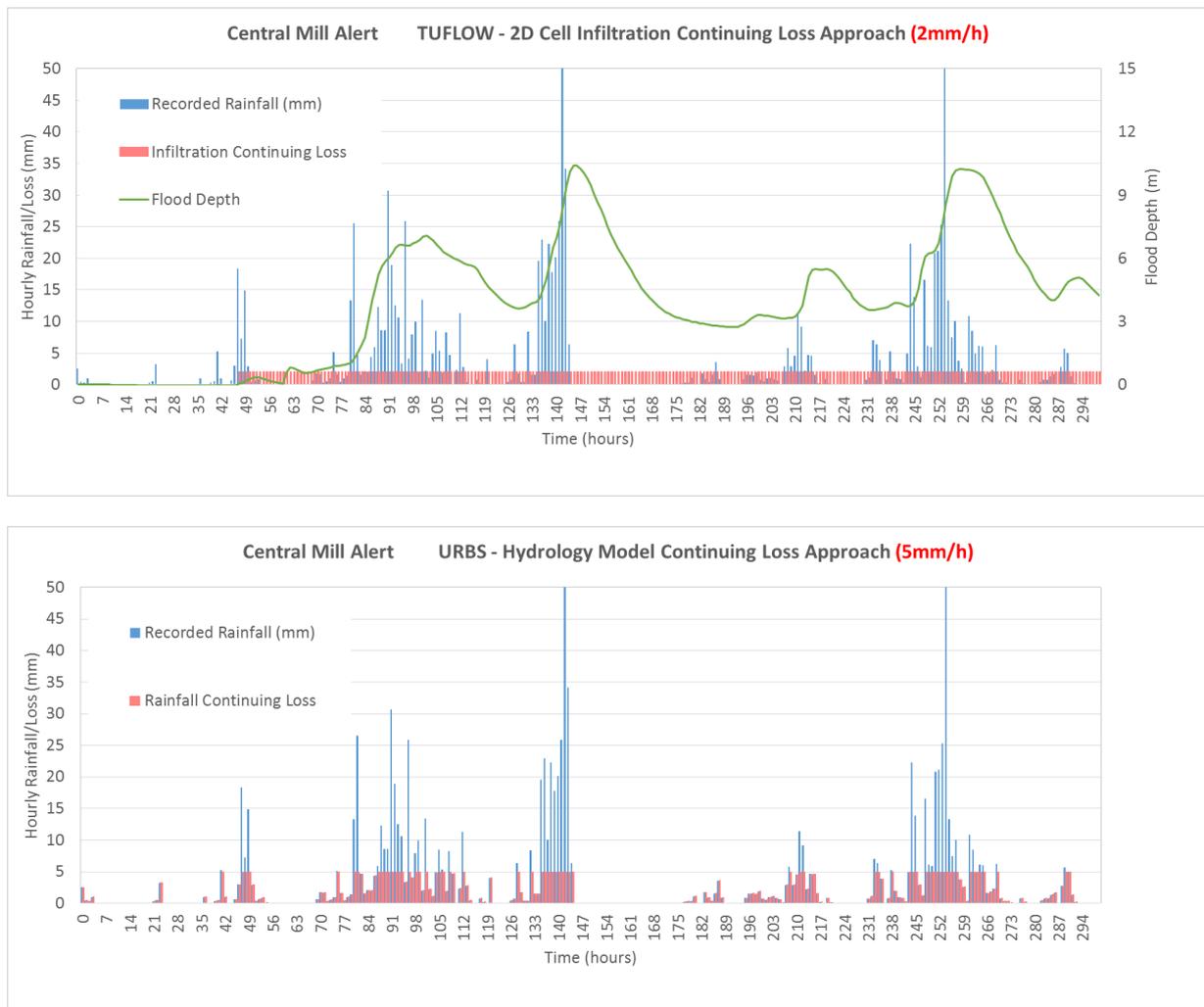


Figure 5 Loss Comparison (Hydraulic Model Infiltration vs Hydrology Model Rainfall Loss)

2.6 TUFLOW GPU Model Resolution Sensitivity Testing

Model cell size sensitivity testing has been completed for the purpose of identifying result convergence trends. The Johnstone River model was run for a range of grid resolutions: 120m, 60m, 30m, 25m and 20m. The water level and flow results at the Central Mill gauge location are shown in the Figure 6.

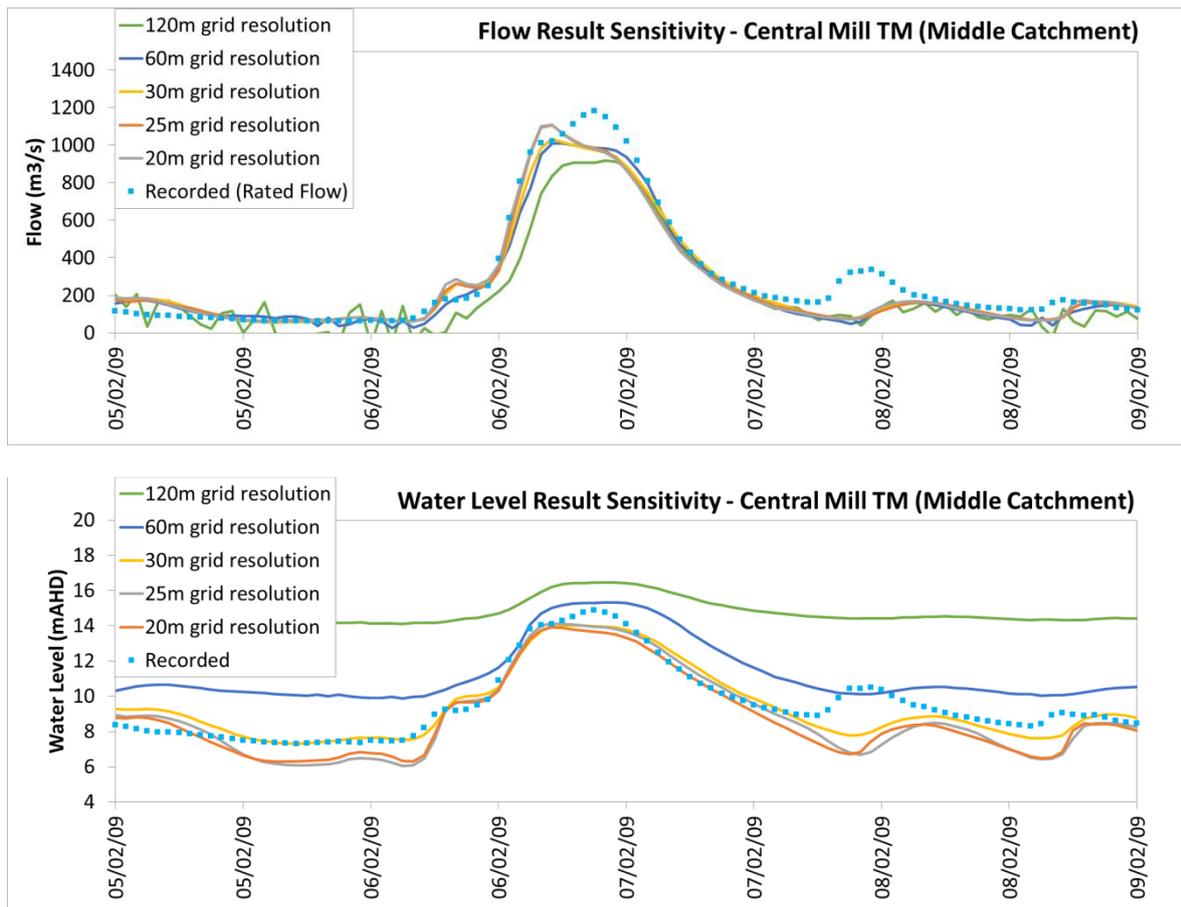


Figure 6 TUFLOW GPU Model Resolution Sensitivity Test Results

The Johnstone River TUFLOW GPU model resolution sensitivity test results highlight:

- 1) Flow estimates converge to a common result at a grid resolution of 60m or less.
- 2) Level estimates converge at a grid resolution of 30m or less.

This result trend has significant implications for practitioners. If the model purpose is focused on flow estimation, larger cell sizes can be used successfully. Finer grid resolution will however be required if the desired output is accurate flow, level, velocity and depth.

Translating this finding to practical applications, if a studies area of interest is in the downstream floodplain portion of a catchment, focused attention to the model grid resolution should be based on that region of the catchment. A minimum of four to six cells should represent the main river channel at the area of interest. Less resolved discretization of tributaries upstream of the subject area will have limited impact on the flow estimate originating from those catchments.

2.6. GPU Hardware Configuration Sensitivity Testing

TUFLOW GPU can run on a single GPU or across multiple GPU cards in parallel. Gold Coast City Council have tested the impact of running multiple GPU cards on simulation time. Their testing considers one model at two resolutions. The coarse test model uses a 10m grid resolution, producing 750,000 cells. The finer test model adopts a 2m grid resolution, producing 18,750,000 cells. All remaining inputs to both models are identical. The assessment results are presented in Figure 7.

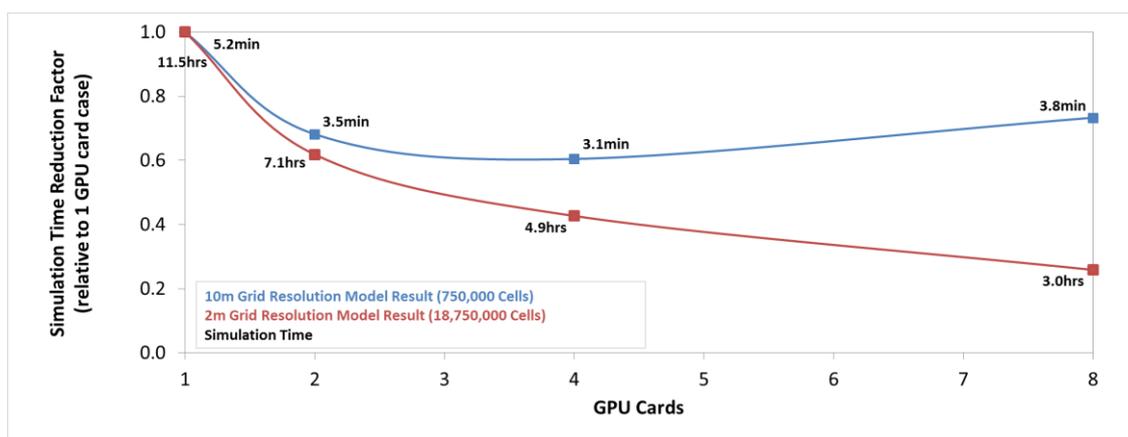


Figure 7 GPU Hardware Optimization

This testing highlights that multiple GPU cards can be used to significantly reduce larger models simulation time. Using multiple GPU cards reduced the 2m resolution model simulation time from 11.5 to 3.0 hours. By comparison the CPU simulation time was 449 hours! It is however worth noting that using multiple GPU cards does not necessarily result in reduced simulation times in all cases. This is evident in the Figure 7 10m grid resolution results. The test model ran slower on 8 GPU cards than it did on 4. This occurs due to parallelisation overhead (the time required to communicate information between the neighboring GPU cards) dominating the simulation time instead of the hydraulic calculations. This is worth considering when allocating hardware to a simulation. The test results suggest there may be benefit using an additional GPU card for each additional 500,000 to 1,000,000 2D cells.

In addition to GPU card configuration, we have also coordinated some GPU card benchmarking. The work compares the performance of approximately 30 different types of card. This is a useful dataset for people wishing to design a computer for the specific purpose of TUFLOW GPU modeling. The benchmark results are available here: http://wiki.tuflow.com/index.php?title=Hardware_Benchmarking

3. DISCUSSION AND CONCLUSION

This paper highlights that catchment scale GPU direct rainfall hydraulic modelling can be used as a suitable alternative to runoff-routing hydrology modelling. It is particularly useful for situations requiring flow, water level, depth and velocity information across the entire catchment. By comparison hydrology modelling can only produce flow estimates in discrete locations. The paper provides a number of key findings, including:

- Rainfall loss parameters used by runoff-routing hydrology models are not directly transferable to direct rainfall hydraulic models. Practitioners are warned against using hydrology loss parameters within direct rainfall hydraulic models. Calibration should be used to identify correct parameter values. In addition, further testing of more advanced infiltration methods such as Horton and Green-Ampt is recommend.
- Hydraulic modelling is more sensitive to topography data quality than traditional hydrologic methods. Improved data treatment approaches should be investigated for regions of poor data quality.
- Purpose should define the model design when using TUFLOW GPU. If the purpose is focused on flow estimation, coarser grid resolution and lower quality topography data can be used. If accurate flood level, depth and velocity data is required, a finer grid resolution and higher quality topography data will be required.
- Multiple GPU cards can be used in parallel to speed up TUFLOW GPU simulations. However, model size should be considered prior to allocating hardware to a simulation.

A key learning from this work is that calibration is an essential element of any modelling investigation. Recorded data comparison is the most robust and defensible means to manage modelling uncertainty. This study would not have been possible without it. Agencies need to support installation of data recorders and practitioners need to emphasise the need for calibration during project scoping with end users.

4. REFERENCES

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