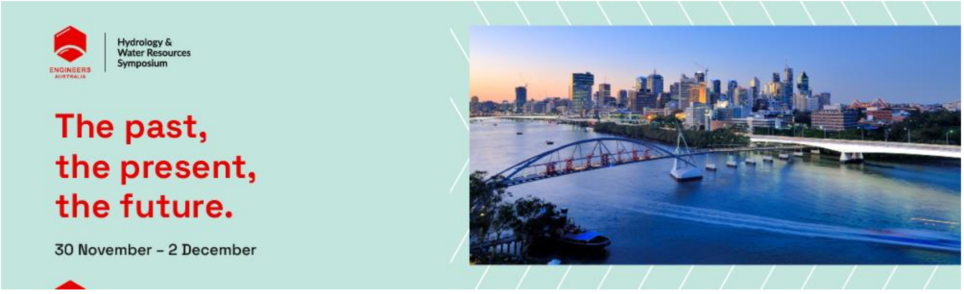

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Hydraulic Modelling 2D Cell Size Result Convergence – Comparing the Performance of Different Shallow Water Equation Solution Schemes

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ABSTRACT

The 2D cell or element sizes used for a 2D hydraulic model can have a major bearing on the accuracy and defensibility of the model. If the 2D cell sizes are too coarse, the physical terrain and hydraulic complexity may be poorly represented leading to unacceptable inaccuracies and a high degree of uncertainty in the model outputs. Conversely, 2D cell sizes that are unnecessarily too fine can result in excessively long simulation times and workflow inefficiencies. The need for cell size convergence testing, the demonstration that by reducing the cell size there is no demonstrable change in results, is an important quality control check, often overlooked. In addition, recent developments in utilising a sub-grid sampling approach to representation of the 2D cell bathymetry can substantially improve cell size convergence to the point where models can be confidently simulated using much coarser resolutions, greatly reducing simulation times and improving workflow efficiency.

Models that can experience the most acute inaccuracies due to cell resolution are whole of catchment, direct rainfall or rain-on-grid, models, and riverine and urban surface water flood models where the primary flow paths are poorly represented by the selected model cell size. Whole of catchment models often utilise 2D cells larger than the width of the creeks and rivers, particularly in the upper catchment areas. This can cause substantial retention of water and poor conveyance as the flows down the waterways are often choked and obstructed due to the poor definition of the channel bathymetry by the large grid cells, which averages out the topographic variability. Similarly, for flood models, poor spatial representation of the main flow path bathymetry results in falsely steepening the water surface gradient, producing unreliable results.

Examples of various cell size convergence tests for first-order, second-order traditional and second-order sub-grid sampled 2D schemes are discussed and presented. The research findings highlight that the solution convergence performance varies significantly depending on the chosen scheme.

PAPER

Introduction

The 2D cell or element sizes used for a 2D hydraulic model can have a major bearing on the accuracy and defensibility of the model. If the 2D cell sizes are too coarse, the physical terrain and hydraulic complexity may be poorly represented leading to unacceptable inaccuracies and a high degree of uncertainty in the results. Conversely, 2D cell sizes that are unnecessarily too fine can result in excessively long simulation times and workflow inefficiencies. It is the modellers responsibility to select an appropriate cell size for the model area being studied. One size does not fit all. The appropriate cell resolution will depend on multiple factors, including, although not limited to, the physical features present in the subject area, the desired objectives of the study and the underlying calculation methods used by the 2D hydraulic modelling software.

Cell size result convergence testing is a robust practical approach to assess and confirm that the predictive performance of a hydraulic model is independent of user defined cell resolution assumptions. This paper introduces the concept of cell size result convergence testing and uses two case study examples to highlight how the fidelity of the calculation approach used by the hydraulic modelling software can influence the selection of an appropriate cell size. Three different calculation approaches are tested using TUFLOW HPC version 2020-10-AD.

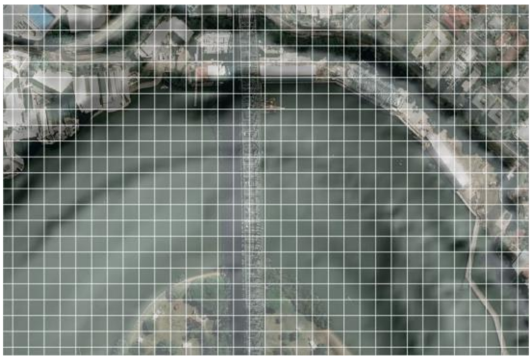
Background

Cell Size Result Convergence Testing

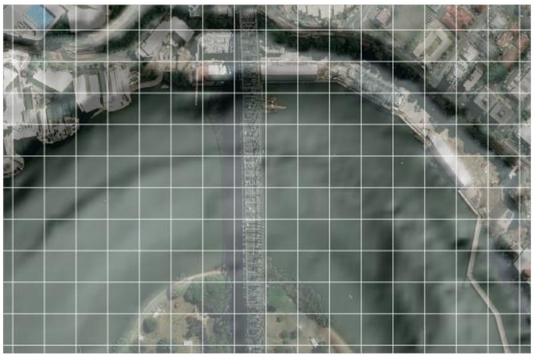
Solution convergence to cell size refers to the tendency for model simulations results to trend towards a common answer as cell size decreases. In well-designed hydraulic modelling software this behaviour occurs due to the discretisation of topographic features that influence the hydraulic flow behaviour better approximating reality as resolution increases.

The practical test required to complete cell size converge testing is simple, yet extremely high impact in terms of project outcomes. As described above, the test involves reducing a model's cell resolution and reviewing results to assess the cell size assumption influence on the simulation results. The process aims to identify the largest cell size possible to achieve a consistent simulation result (i.e. a simulation result that is independent of the user defined cell size assumption). Identifying this optimum value will avoid the situation where an unnecessarily small cell size is chosen, which subsequently translates to longer than necessary simulation times with no significant improvement in simulation result. Figure 1 demonstrates this concept. The 40 x 40 metre cell resolution model produces a result at the reporting location that is consistent with the finer cell resolution model simulations. Its simulation time is however significantly less. It represents the optimum cell size value to achieve reliable results in the fastest possible time.

This paper does not discuss the question of convergence acceptability criteria for catchment scale flood study applications. Broader consultation with industry is required to establish guidelines on this topic. It is however expected that "acceptability" criteria values or targets would vary depending on study objectives and flood sensitivity of the local environment and receptors, including residents, in recognition of their unique site specific risk profiles.



20m Cell Size Example (Kangaroo Point, Brisbane River)



40m Cell Size Example (Kangaroo Point, Brisbane River)

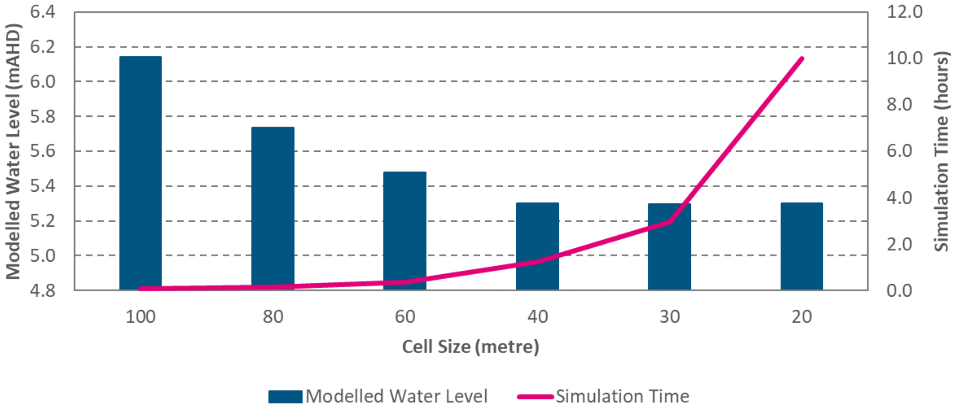


Figure 1. Cell Size Convergence Concept Example

Software Scheme Influence on Cell Size Convergence Performance

2D cell size convergence performance is influenced by the solution scheme assumptions adopted by 2D hydraulic modelling software to solve the 2D depth averaged Navier Stokes equations (also known as the Shallow Water Equations (SWE)).

This research compares hydraulic model results to recorded flood levels during historic events at two case study locations to assess the relative convergence performance associated with three common commercially used calculation approaches. Listed in increasing order of computational complexity, the three tested calculation approaches are as follows:

1. First-order (1st Order) spatial scheme using traditional cell centre/side topography sampling (1st Order Traditional).
2. Second-order (2nd Order) spatial scheme, traditional cell centre/side topography sampling (2nd Order Traditional).
3. 2nd Order spatial scheme, Sub-Grid Sampled (SGS) topography sampling (2nd Order SGS).

Of the above options, 1st Order and 2nd Order refers to the approximation precision of the SWE momentum equation solution, with high order approximations exhibiting greater precision. Traditional and SGS topography sampling refers to the approach used for the topography data interpretation.

In both the Traditional and SGS topography sampling approaches, Digital Elevation Model (DEM) topography data is typically available at a finer resolution than the hydraulic model computational grid resolution.

- Traditional topography sampling sets the cell elevation as either the DEM elevation at the cell centroid or the average elevation within the cell. The resulting mesh is a series of flat-bottomed cells with linear relationships between water surface elevations and cell water volume (cell water depth multiplied by cell area). Furthermore, connections between adjacent cells and the cell faces are rectangular in shape, with linear relationships between water surface elevation and the face flux area used to convey flow.

- SGS topography sampling extracts sub-grid data from an underlying DEM to develop a non-linear relationship between the water surface elevation and the cell's volume to describe the cells' storage capacity. SGS also generates a non-linear relationship between the water surface elevation and the cell face area and cell width (or wetted perimeter) to improve the representation of the fluxes across the cell faces as flow is conveyed throughout the model domain. The SGS approach still computes a single water level for each cell, but the computations to determine the cell volume and cell face fluxes utilise the higher resolution terrain data.

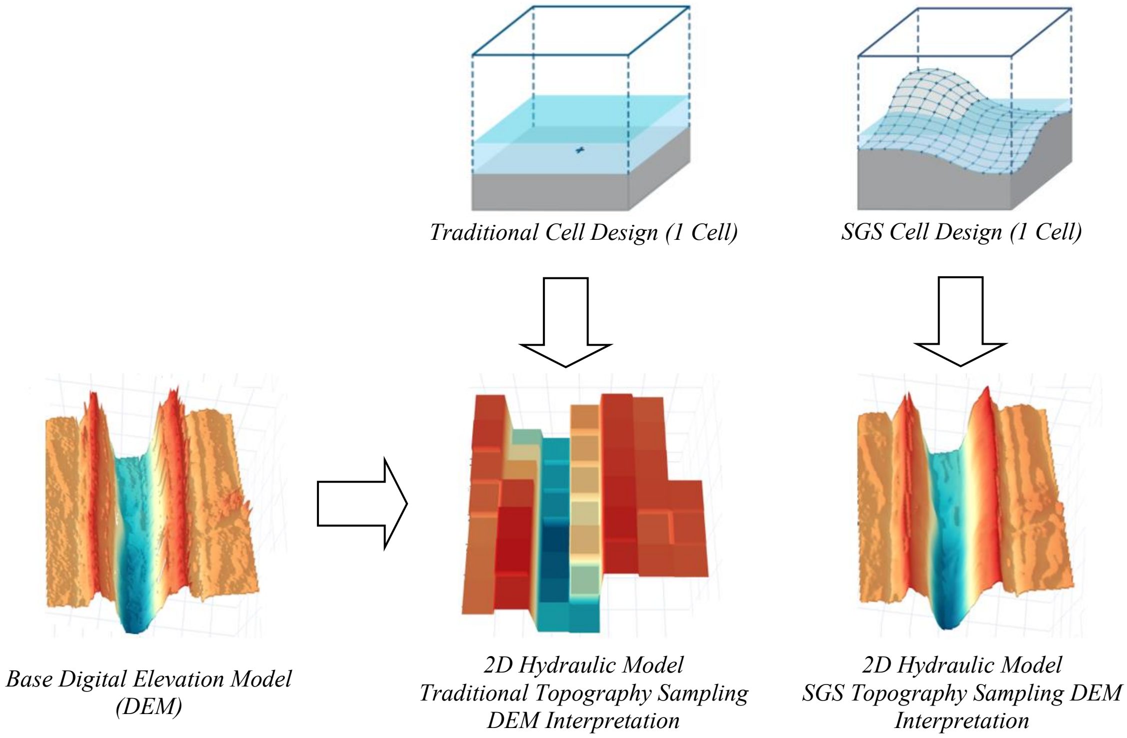


Figure 2. 2D Topography Sampling Concept and DEM Interpretation (Traditional vs SGS)

Case Study Assessments

This paper uses two case study locations to assess the relative cell size result convergence performance associated with the above-mentioned calculation approaches, 1st Order Traditional, 2nd Order Traditional and 2nd Order SGS.

Case Study 1: Brisbane River

The 2011 Brisbane River flood event represents an excellent dataset for testing hydraulic modelling software. The data inputs available for model development and validation are of excellent quality and reliability, including:

1. High quality river bathymeter data, land-based LiDAR and landuse data (BMT WBM, 2016).
2. Extensive historic event flood calibration data for model validation purposes (BMT WBM, 2016).
3. High certainty catchment flow and water level boundary condition information:
    - Inflows are derived by independent URBS hydrology modelling as part of the *Brisbane River Catchment Flood Study: Comprehensive Hydrologic Assessment*.

Validated to multiple river gauges. (Aurecon, 2015).

- The flood model developed for the *Brisbane River Catchment Flood Study: Comprehensive Hydraulic Assessment* was extensively calibrated to 1000's of peak flood level marks and over a dozen river gauges for multiple events of varying magnitude (BMT WBM, 2016).
- The hydrology and hydraulic model flow estimates were further validated by physical Acoustic Doppler Current Profiler flow gauging at the Centenary Bridge (upstream of the model extents shown in Figure 3 for this benchmarking exercise) (BMT WBM, 2016).

The hydraulic conditions associated with the river flooding are complex. The flows are extremely dynamic; up to 30 metres deep and 4 m/s with numerous 90-to-180-degree river bends creating regions of high turbulence with associated hydraulic losses.

A 10-kilometre stretch of the Brisbane River has been extracted from the broader Brisbane River catchment dataset (BMT WBM, 2016) for the purpose of this testing. The model extent, boundary condition locations, and the surveyed peak flood marks used for this research are presented in Figure 3. The boundary condition values are shown in Figure 4.

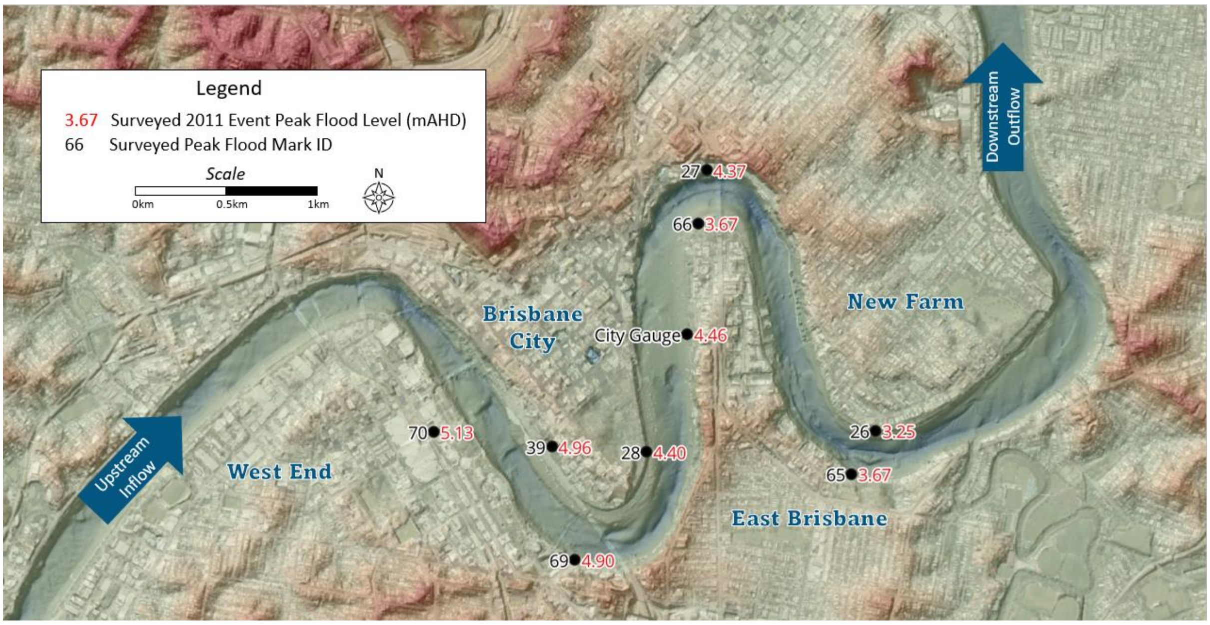


Figure 3. Brisbane River Model Area

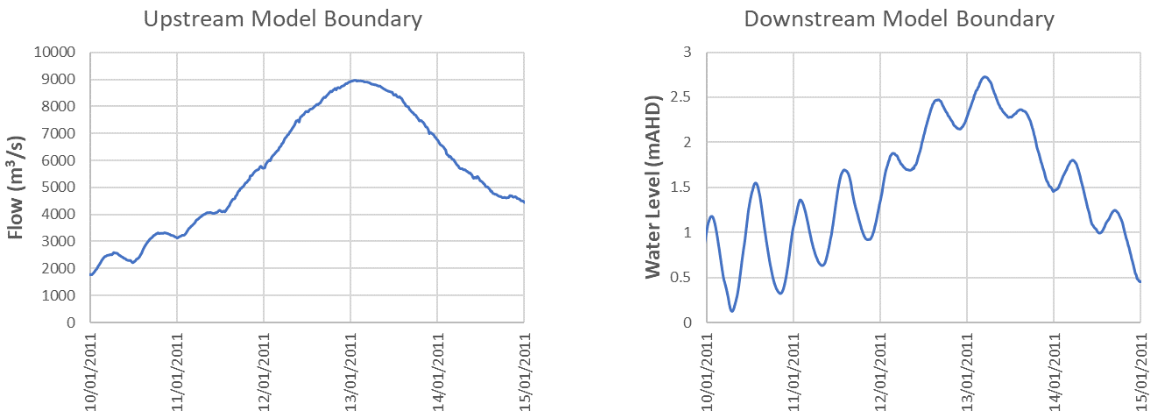


Figure 4. Model Boundary Conditions

The cut-down Brisbane River model has been configured to run 15 different simulations, testing 5 cell sizes (20m, 30m, 40m 50m, 60m) using the three previously described calculation methods (1st Order Traditional, 2nd Order Traditional, 2nd Order SGS). Results are presented in Table 1 comparing model peak water level result to surveyed 2011 event peak flood mark levels at 9 locations within the study area. Calibration performance is colour coded. In this paper green values represent a model result that is considered a good calibration, within ±0.2 metre of the recorded surveyed 2011 peak flood level. Red values are are considered a poor calibration result, greater than ±0.2 metre of the recorded surveyed 2011 peak flood level.

Table 1. Model Result Performance Summary

Flood Mark ID / Reporting Location (see Figure 3)			**26**	**27**	**28**	**39**	**65**	**66**	**69**	**70**	**City Gauge**
Surveyed Peak Flood Level (mAHD)			3.25	4.37	4.40	4.96	3.67	3.67	4.90	5.13	4.46
Test Case	**Model Cell Size (m)**	**Simulation Time (min)**	**Model Accuracy (m)** Modelled Peak Flood Level minus Surveyed 2011 Event Peak Flood Level								
1st Order Traditional	20m	22:47	0.24	0.45	0.58	0.74	0.26	0.49	0.77	0.71	0.52
	30m	15:34	0.45	0.75	0.90	1.09	0.44	0.99	1.12	1.09	0.88
	40m	11:54	0.71	1.12	1.27	1.46	0.63	1.35	1.51	1.50	1.24
	50m	9:27	0.88	1.30	1.53	1.78	0.74	1.51	1.78	1.82	1.49
	60m	7:56	1.09	1.57	1.99	2.25	0.94	2.02	2.18	2.28	2.00
2nd Order Traditional	20m	22:27	-0.12	-0.17	-0.11	-0.04	-0.09	-0.19	0.05	-0.08	-0.17
	30m	15:33	-0.02	-0.06	0.00	0.09	-0.01	-0.06	0.18	0.04	-0.05
	40m	11:50	0.01	-0.01	0.11	0.17	0.02	0.05	0.27	0.18	0.04
	50m	9:32	0.13	0.08	0.17	0.28	0.04	0.09	0.33	0.31	0.11
	60m	7:57	0.30	0.28	0.49	0.57	0.17	0.48	0.52	0.55	0.44
2nd Order SGS	20m	24:36	-0.06	-0.11	0.01	0.07	-0.03	-0.15	0.14	0.01	-0.08
	30m	15:44	-0.09	-0.18	-0.07	-0.01	-0.05	-0.16	0.06	-0.06	-0.15
	40m	11:59	-0.12	-0.18	-0.09	-0.06	-0.06	-0.16	0.07	-0.10	-0.18
	50m	9:40	-0.05	-0.14	-0.09	-0.05	-0.01	-0.16	0.06	-0.06	-0.13
	60m	8:14	-0.08	-0.22	-0.09	-0.04	-0.14	-0.19	0.00	-0.13	-0.19

Result Legend (Modelled – Recorded)	
<-0.2	Poor Model Performance
-0.2m to 0.2m	Good Model Performance
>0.2m	Poor Model Performance

The above results highlight the following general model performance trends:

1. The simulation speed performance of all three solutions, 1st Order Traditional, 2nd Order Traditional and 2nd Order SGS are comparable. There are negligible simulation speed benefits associated with the simplier 1st Order Traditional scheme compared to the more details 2nd Order SGS.
2. 1st Order Traditional: Modelled water levels do not match the recorded peak flood levels well at any of the tested 2D cell resolutions. The reason for this poor performance is outlined in the Discussion section of this paper.
3. 2nd Order Traditional: Modelled water levels are in good agreement with the recorded peak flood levels when the model 2D cell resolution is equal to or less than 30 x 30 metres.
4. 2nd Order SGS: Modelled water levels are in good agreement with the recorded peak flood levels when the model 2D cell resolution is equal to or less than 50 x 50 metres. This model scenario provides the greatest cell size convergence result consistency.

It is noted that recalibration of different solution schemes by fine tuning parameters, such as Manning's roughness, is a common approach to improve model performance. The results do however highlight that the 2nd order solution has superior result convergence performance compared to the 1st

Order solution. SGS topography sampling further improves the performance of the Traditional 2nd order solution. This result trend is a significant finding. A single model parameter set produces consistent results for a large range of cell sizes using a 2nd Order SGS scheme. By comparison, to achieve consistent results model parameters would require fine tuning for each cell size using the 1st Order Traditional scheme! This is an undesirable solution scheme behaviour. It increases predictive uncertainty due to the simulation results having a greater dependency on modeller assumptions to achieve a reliable result.

Case Study 2: Throsby Creek Catchment

The *Throsby, Cottage and CBD Flood Study* (BMT WBM Pty Ltd) was completed for Newcastle City Council (Council) in 2008. The 2008 model has been updated for this research. Updates include:

1. The hydraulic model was converted from TUFLOW Classic (Software Version 2007-07) to TUFLOW HPC (Software Version 2020-10-AD).
2. Nested 1D open channels features have been replaced with 2D cells. This update is necessary to adequately test the 2D cell assumptions, the focus of this research.
3. The hydraulic model extent was increased to the upper limit of the catchment boundary
4. The model design was upgraded from a coupled hydrology model / hydraulic model configuration to a pure hydraulic model design using 2D direct rainfall (rain-on-grid) to generate catchment inflows. For a description of 2D direct rainfall modelling refer to Australian Water School: Direct Rainfall (rain-on-grid) Webinar.

Beyond these minor changes, the model inputs from the 2008 study remain unchanged. For a full description of the flood model and overview of the 2008 assessment, refer to the 2008 study report hosted online by Council: Report-Throsby-Cottage-CBD-Flood-Study.pdf (BMT WBM Pty Ltd, 2008).

The Throsby, Cottage and CBD Flood Study area represents an excellent urban case study location suitable for real-world software benchmarking.

- The catchment is heavily urbanised, including the central business district of Newcastle, New South Wales's second most populated city.
- The catchment topography, landuse and stormwater drainage data required to build a flood model are complete and of high quality (BMT WBM Pty Ltd, 2008).
- Pluviograph coverage within and surrounding the catchment is reasonable. Six rainfall gauges are located with the catchment. There are a further six additional rainfall gauges in neighbouring catchments to the north, west and south close the catchment boundary.
- Council have proactively collected historic flood data following notable events.

This research focuses on comparing model results to recorded data from the 1990 flood event. The 1990 event saw several intense rainfall bursts over a 48-hour period on the 2nd and 3rd of February 1990. Rainfall across the catchment was relatively uniform, varying from around 316 mm in the west to 250 mm in the east" (BMT WBM Pty Ltd, 2008). Following the 1990 event Council collected 70 surveyed peak flood marks and water level timeseries data from five gauge recorders.

The flood model has been configured to run 9 different simulations for this research, testing four different 2D cell sizes (3, 6, 9 and 12 metre), also using the three previously described calculation methods (1st Order Traditional, 2nd Order Traditional, 2nd Order SGS). Result reporting focuses on two gauge recorders, namely Jellicoe and Litchfield, shown in Figure 5. They have specifically been chosen because they represent distinctly different locations in the mid and lower catchment. Assessed in combination they provide a reasonable and succinct method to review broadscale model performance. The Jellicoe Gauge is on the main trunk drainage line for the catchment. It is located within a 20 metre wide concrete lined man-made trapezoidal channel. The Litchfield Gauge is on a tributary drain of the main trunk drainage line. It is also a concrete lined man-made trapezoidal channel construction, although is only approximately 12 metres wide.

The flood model extent, topography and landuse are presented in Figure 5. The 1990 event recorded rainfall data is plotted in Figure 6. Table 2 lists the simulation time for each test model. Model results are compared against recorded water levels at the Jellicoe and Litchfield gauges in Figure 7 to Figure 9.

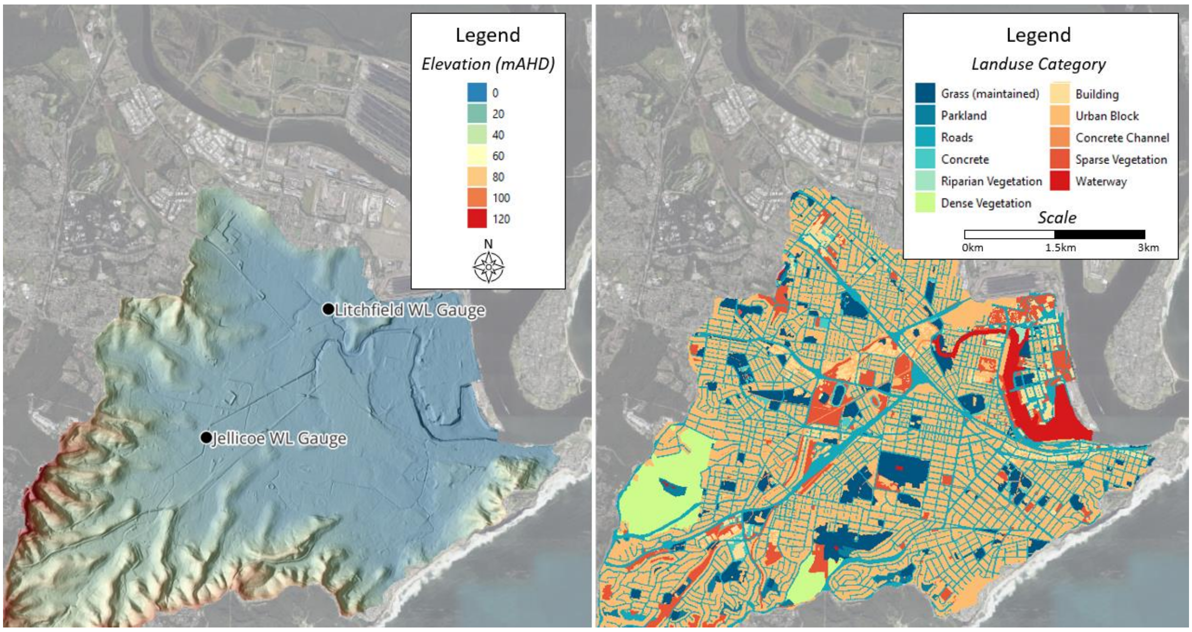


Figure 5. Throsby Creek Catchment TUFLOW Model Topography and Landuse

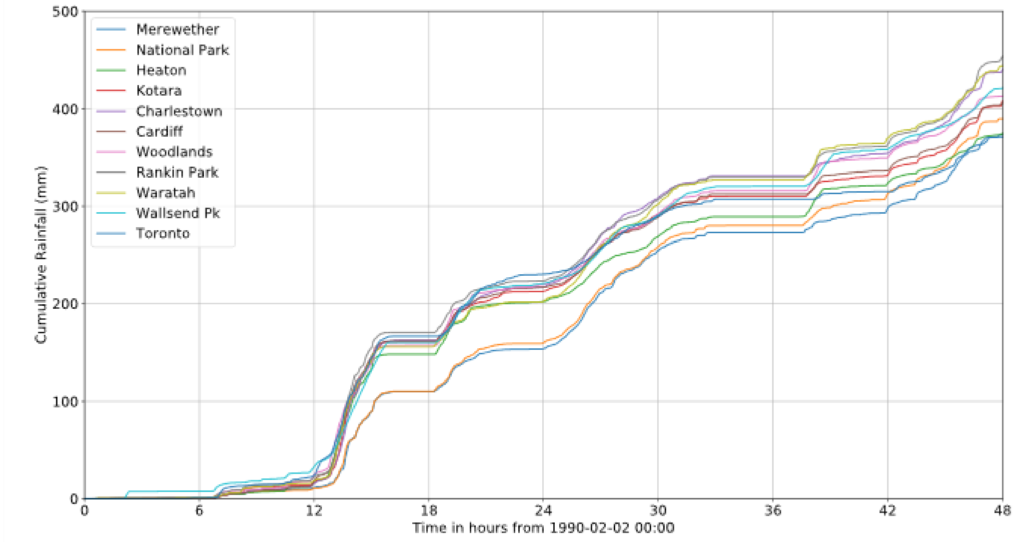


Figure 6. Throsby Creek Catchment 1990 Historic Event Rainfall

Table 2. Throsby Creek Catchment Simulation Speeds

Test Case	Simulation Time (HH:MM)			
	12m Cell Size	9m Cell Size	6m Cell Size	3m Cell Size
1st Order Traditional	00:26	00:33	01:38	04:59
2nd Order Traditional	00:29	00:34	01:40	05:00
2nd Order SGS	00:31	00:37	02:30	05:59

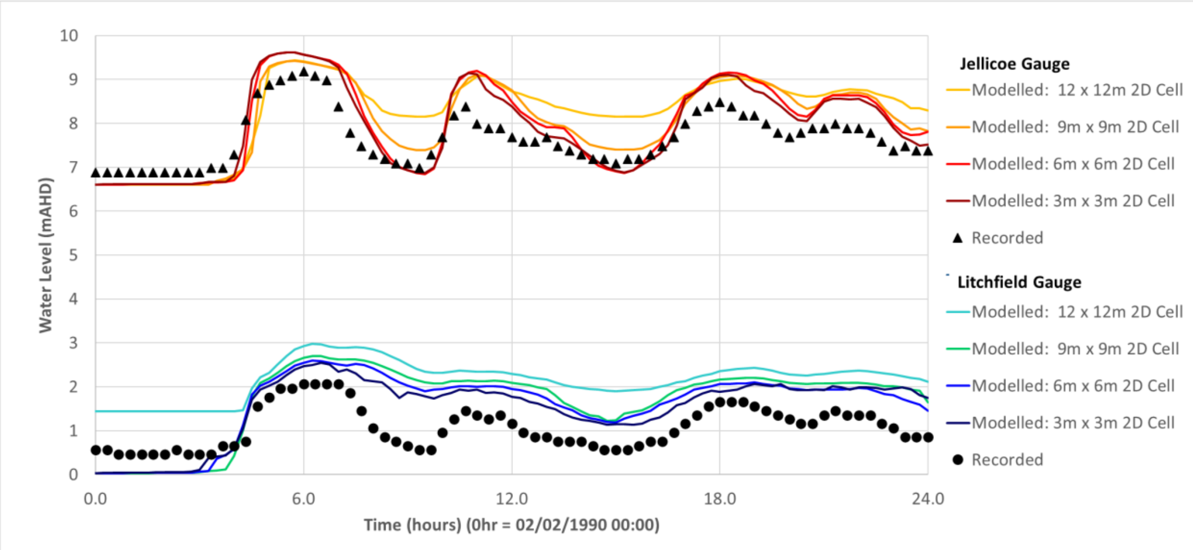


Figure 7. Throsby Creek Model Result – 1st Order Traditional Topography Sampling

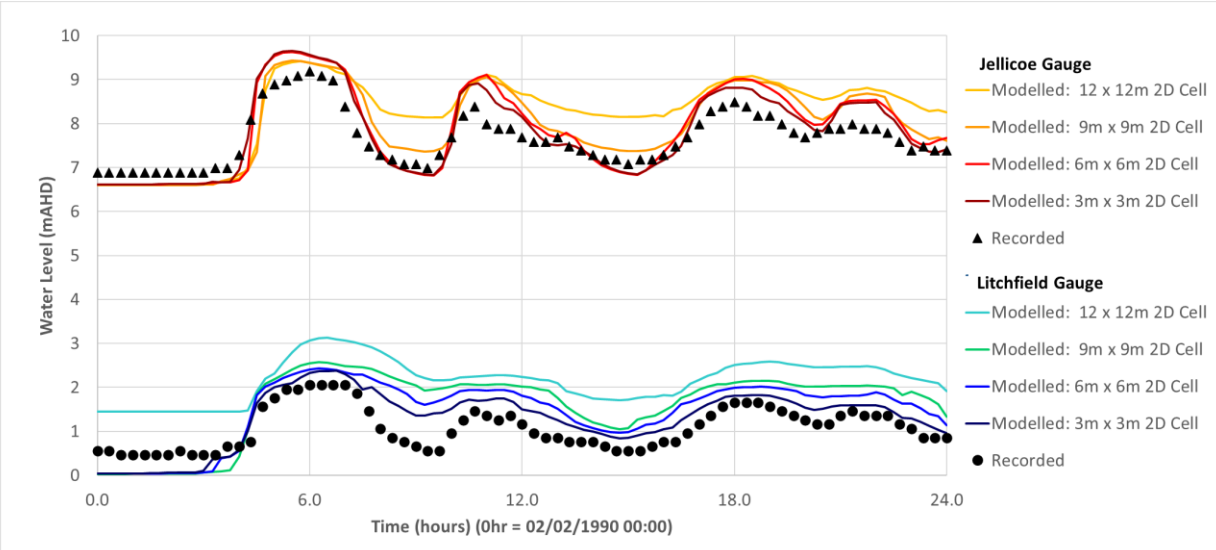


Figure 8. Throsby Creek Model Result – 2nd Order Traditional Topography Sampling

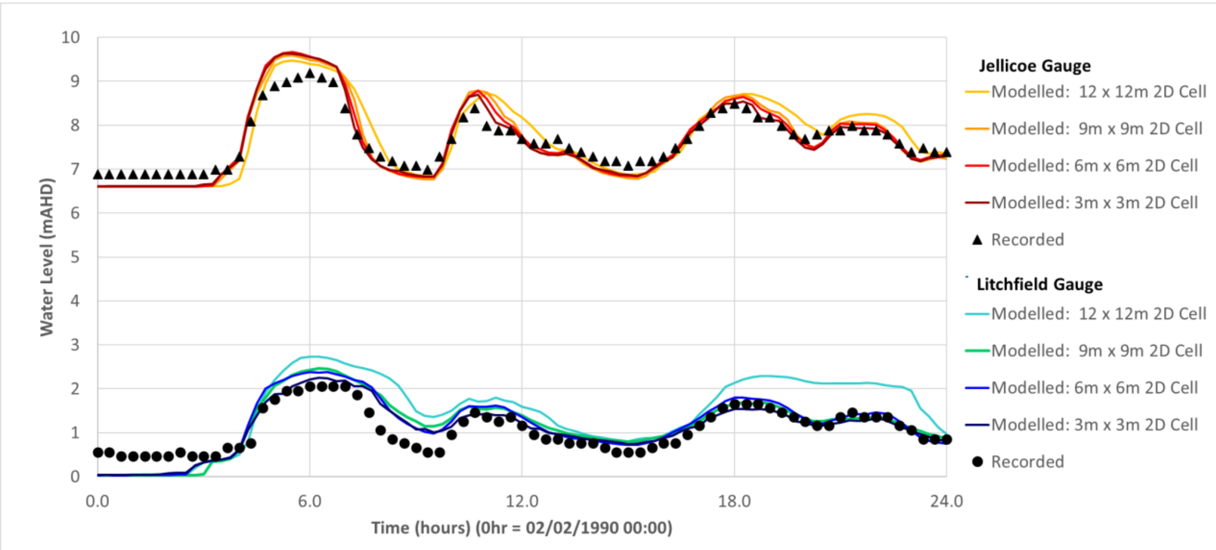


Figure 9. Throsby Creek Model Result – 2nd Order SGS Topography Sampling

The above results highlight the following general model performance trends:

1. 2nd Order SGS simulation speed was slower than 1st Order and 2nd Order Traditional. The simulation slow down ranges from 12% to 50%.
2. 1st Order and 2nd Order Traditional: Modelled water levels are in reasonable agreement with the recorded flood levels at the Jellicoe Gauge when using a cell resolution less than 6 x 6 metres. Modelled water levels do not match well with the recorded flood levels or converge to a single solution at the Litchfield Gauge. A finer model cell resolution would be required in the tributary drain associated with the Litchfield Gauge to adequately define the geometry of the 12m wide trapezoidal channel when using Traditional topography sampling.
3. 2nd Order SGS: Modelled water levels are in good agreement with the recorded flood levels at the Jellicoe Gauge for model scenarios adopting a cell resolution less than 12 x 12 metres and the Litchfield Gauge for cell resolutions less than 9 x 9 metres. 2nd Order SGS topography sampling demonstrates excellent cell size result convergence performance below the above-mentioned cell resolution values.

Discussion

The Brisbane River and Throsby Creek case study models represent drastically different hydraulic scenarios. The Brisbane River model is representative of open channel hydraulics. The Throsby Creek model is representative of a catchment scale distributed direct rainfall (rain-on-grid) urban model with complex rainfall/runoff characteristics, flowing overland into an engineered network of above and below ground urban stormwater drainage network. Despite the different hydraulic characteristics associated with both case study locations the relative performance of the three assessed topography sampling options is consistent. Cell size result convergence testing has demonstrated:

- 2nd Order SGS is the most accurate of the tested topography processing options. It provides result consistency for a large range of cell sizes.
- 2nd Order Traditional is also an accurate solution, though requires a finer resolution cell size than SGS to achieve a converged solution representing reality.
- 1st Order Traditional is not an accurate option for hydraulically complex open channel or direct rainfall urban flood scenarios (i.e. deep, high velocity, high turbulence flow).

There are several reasons for these accuracy trends:

- Numerically, 1st Order solutions generally perform poorly in situations where there are high gradients in velocity, water level and turbulence. The lower precision solution is numerically diffusive. In real terms this numerically diffusive trend presents similar to a solution that exhibits hydraulic losses greater than reality. This is not desirable behaviour for hydraulic modelling software. Due to this behaviour, 1st Order solutions are only recommended in areas of relatively benign hydraulics. For example, in low velocity flood storage zones.
- 2nd Order solution performance is superior compared to 1st Order. The extra level of precision avoids the undesirable numerical diffusion of the 1st Order solution. 2nd Order solutions are appropriate for the full range of hydraulic conditions typically associated with flooding, whether they be high turbulence flood conveyance zones (rivers, creeks and drains) or benign flood storage areas (floodplain).
- SGS topography sampling is superior compared to traditional topography sampling:
  - SGS provides an improved definition of the cell storage definition used by a 2D cell compared to the Traditional approach that simplifies real-world topography to a single elevation value volume per cell. (Huxley and Syme, 2020)
  - SGS also provides an improved definition of the wetted perimeter and hydraulic radius at each cell face compared to the Traditional approach. This data processing and calculation approach improvement successfully resolves the undesirable artificial depression storage artifacts common in direct rainfall (rain-on-grid) models using the

Traditional approach (Huxley and Syme, 2016). "Artificial depression storage" refers to the model behaviour where water is retained in a 2D cell for longer than reality due to the Traditional approach of using a single elevation value to define the cell face elevation. This simplification does not reflect reality if the real-world data includes a finer resolution feature, as compared to the modelled 2D cell size, that would let water flow from the upstream area earlier than the model allows.

- Combined, the 2nd Order solution with SGS topography sampling produces a robust solution that accurately represents reality for a very wide range of hydraulic conditions. Cell size result convergence testing demonstrates that consistent results are achieved at a much larger cell size using this approach compared to the other simpler calculation alternatives. These results support the findings by Kitts (2020),*"Mesh orientation and cell size sensitivity in 2D SWE solvers"*.

The findings documented in this research paper's scenario testing demonstrates how different hydraulic modelling software solutions have different cell size result convergence performance. Cell size assumptions suitable for one software may not be appropriate for a different software using a different calculation approach. For this reason, cell size convergence testing is a must do task when developing any hydraulic model. It provides a practical workflow to ensure hydraulic model simulation results are independent of model cell size assumptions. It also assists modellers to choose the largest suitable cell size for a given assessment. Models using a larger cell size have a smaller cell count / compute load, translating to faster simulation times. Faster simulation times improve project execution efficiency, a desirable outcome for all engineers and scientists who are undertaking hydraulic modelling.

Conclusion

The 2D cell size used for a 2D hydraulic model can have a major bearing on the accuracy and defensibility of the model. If the 2D cell sizes are too coarse, the physical terrain and hydraulic complexity may be poorly represented leading to unacceptable inaccuracies and a high degree of uncertainty in the results. Conversely, 2D cell sizes that are unnecessarily too fine results in excessively long simulation times and workflow inefficiencies. Cell size convergence testing is a practical workflow for identifying the appropriate cell size for a given assessment task.

This research assessed the cell size result convergence performance for three solution scheme alternatives at two case study locations. Model results were compared against recorded flood levels associate with historic flood events to assess model accuracy. The research results highlight the superior performance of 2nd Order solutions using SGS topography sampling, when compared to 1st or 2nd Order solutions using Traditional topography sampling.

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BIOGRAPHY

Chris is a Principal Engineer for BMT (TUFLOW) with over 18 years' experience in the field of flood / stormwater modelling and floodplain management. Chris is currently a senior member of the TUFLOW hydraulic modelling software development team and an Adjunct Lecturer at Central Queensland University where he teaches hydraulic modelling. Prior to his current role Chris worked in consulting and successfully completed a diverse range of projects in Australia and the USA addressing a wide range of topics: including stormwater management; infrastructure design; flood risk management; flood mitigation; land use development planning, approvals and emergency response planning.

Bill Syme has 37 years' experience primarily in the flood hydraulics field. During this time, he successfully managed and led a wide range of studies in Australia and overseas. The widely used TUFLOW hydrodynamic modelling software was first developed by Bill starting in 1989. Today, Bill is BMT's Software Business Lead, managing TUFLOW's global operations, and continues to provide specialist hydraulic modelling and flood risk management advice. He was the Project Manager for the award-winning Brisbane River Flood Study Hydraulic Assessment, and in 2022, Bill was the recipient of the FMA Allan Ezzy Flood Risk Manager of the Year Award.

Phil Ryan is software development lead for the TUFLOW Classic and HPC hydraulic modelling software products. Phil been actively involved in a range of consultancy projects over 15+ years. These include flood studies, floodplain management studies, flood impact assessments, storm tide studies, Monte Carlo analysis, wave modelling, coastal hydrodynamic and advection-dispersion modelling.

Greg Collecutt is the principle GPU software developer at TUFLOW. He has degrees in mechanical engineering and a PhD in theoretical physics, and has spent most of the last twenty years working in computational fluid dynamics and flood modelling. In this role he is primarily involved with the implementation and benchmarking of new modelling features in the TUFLOW HPC 2D engine.