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The End of the 1D Open Channel Cross-Section?

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ABSTRACT

Many hydraulic models for flood risk management are constructed with 1D open channels carved through a 2D domain. However, recent developments in utilising sub-grid sampling (SGS) of terrain data has substantially improved modelling accuracy of 2D regular mesh models for open channel flow with deep-sided channel walls. In addition, SGS can be combined with quadtree refinement to increase mesh resolution along the channels, without significantly increasing the number of 2D cells. These two hydraulic modelling techniques are redefining 2D hydraulic model design and reducing the need to use 1D for narrow open channels. However, a 1D approach is still required to model most hydraulic structures such as culverts and bridges as their flow characteristics are best defined by their specific 1D structure flow equations.

Where 1D open channels are replaced by 2D, the adjustments of 1D structure entry and exit losses according to the approach and departure velocities needs to consider the upstream and downstream 2D velocities. A new 1D-2D linking approach has been developed in the TUFLOW hydraulic modelling software to consider 1D structure entry/exit losses adjustment and the high momentum flux at the 2D boundary cells. The comparison with flume experiment data shows the new approach produces stable, conservative, and spatially smooth mass and momentum transfer between 1D structure and 2D domain along a fast-flowing channel. The proposed 1D-2D linking approach, together with SGS and quadtree refinement are applied to a real-world case study with a high-quality benchmarking data set with the results showing agreement with the recorded data.

Other benefits discussed are the cost savings in not needing to carve 1D channels through 2D domains and the benefit of utilising a full 2D solution that better handles momentum transfer and energy losses between open channel and floodplain.

INTRODUCTION

Since the advent of 1D-2D linking, hydraulic models for flood risk management are commonly constructed using a 1D solution for the open channels (Syme 2006). The 1D channel topographies are represented by cross-sections carved through the 2D domain, which covers the floodplains or regions subject to inundation from surface water. This linked 1D-2D approach was adopted for several reasons including no or limited bathymetric data in-bank and limitations in the 2D software solution schemes causing inaccuracies because of (a) the 2D mesh resolution was not sufficient to resolve in-bank flow paths, and (b) the mesh of cartesian grid solvers is usually misaligned with primary flow paths such as engineered concrete lined channels.

Recent advances in remote surveying techniques have made it easier and cheaper to collect in-bank survey data and it is increasingly less of a constraint. The 2D solution inaccuracies arise when channel bathymetry is represented by a small number of flat-bottom 2D cells, resulting in cell size results dependency, inaccuracy and streamline distortion. However, recent developments on a cell size independent turbulence term and sub-grid sampling (SGS) of terrain data are resolving these constraints (Collecutt and Syme 2017; Gao et al. 2020a). A regular 2D mesh can now be used at a moderate resolution at any orientation to accurately simulate flow along deep-sided channels. Together with the application of quadtree refinement (Gao et al. 2020b, Huxley and Syme 2021), these outcomes are redefining 2D hydraulic model design, with 1D increasingly not needed for open channels.

However, the linked 1D-2D approach is still often needed to model embedded 1D structures such as culverts, bridges, gates, etc that are best represented by their specific structure flow equations. With the 1D open channels replaced by 2D, 1D-2D linking must now consider the effect of the 2D approach and departure velocities on the structure's energy losses. Therefore, it is necessary to reconsider (1) the adjustment of entry and exit losses in the 1D structure, and (2) the momentum flux at the linked 2D cells so as to correctly predict the energy loss across the 1D structure.

In this study, an overview of the 2D solution scheme and 1D-2D linking approaches are presented. The performances of the different 1D-2D linking approaches are verified against a lab experiment with a smooth flow contraction/expansion (Khafagi 1942). Practical applications to a case study modelled using the proposed 2D solution scheme and 1D-2D linking approach are presented. Comparisons with the measured data, the more efficient model build effort (in not needing to carve 1D channels through 2D domains) and the added benefit of now utilising a full 2D solution that more accurately preserves momentum transfer and energy loss interactions between open channel and floodplain are discussed.

2D SOLUTION SCHEME

TUFLOW's HPC 2D Shallow Water Equation (SWE) solver (Collecutt and Syme 2017) was used for carrying out this investigation. The solver uses an explicit 4th order in time and 2nd order in space Runge-Kutta finite volume TVD scheme to track cell averaged depth and face centred velocities.

Sub-Grid Sampling (SGS)

Sub-grid sampling of terrain data was applied to model open channels across a regular grid mesh. Partially wet cells and faces may be considered by sampling the digital elevation model (DEM) at a sub-cell resolution and computing the water surface elevation as a function of cell stored volume and conveyance. The sampling process is shown conceptually in Figure 1. Without SGS the cell is flat-bottomed with linear relationships between water surface elevations and cell water volume, while the cell face cross-sections are rectangular in shape with linear relationships between water surface elevation and the face flow area. This first order representation of the DEM can cause streamline distortion and inaccuracy in a regular grid mesh when the open channel is not well aligned with the 2D grid and/or the 2D cell size across the open channel is too coarse.

SGS allows for the creation of water level vs cell volume relationship at cells, and conveyance vs water level relationships at the faces. This higher-order representation of the DEM elevations enables cells/faces to be considered as 'partially wet'. Gao et al. (2020a) demonstrated in both flume experiments and a field study that SGS significantly reduces artificial energy losses associated with the misalignment between regular grid and wet/dry boundary, improves cell size results convergence and greatly reduces mesh alignment issues. With SGS it is possible to represent narrow/deep channels with significantly less 2D cells than without SGS.

Quadtree Mesh Refinement

Another modelling advancement for cartesian 2D mesh solutions that assists in replacing 1D open channels is using a quadtree mesh. A quadtree mesh is constructed by dividing a cell into four cells, with these cells able to be divided further into four, and so on, allowing modellers to use larger cells in areas of flat terrain (e.g. large flat floodplains) and smaller cells along primary flow paths (e.g. river channels). The scheme is described in detail by Gao et al. (2020b). An example of quadtree mesh model is illustrated in Figure 2. The main benefit of quadtree refinement is to improve mesh resolution where most needed and coarsen where terrain is flat or well removed from the area of interest. With quadtree, combined with SGS, it is now practically feasible to represent most, if not all, 1D open channels in the 2D domain.

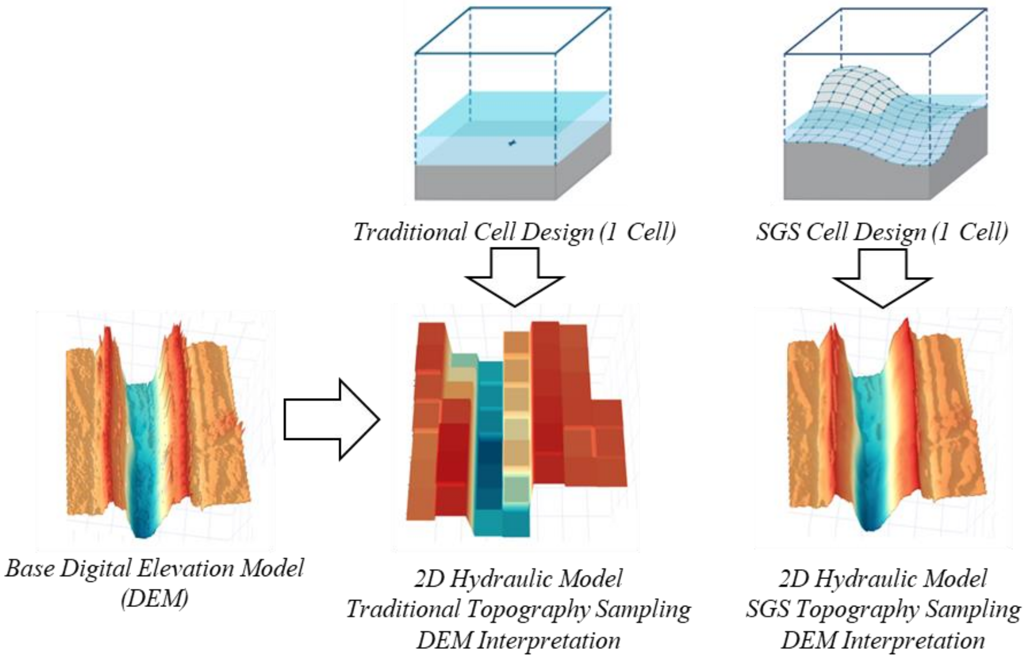


Figure 1. 2D Topography Sampling and DEM Interpretation of Traditional and SGS Models

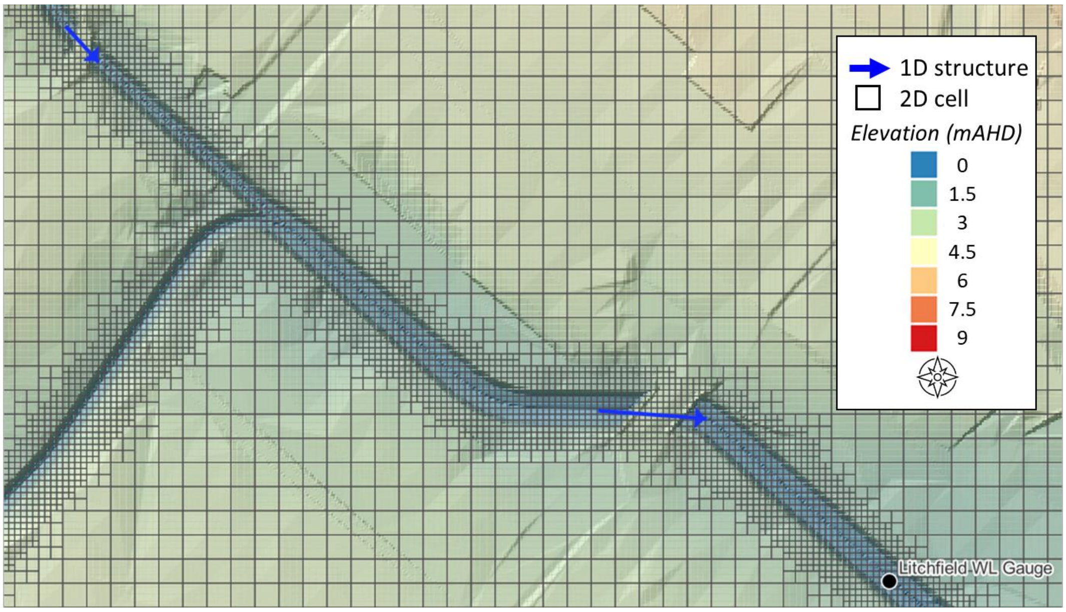


Figure 2. Example of Quadtree Mesh Refinement in Throsby Creek Catchment Modelling

1D Structures

Hydraulic structures such as culverts and bridges are mostly best represented using their structure flow equations. With 1D open channels replaced by 2D, the 1D-2D linking must now connect the 1D structures to 2D sometimes in fast-flowing main flow paths. This is more challenging than connecting 1D structures to stagnant or slow-moving 2D flows for two reasons.

Firstly, the change of flow width at the structure can cause contraction/expansion energy losses as illustrated in Figure 3. The entry and exit loss coefficients of the 1D structure (K_{entry} and K_{exit}) need to be adjusted based on the approach and the departure velocities (V_{app} and V_{dep}), which are now calculated in the 2D solution. Therefore, the 1D-2D linking must extract these velocities from the 2D solution and pass them to the 1D solution to avoid the overestimation of the entry and exit losses.

Secondly, the 1D-2D linking needs to handle the momentum transfer between the 1D and 2D as neglecting it in a fast-flowing channel can cause an artificial "wall" at the linking cells.

VERIFICATION OF 1D-2D LINKING APPROACHES

Four types of 1D-2D linking approaches are compared in this section. All approaches utilise 2D water levels at the entry and the exit of the 1D structure to derive the 1D structure's flowrate. The 1D flowrate is applied as the mass source term in the linked 2D cells. The differences lie in the handling of the entry/exit losses and the momentum flux. The following cases were used for the benchmarking:

- Case 2D is a 2D only model used for comparison (ie. assumes the 2D solution adequately resolves the energy losses at the structure).
- Case B is the base 1D-2D model that applies the 1D flowrate as a source term in the continuity equation only.
- Case A extracts the approach and departure velocities from the linked 2D cells and uses them to adjust the entry and exit losses based on the equations in Figure 3.
- Case M adds the momentum fluxes at the 2D linked cells based on the 1D structure flowrate.
- Case AM is the combination of Case A and M.

Total energy loss:

$$\Delta h = \left(K_{entry} + K_{exit}\right)\frac{V_{structure}^2}{2g}$$

Adjusted entry loss coefficient:

$$K_{entry\_adjusted} = K_{entry}\left[1 - \frac{V_{app}}{V_{structure}}\right]$$

Adjusted exit loss coefficient:

$$K_{exit\_adjusted} = K_{exit}\left[1 - \frac{V_{dep}}{V_{structure}}\right]^2$$

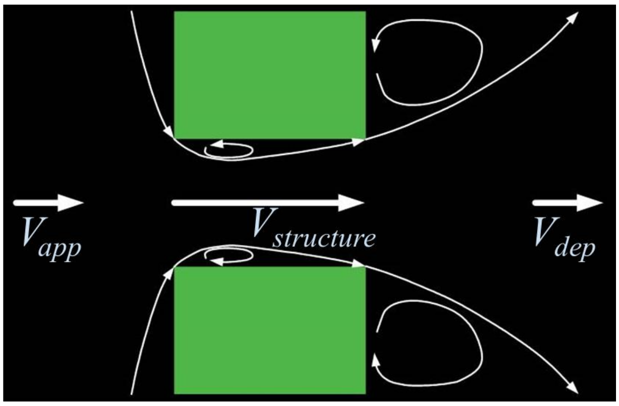


Figure 3. Structure Contraction/Expansion Energy Losses

Flume Experiment (Khafagi 1942)

The performance of the four 1D-2D linking approaches are compared by modelling the water surface slope recorded in a Venturi flume experiment conducted by Khafagi (1942). The geometry of the flume is shown in Figure 4. The flat-bed channel is 0.3 m wide and has a smooth converging section, a short 0.12 m wide contracted section, and a linear expansion zone with relatively small expansion rate (1/8). The flow rate of 17.5 l/s with 4 downstream depths was modelled.

This experiment was chosen because the flow contraction/expansion is significant, and thus it is crucial to consider the loss adjustments and the momentum flux. In addition, 3 out of 4 cases recorded super-critical flow downstream the contracted section, and this type of flow is particularly challenging to model using 1D-2D linking. The model cell size was 3 cm and the Manning's *n* was assumed to be 0.010. For the 1D modelling, the narrowest section was replaced by the BB bridge type TUFLOW 1D channel with infinite deck height to account for the entry/exit losses only. The unadjusted entry/exit losses were assumed as 0.5 and 1.0.

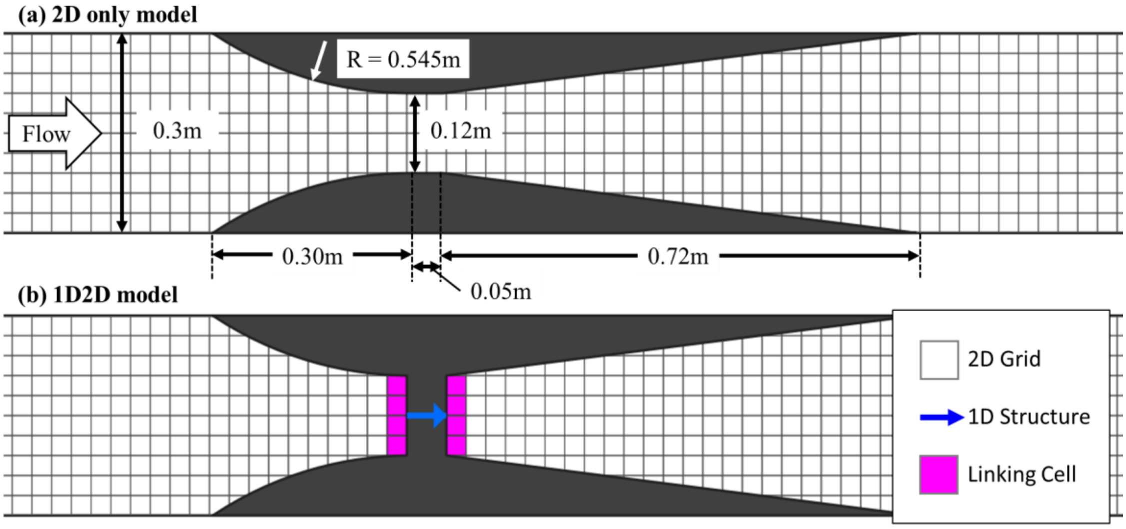


Figure 4. Schematic Diagram of Flume Experiment, Model Grid and 1D-2D Linking

Modelling Result

Figure 5 Case 2D compares the measured and modelled water levels along the channel centreline. The TUFLOW HPC 2D solver predicted the drop of water level at the contraction and the recovery of the water level at the expansion for all cases. For the three cases with supercritical flow (downstream depth = 16.8, 13.2 and 12.3 cm), the SWE solver predicted a sharper increase in water level at the location of hydraulic jumps. This is most probably caused by the assumption of negligible vertical accelerations and hydrostatic pressure distribution in the 2D SWE (Cueto-Felgueroso et al. 2019). But importantly, the upstream water levels were predicted for those upstream controlled 'choked' flow conditions where the downstream water levels had little or no impact on the water level upstream of the contraction.

Figure 5 Case B presents the simulation results for the base 1D-2D model that does not adjust loss coefficients nor apply momentum flux. Comparing to the 2D only model and the measured data, Case B generated higher upstream water levels due to the unadjusted entry and exit losses. In addition, increase in water level upstream/downstream the 1D structure were observed due to the lack of momentum transfer. The locations of the hydraulic jump also shifted slightly upstream for the three supercritical flow cases.

Case A extracts approach/departure velocities from the 1D-2D linking cells and used them to adjust the entry/loss coefficients. The results show that the water levels upstream of the 1D structure better match the measured data, but the spikes in water surface are not eliminated. Case M applies momentum fluxes at the 1D-2D linked cells eliminating the spikes and shifting the locations of the hydraulic jump back downstream to similar locations predicted in the 2D only Case 2D model.

Finally, by combining the loss adjustment and momentum flux, Case AM predicted the upstream water levels and generated smooth water level profiles across the 1D structure. The results clearly demonstrate the importance of the entry/exit loss adjustment based on the approach/departure velocities and the addition of the momentum flux.

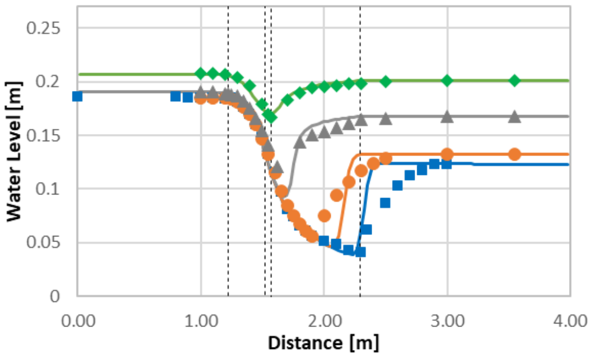
CASE STUDY THROSBY CREEK CATCHMENT

The 1D-2D linking approach used for Case AM was adopted for the Throsby Creek model developed for the *Throsby, Cottage and CBD Flood Study* (BMT WBM 2008). The catchment area represents an excellent real-world urban case study with high-quality calibration data for benchmarking the importance and the usability of the quadtree mesh, SGS and the 1D-2D linking approach:

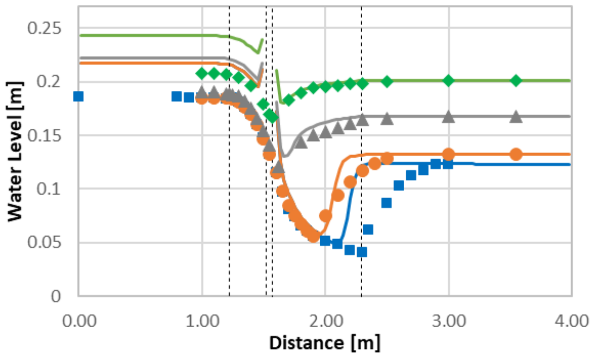
- The catchment is mostly urbanised, and has a heavily engineered drainage system, with extensive concrete open channels and culverts, with evidence of very high flood velocities, see

Figure 6.

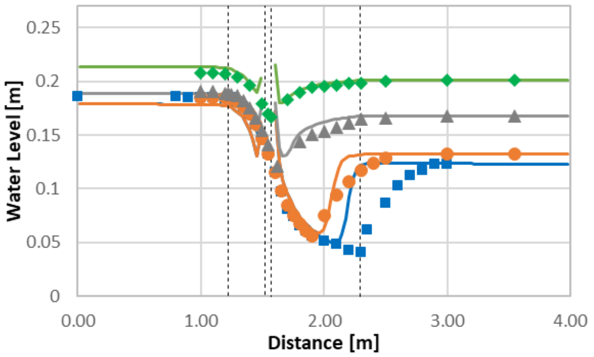
Case 2D: 2D only model



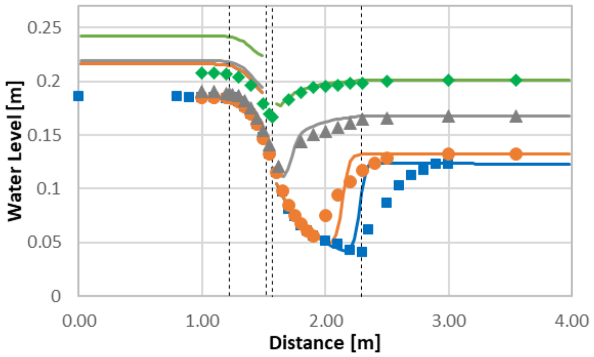
Case B: 1D2D base model



Case A: 1D2D model with loss adjustment



Case M: 1D2D model with momentum flux



Case AM: 1D2D model with loss adjustment and momentum flux

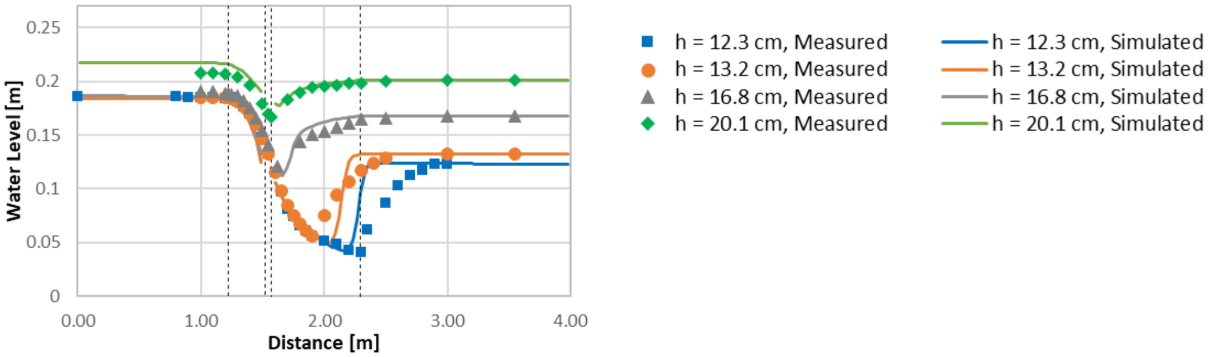


Figure 5. Benchmarking to Khafagi 1942 Flume Experiment

- The catchment topography, landuse and stormwater drainage data required to build a flood model are complete and of high-quality (Figure 7).
  Good rainfall pluviograph coverage within and surrounding the catchment. Six rainfall gauges are located within the catchment and there are a further six rainfall gauges in the neighbouring catchments to the north, west and south (Figure 8).

- Council have proactively collected extensive historic flood data following notable events.

The application of SGS and the 1D-2D linking approach is crucial for predicting realistic flood levels along the heavily engineered channels, and multi-cell size quadtree mesh models can be used to cover the whole catchment in the 2D model whilst retaining high mesh resolution in along the channels.

Figure 6. Fast-Flowing Concrete Open Channel in Throsby Creek Catchment (Top image courtesy of David Gibbins)

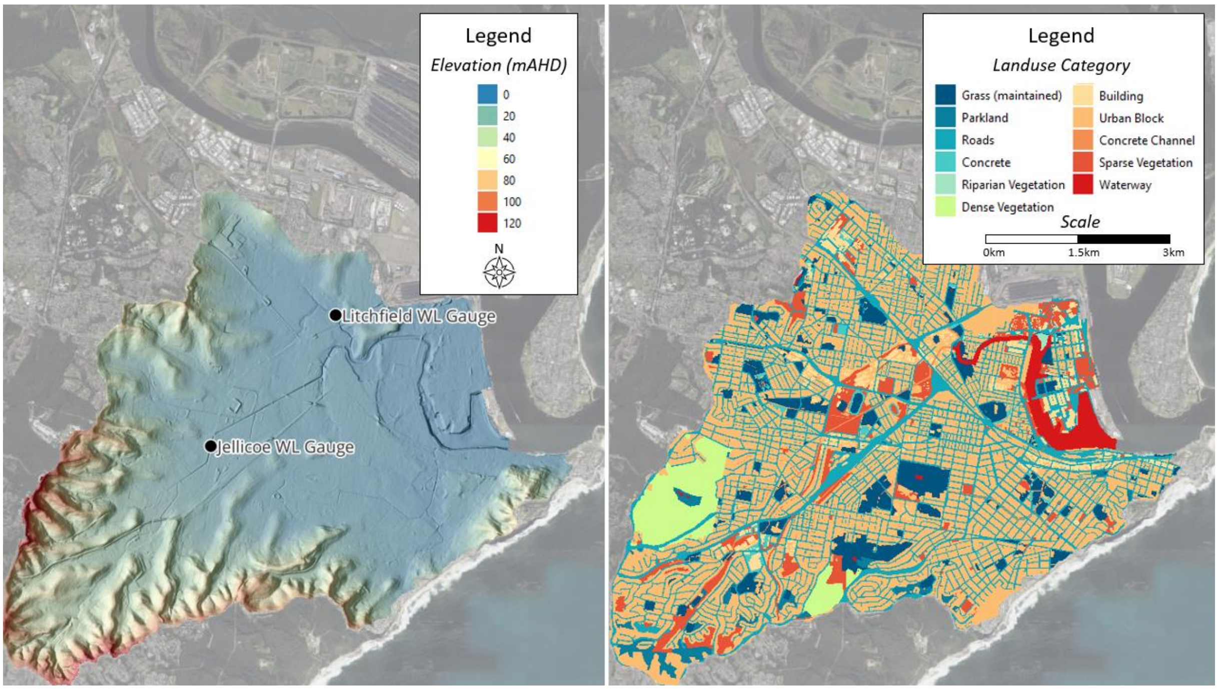


Figure 7. Throsby Creek Catchment TUFLOW Model Layout (BMT WBM 2008)

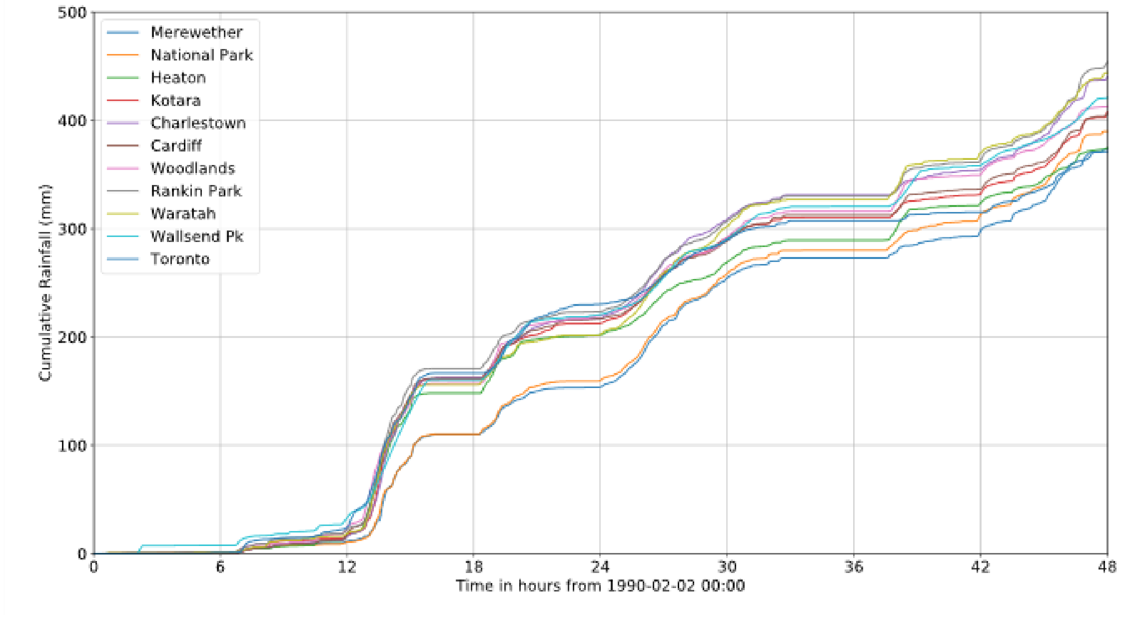


Figure 8. Throsby Creek Catchment 1990 Historic Rainfall Event

The benchmarking focuses on comparing the model results for the following three cases to demonstrate the feasibly and the benefit of replacing 1D open channels with 2D cells, and the importance of the 1D-2D linking approach at structures modelled in 1D:

- Case 1: An updated version of the 2008 flood study model with 10 m 2D cells and 1D open channels. The updates for this were:
    1) the model domain was extended to include the whole catchment boundary; and
    2) the 2D solver was changed from TUFLOW Classic to TUFLOW HPC (Software Version 2020-10-AD) and converted to a direct rainfall approach along with confirming calibration to the 1990 flood measurements (Ryan et al. 2022).
- Case 2: The 1D open channel in Case 1 was replaced by 2D SGS cells. Quadtree refinement was applied to vary the cell size from 2.5m in the open channels to 10m on the floodplains (Figure 2).
- Case 3: The proposed 1D-2D linking approach was applied to the Case 2 model.

Results and Discussions

Figure 9 compares the simulated water level at the Jellicoe and Lichfield gauge points. In general, all approaches produced agreement with the measured data. The differences between the 1D open channel and 2D open channel approaches are expected due to the difference in the numerical schemes and the lengthwise resolution of the 1D channels (30 m ~ 150 m) compared with the 2D cell size (2.5 m in the channels). At the Lichfield gauge points, the 2D open channel approach with existing 1D-2D linking approach (Case 2) produced higher peak water levels compared to the other two models, while the model with the new 1D-2D linking approach (Case 3) had similar peak water levels with the 1D open channel approach.

Figure 10 compares the longitudinal profiles of maximum water level along the open channel near the Lichfield gauge. As shown in the previous section, Case 2 predicted higher water levels in this section due to the unadjusted 1D structural losses and the handling of momentum flux. However, the 2D open channel models generated more details in the change of water level along the water course due to the improved spatial resolution. This benefit cannot be understated as the overtopping of the channel banks can now be calculated on cell-by-cell basis, rather than relying on the interpolation between the water levels stored at 1D channel nodes.

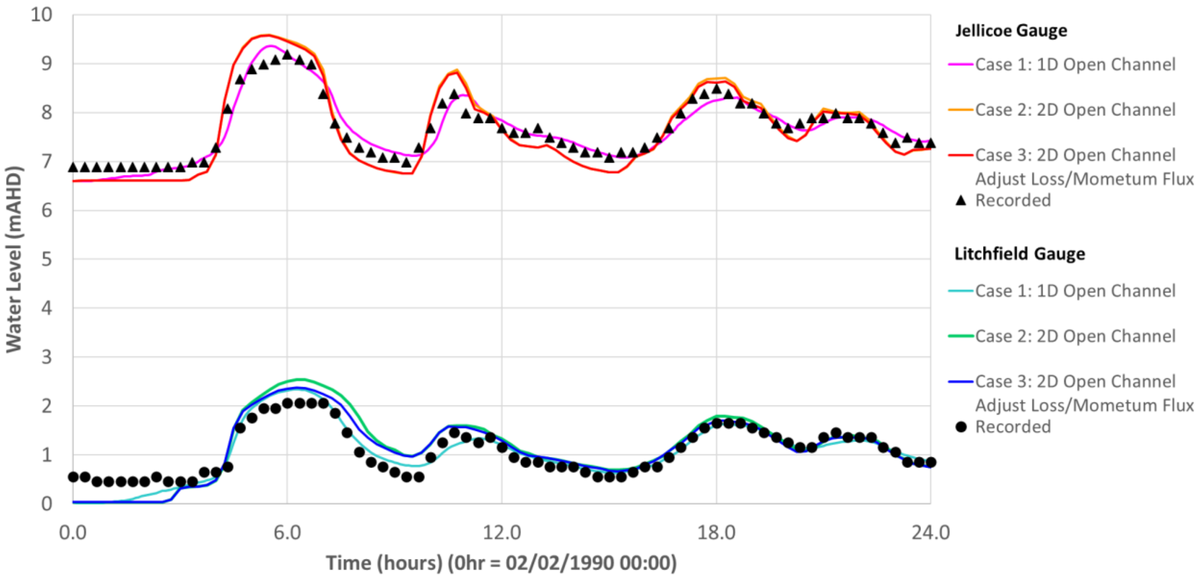


Figure 9. Throsby Creek Measured and Modelled Water Level at Gauges

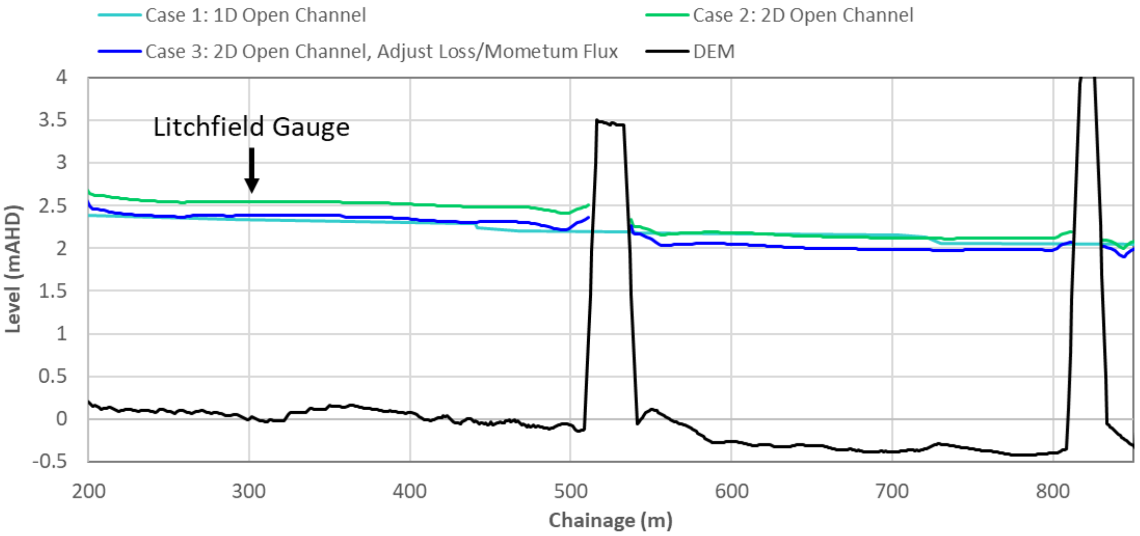


Figure 10. Longitudinal Profile of Maximum Water Level Near Lichfield Gauge

This advantage can be seen from the 2D mapping of depth and velocity outputs. Figure 11 and Figure 12 compare the modelled depth and velocity outputs near the Lichfield gauge station between Case 1 and Case 3. Despite the two models predicting similar overbank flood extents in this area, the 2D open channel model has clearly preserved more details in flow velocity along the channel banks. This means the mass and momentum transfer between the open channel and the floodplain can now be modelled seamlessly within a single 2D solver, instead of using a large number of 1D-2D linking cells.

This study focused on the feasibility of replacing 1D open channels with 2D cells in hydraulic models for flood risk management. In addition to the SGS and the quadtree refinement techniques, the 1D-2D linking approaches were reviewed and verified by modelling a Venturi flume test. The results highlight the need for structure loss adjustment according to the approach and departure velocity fields and representation of the momentum flux are required to reproduce a smooth and accurate flow transition between 1D structures and 2D cells in a fast-flowing water course.

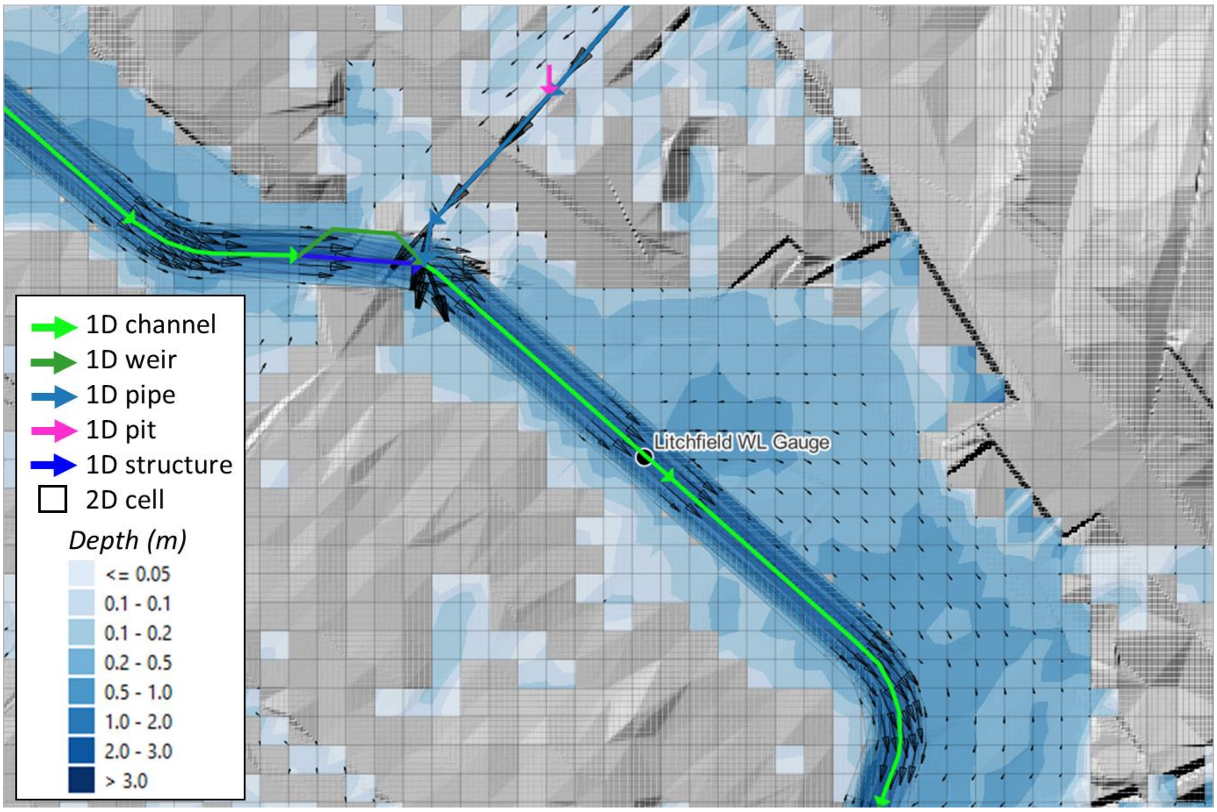


Figure 11. Modelled Depth and Velocity Near Lichfield Gauge Using 1D Open Channel (Case 1)

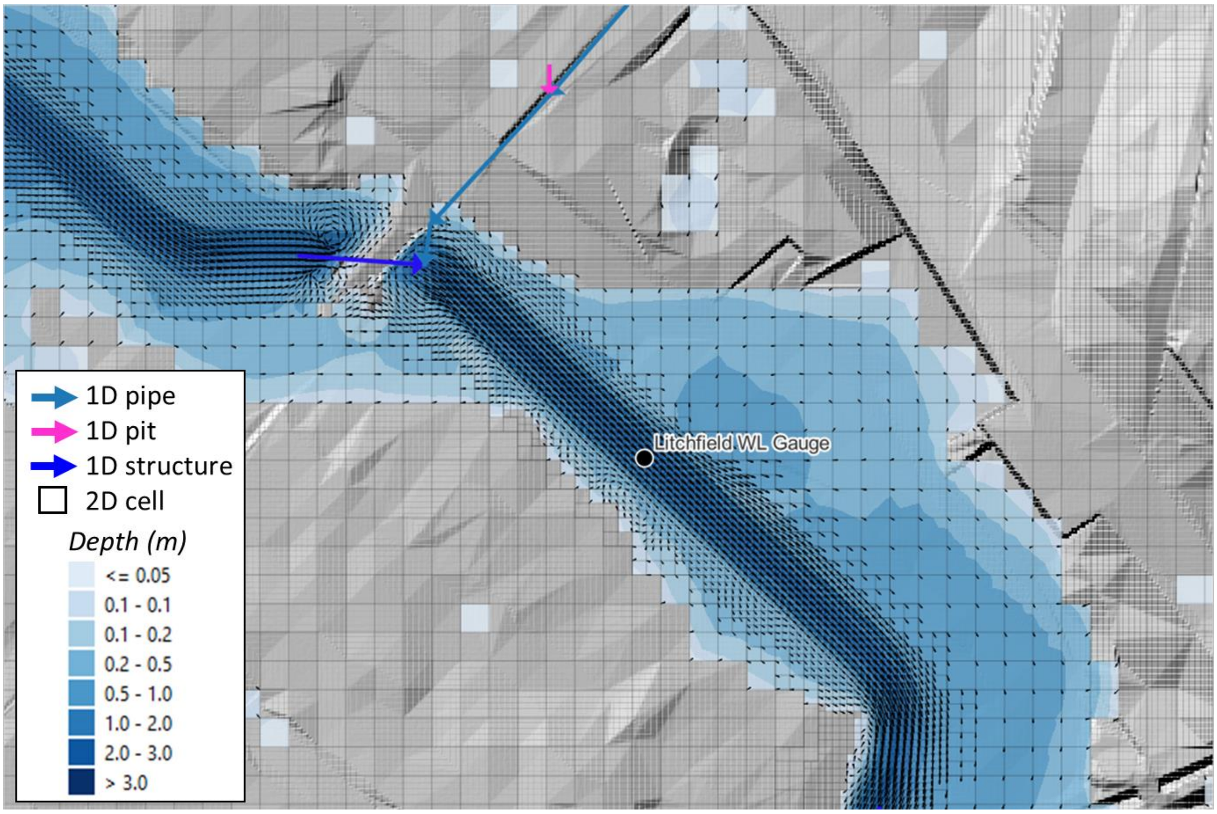


Figure 12. Modelled Depth and Velocity Near Lichfield Gauge Using 2D Cells (Case 3)

CONCLUSION

The real-world model application demonstrates the utility of the 2D open channel approach with SGS and quadtree refinement. The improved 1D/2D linking method considers the adjustment of 1D structure losses based on the 2D velocity field. In addition, the benefits of modelling both open channels and floodplain inside the same 2D solver are:

1. The improvement of spatial resolution in modelled water level and the savings in model build effort without needing to carve a 1D channel through 2D domains are significant.
2. The added benefit of utilising a full 2D solution that preserves momentum transfer and energy loss interactions between open channel and floodplain can be significant and is an area that warrants further investigation.

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BIOGRAPHY

Shuang Gao graduated from Tokyo Institute of Technology with a PhD degree in Environmental Hydraulic Engineering. He joined the TUFLOW software development team in 2017 and has been involved in varieties of R&D projects, flood and coastal modelling, technical support and training. His main interests lie in the development of cutting-edge modelling methods applied to real-world engineering problems.

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.

Bill Syme has 38 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.

Greg Collecutt is the principal 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.