“Where will our knowledge take you?”

TUFLOW HPC

2018 TUFLOW UK Conference, Bristol

Bill Syme

TUFLOW HPC
Presentation Overview

Background

Benchmarking

- Physical Processes
- Solution Accuracy
- Mesh Convergence
- Benchmarking

Time-stepping and Stability

1D/2D Linking and HPC vs Classic

HPC vs old GPU Solver

Hardware

TUFLOW HPC

Why?

Accuracy Issues with TUFLOW GPU

TUFLOW GPU

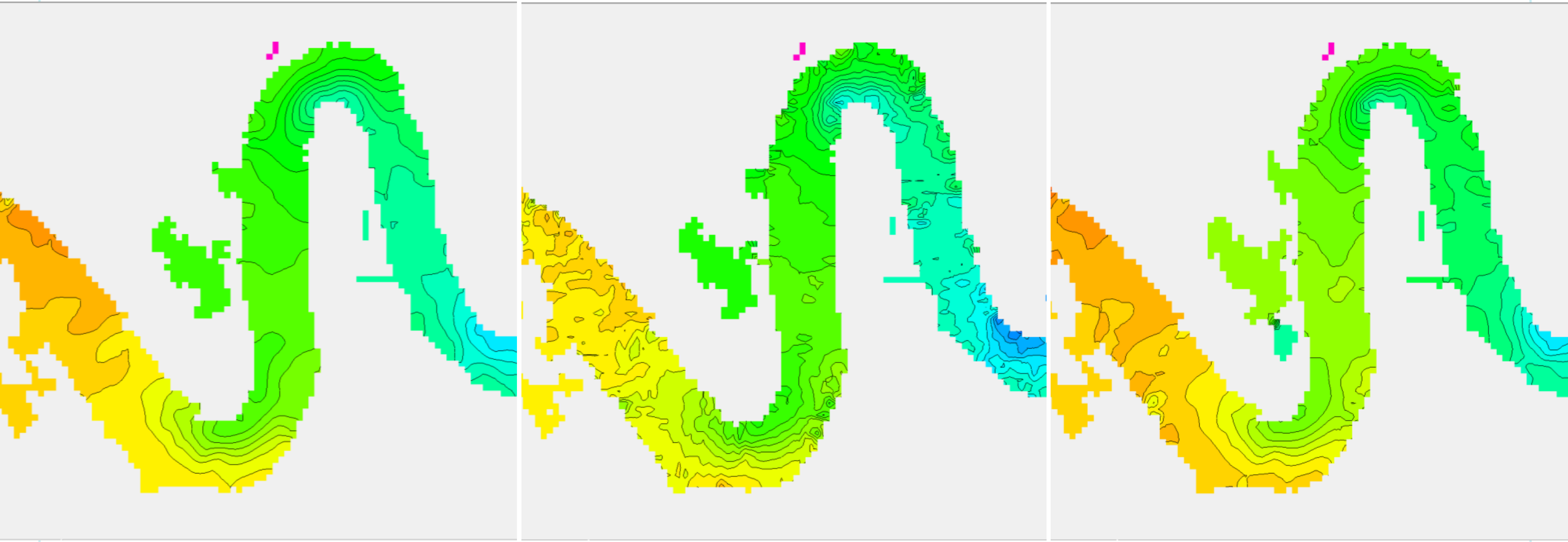
- Simplistic 1^{st} order spatial solution
- Intended for broad-scale, rapid assessment
- BUT, was increasingly being used beyond our comfort zone

Objective: parallelised scheme of similar performance to Classic

TUFLOW GPU

Issue 1: Numerical “Noise”

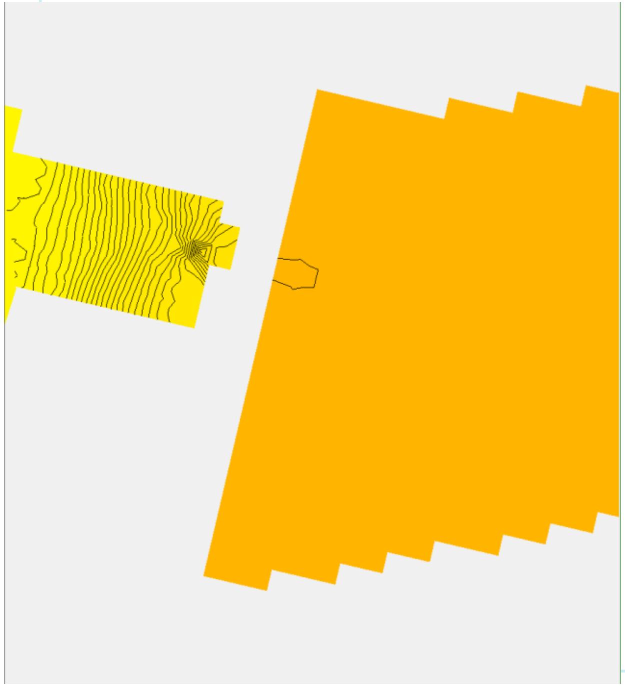
Classic | Original GPU Scheme | TUFLOW HPC



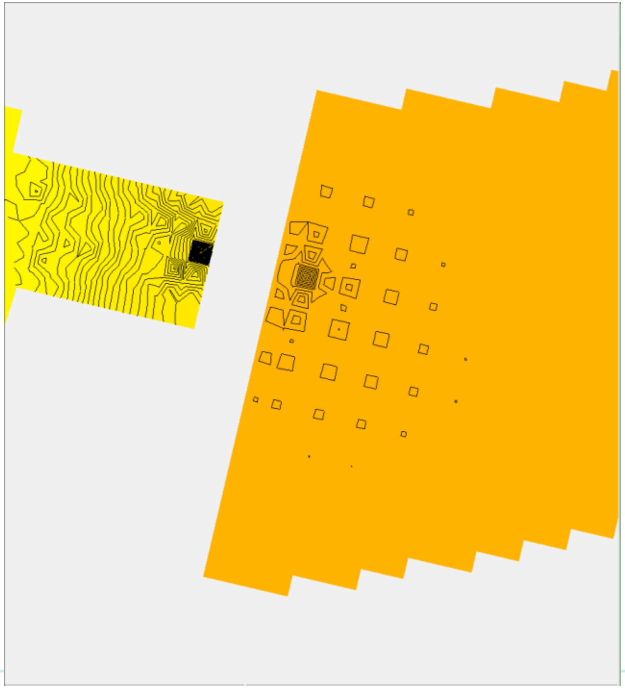
TUFLOW GPU

Issue 2: Checkerboarding

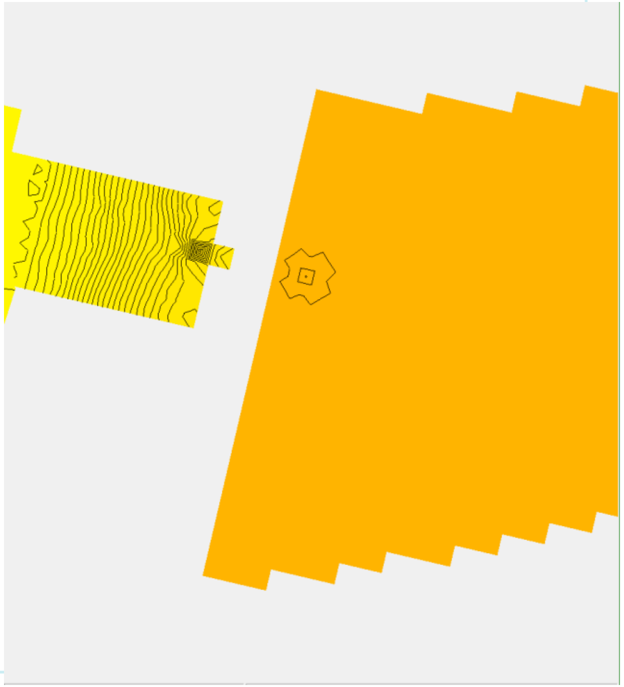
Classic



Original GPU Scheme



TUFLOW HPC



TUFLOW HPC
Overview

TUFLOW GPU Mark II

- New 2nd Order spatial solution
- Schematisation now supports cell side elevations and n values (i.e. thin breaklines)

Nearly all of TUFLOW Classic's functionality

- Aiming to include all, or nearly all

All 1D/2D linking functionality (HX and SX)

- Linked to all 1D (ESTRY) functionality and currently being linked to external 1D schemes

Runs on Nvidia GPU devices and CPUs

- Very fast on GPU

TUFLOW HPC
Solution Scheme

Explicit, Finite Volume, TVD shock capturing solution

4th order in time, Runge-Kutta integration solution

- 1st and 2nd order time integrators soft timestep convergence (i.e. different results if you change the timestepping)

2nd order in space

- 1st order in space available

Includes three sub-grid turbulence (eddy viscosity) approaches

  - Smagorinsky, Prandtl, Constant

Much improved solution over original TUFLOW GPU solver

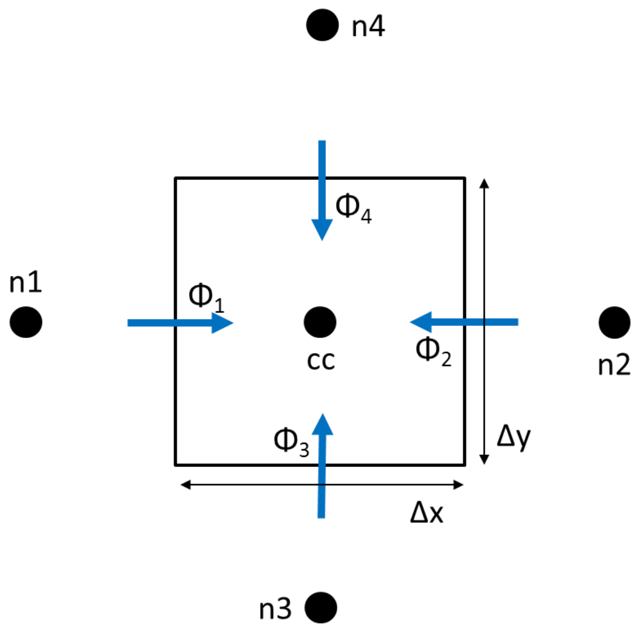
TUFLOW HPC
Cell Discretisation

Same as Classic's discretisation

- Water levels cell centres
- Velocities cell mid-sides
  (allows elevations at cell mid-sides, i.e. thin breaklines)

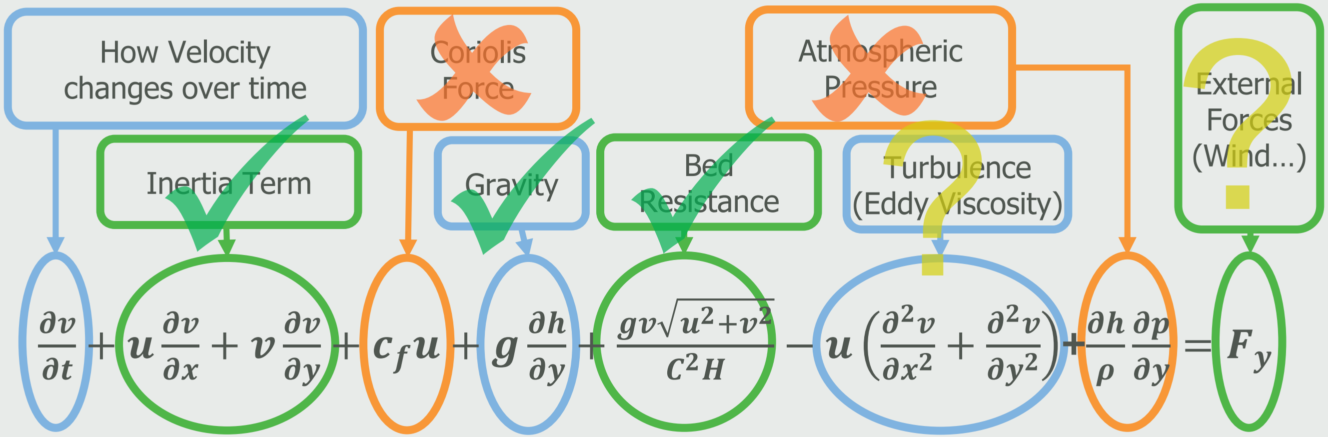
Trialled other approaches for calculating velocities

- Cell centres (TUFLOW GPU approach)
- Cell corners



Mathematical Solutions

What Physical Processes Matter for Flooding?



$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + c_f u + g\frac{\partial h}{\partial y} + \frac{gv\sqrt{u^2+v^2}}{C^2H} - u\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{\partial h}{\rho}\frac{\partial p}{\partial y} = F_y$$

Modelling Turbulent (Eddy) Viscosity

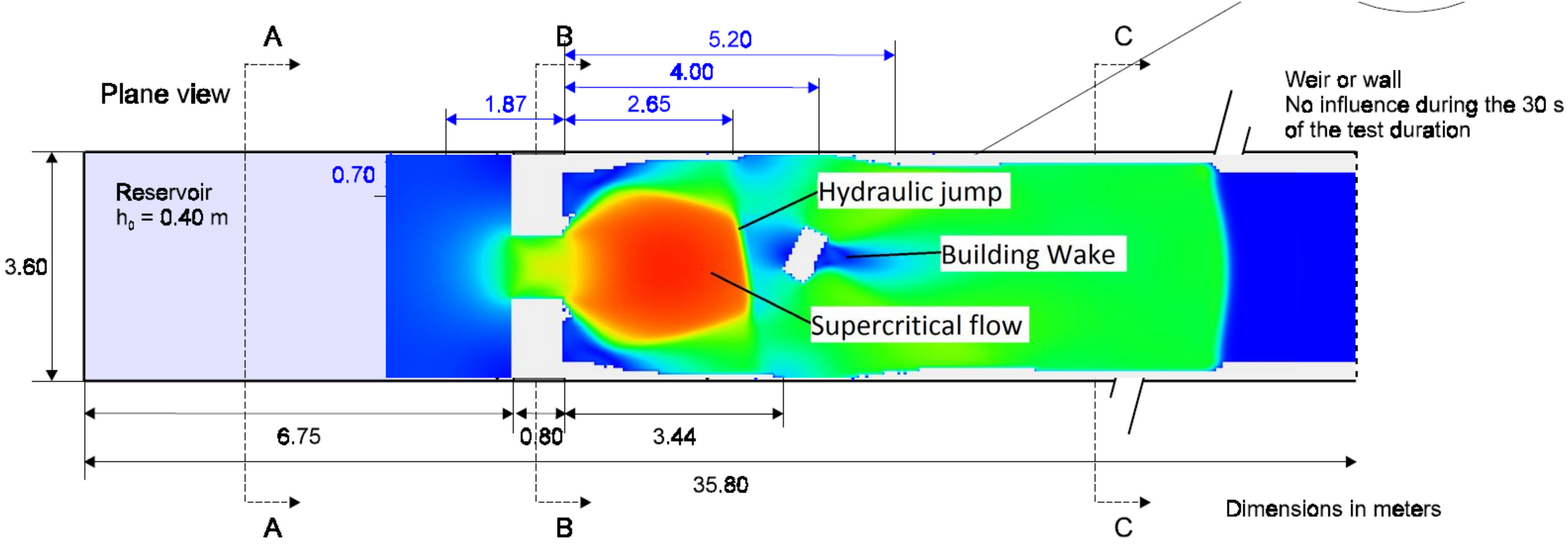
- Turbulence contributes to viscosity
  (Eddy viscosity is the 2D SWE representation of sub-grid scale turbulence)
- 1st order schemes numerically dispersive – distorts turbulence model
- 3D CFD (Navier-Stokes) has many turbulence models
- TUFLOW Classic models traditionally use Smagorinsky + Constant

$$\nu_T = mA\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right]^{\frac{1}{2}} + c$$

- Is a turbulence ‘model’ needed?

Benchmarking TUFLOW HPC

Test Case 6A – UK EA



Bed friction coefficient : Manning n = 0.01 s $m^{-1/3}$

Test duration : 30 s

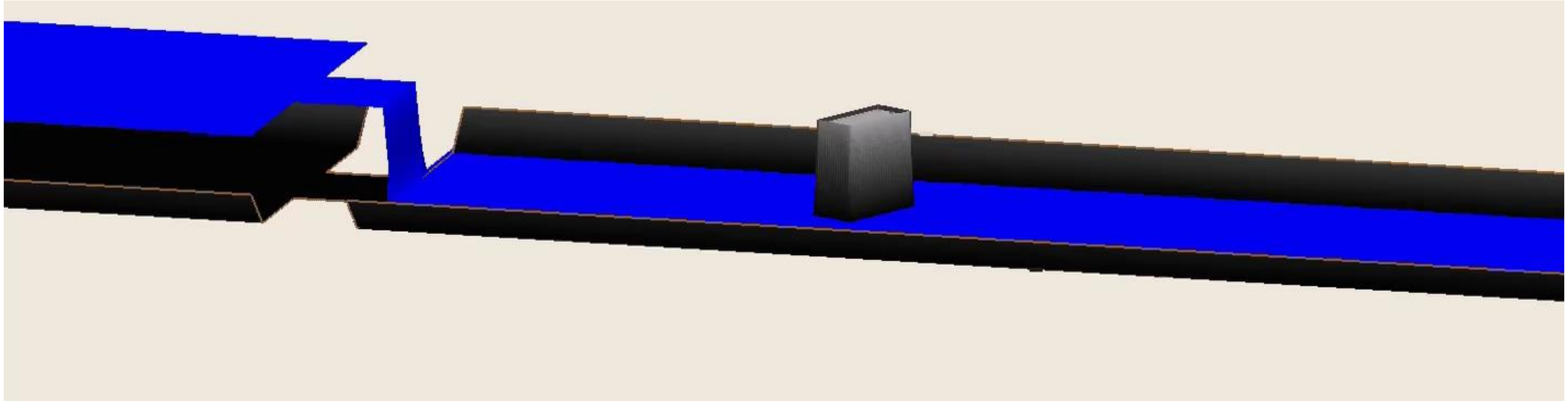
Flume experiment

(Soares Frazao, Noel, Spinewine & Zech, UCL, Belgium)

Benchmarking Physical Processes

Test Case 6A – UK EA 2D Benchmarking

- Hydraulic jump forms in front of building
- Eddy shedding downstream of building
- Jump propagates upstream as flow eases

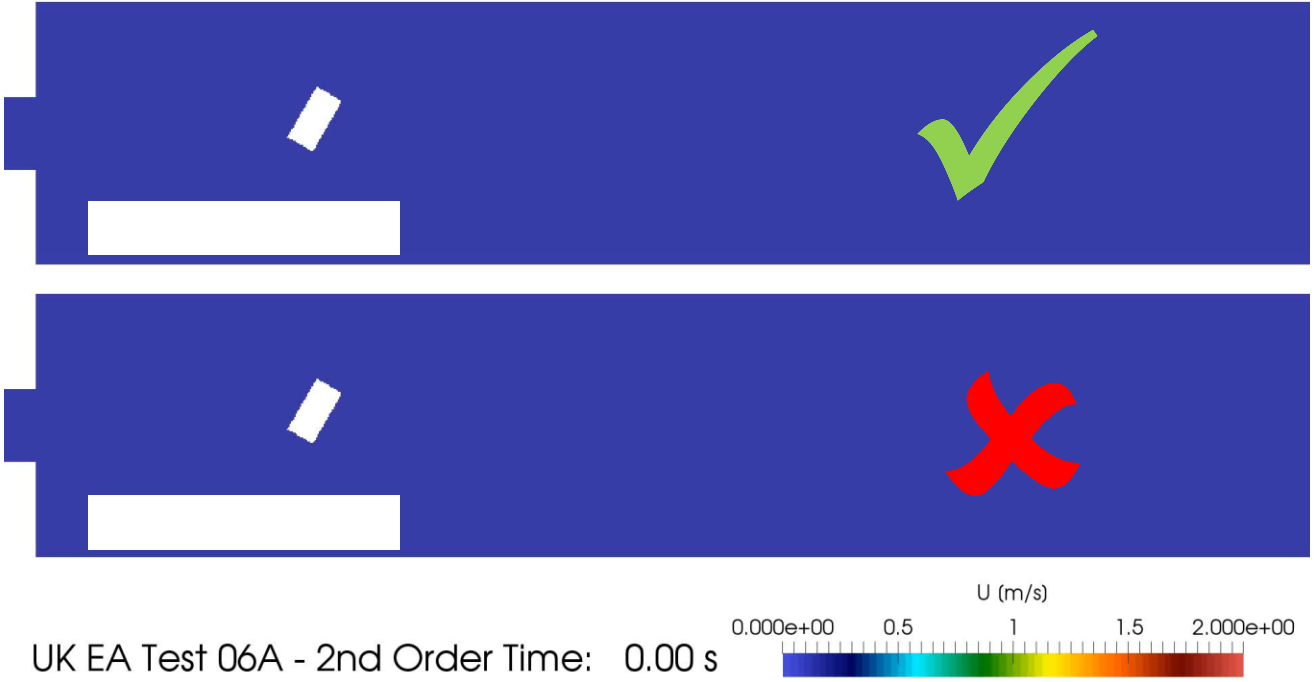


Benchmarking Physical Processes

Test Case 6A – UK EA 2D Benchmarking

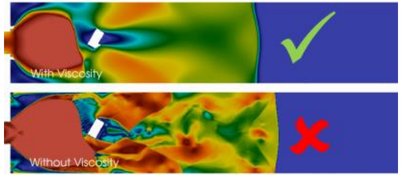
Audience Survey

Which result is least wrong?



Benchmarking

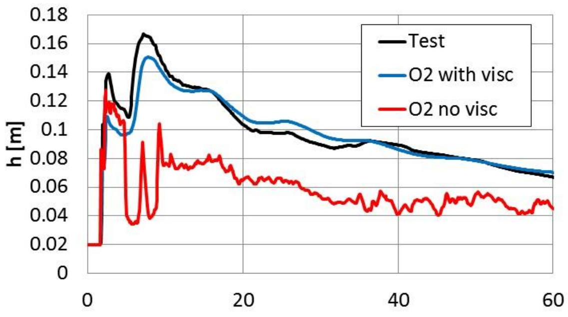
Test Case 6A

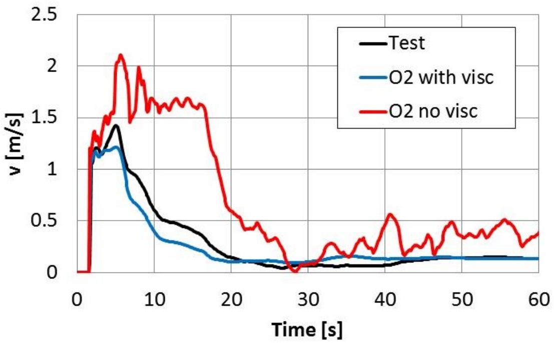


With turbulence (eddy viscosity)

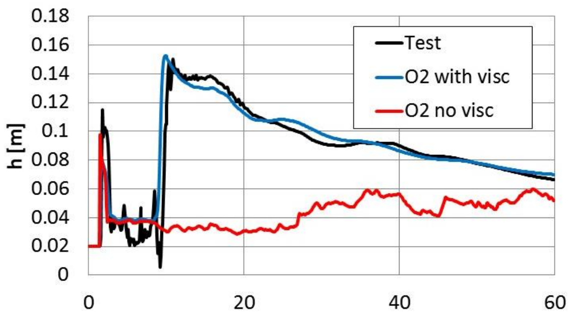
Without turbulence (eddy viscosity)

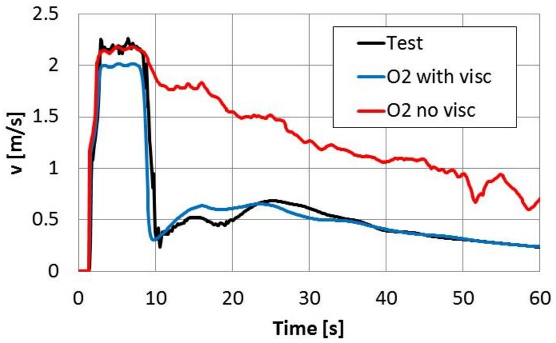
Location 1



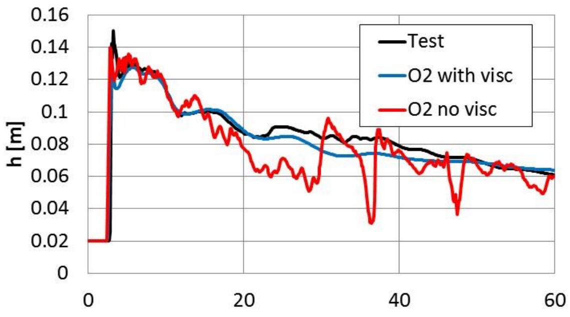


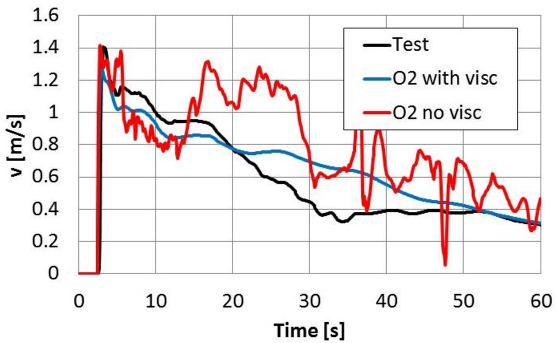
Location 2





Location 3





TUFLOW BMT

Benchmarking Physical Processes

Test Case 6A – UK EA 2D Benchmarking

Beware the cool animation!

Mathematical Solution

Solving the Equations!!!

Momentum

- How Velocity changes over time
- Inertia Term
- Coriolis Force
- Gravity
- Bed Resistance
- Atmospheric Pressure
- Turbulence
- External Forces (Wind…)

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + c_f u + g\frac{\partial h}{\partial y} + \frac{gv\sqrt{u^2+v^2}}{C^2 H} - u\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{\partial h}{\rho}\frac{\partial p}{\partial y} = F_y$$

Can solve using different orders of approximation (e.g. 1st, 2nd, 3rd, … order)

Mathematical Solution

What is 1st Order, 2nd Order?

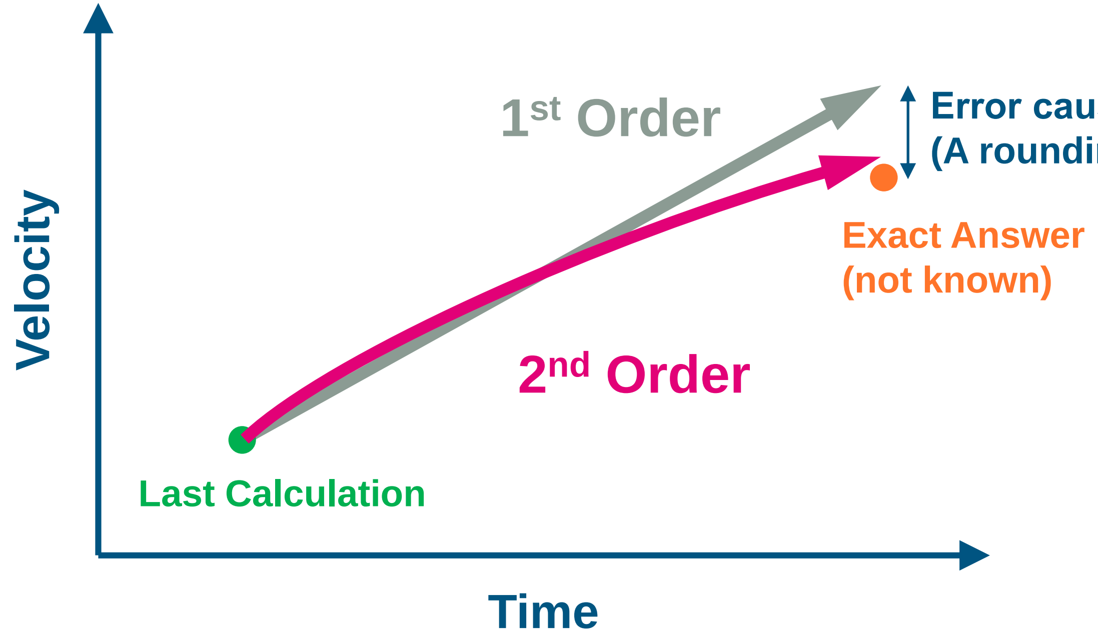
In engineering, **orders of approximation** refer to how precise an approximation is…

… in increasing order of precision, a **zeroth-order** approximation, a **first-order** approximation, a **second-order** approximation, and so forth.

https://en.wikipedia.org/wiki/Order_of_approximation

Mathematical Solution

What is 1st Order, 2nd Order?



Why choose 1st Order?

- Easier to code
- Faster
- More numerically stable

Why not 3rd Order?

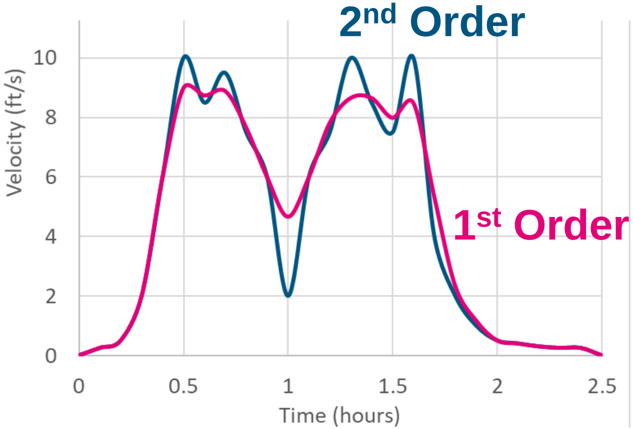
- Not beneficial
  (for long wave hydraulics)

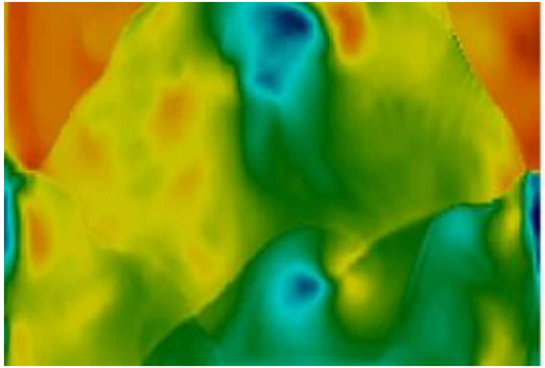
Mathematical Solution

Does 1st Order, 2nd Order Matter?

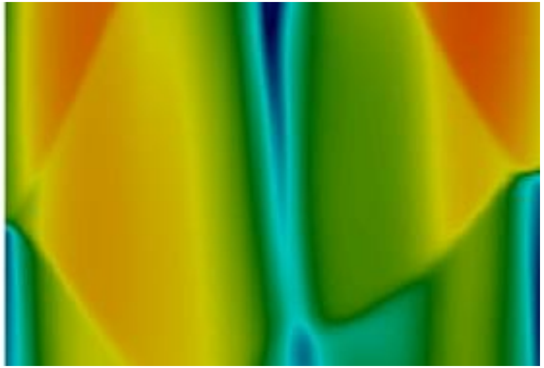
1st Order

- Can exhibit numerical diffusion (smoothing) causing unnatural energy losses in complex flows
- Distorts turbulence term





2nd Order (no turbulence term)



1st Order (no turbulence term)

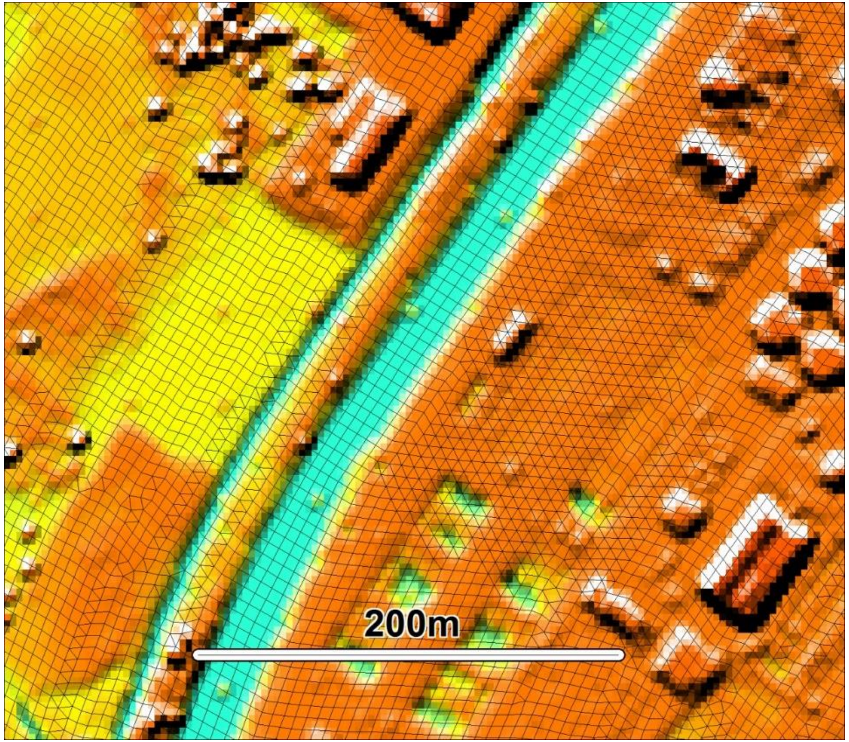
2011 Japanese Tsunami
TUFLOW FV

Model Area

- 300,000 km2
- Five meshes (coarse to fine)
- 0.5 to 1.0 million elements

Mesh Element Sizes

- 10 km off-shore
- 250 to 1,000 m Tsunami Zone to shore
- 5 to 250 m near shore

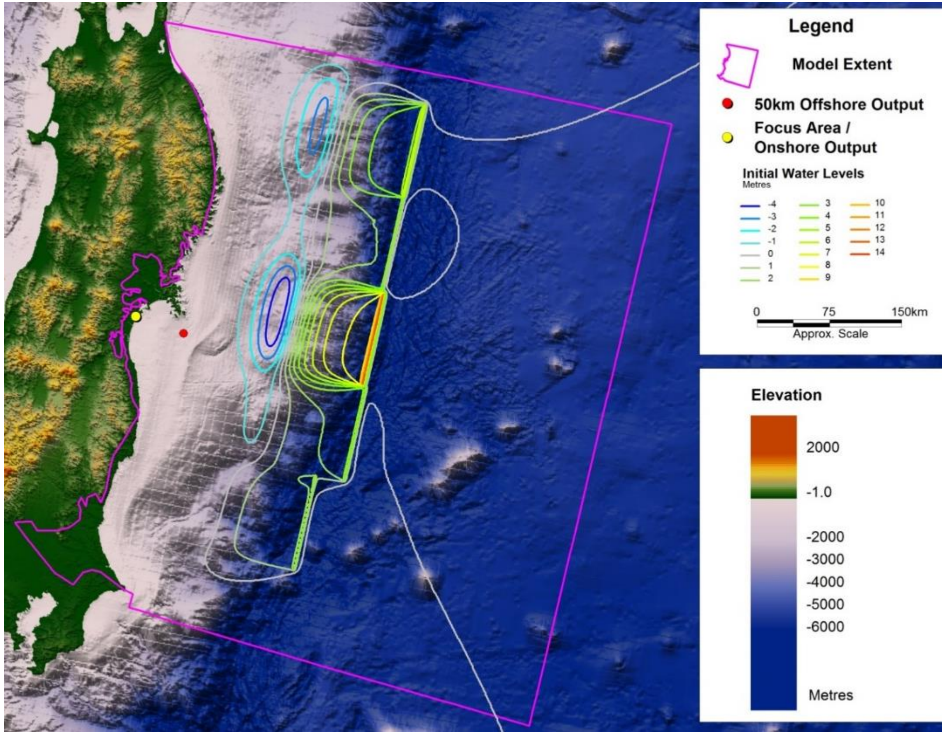


2011 Japanese Tsunami

Initial Water Levels

Initial Water Surface Disturbance

- Leading depression of -4.7 m
- Peak crest height of 15.7 m

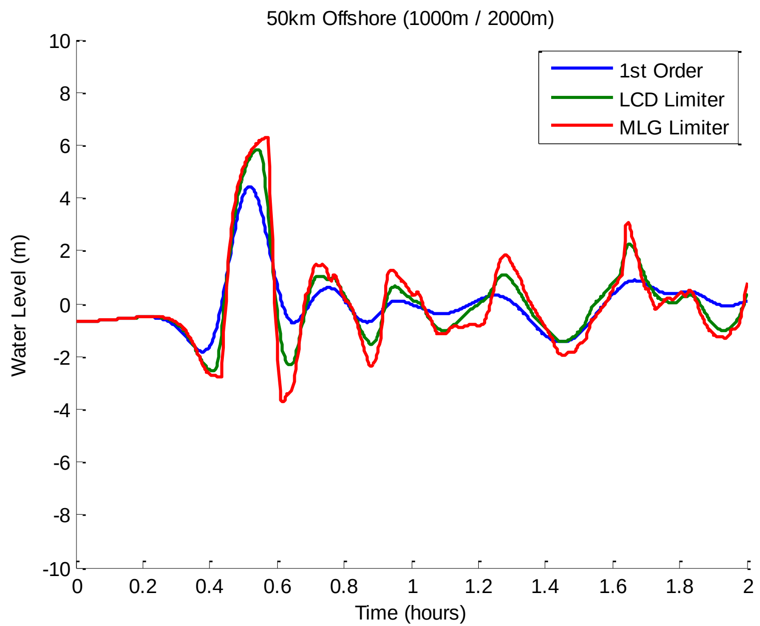


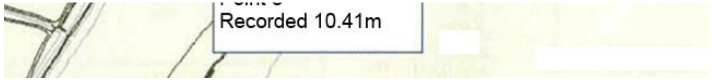
2011 Japanese Tsunami

Model Calibration – 2nd Order Solution Essential

Mesh Resolution	Location 5, Recorded = 10.41 m			Location 4, Recorded = 12.86 m		
	1st Order	2nd Order LCD Limiter	2nd Order MLG Limiter	1st Order	2nd Order LCD Limiter	2nd Order MLG Limiter
1 (Finest)	8.24	10.46	10.75	8.38	10.55	10.7
2	8.24	10.40	10.71	8.41	10.48	10.68
3	7.68	10.20	10.60	7.70	10.12	10.57
4	7.53	10.13	10.59	7.53	10.10	10.54
5 (Coarsest)	6.40	9.73	10.47	6.72	9.67	10.48

Mesh Resolution	Location 3, Recorded = 12.40 m			Location 2 Recorded = 11.38 m		
	1st Order	2nd Order LCD Limiter	2nd Order MLG Limiter	1st Order	2nd Order LCD Limiter	2nd Order MLG Limiter
1 (Finest)	8.42	10.57	11.37	8.98	11.32	11.66
2	8.43	10.50	11.37	9.03	11.25	11.6
3	7.86	10.28	11.52	8.38	11.00	11.87
4	7.74	10.23	11.41	8.25	10.93	11.75
5 (Coarsest)	6.90	9.84	11.15	7.14	10.65	12.02

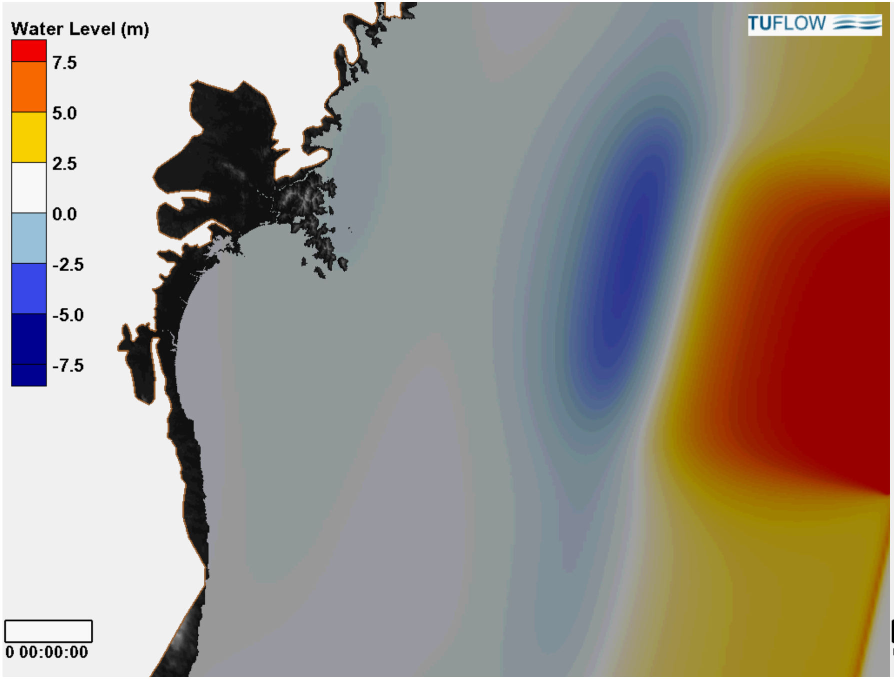




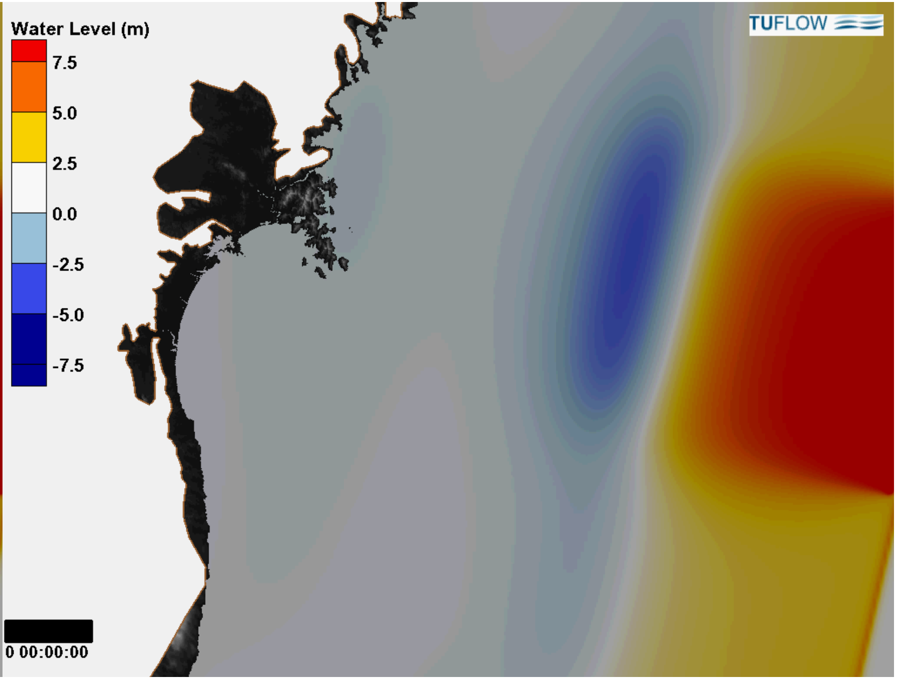
2011 Japanese Tsunami

TUFLOW FV 1st Order vs 2nd Order

1st Order



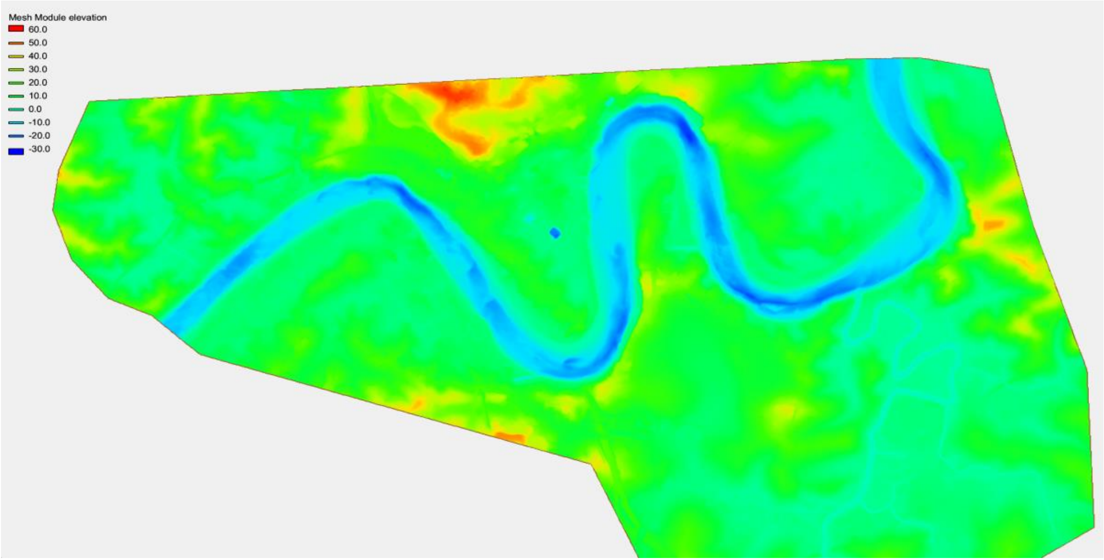
2nd Order, MLG



Real River

Section of the Brisbane River

- D/S water level 2.7m
- U/S Q = 9,000 m^3/s
- Smagorinsky M=0.5 C=0.05
- Steady flow model
- Peak of calibrated flow event
- Undulating bathymetry
- 20 to 30 m deep
- V_{av} 3 to 4 m/s



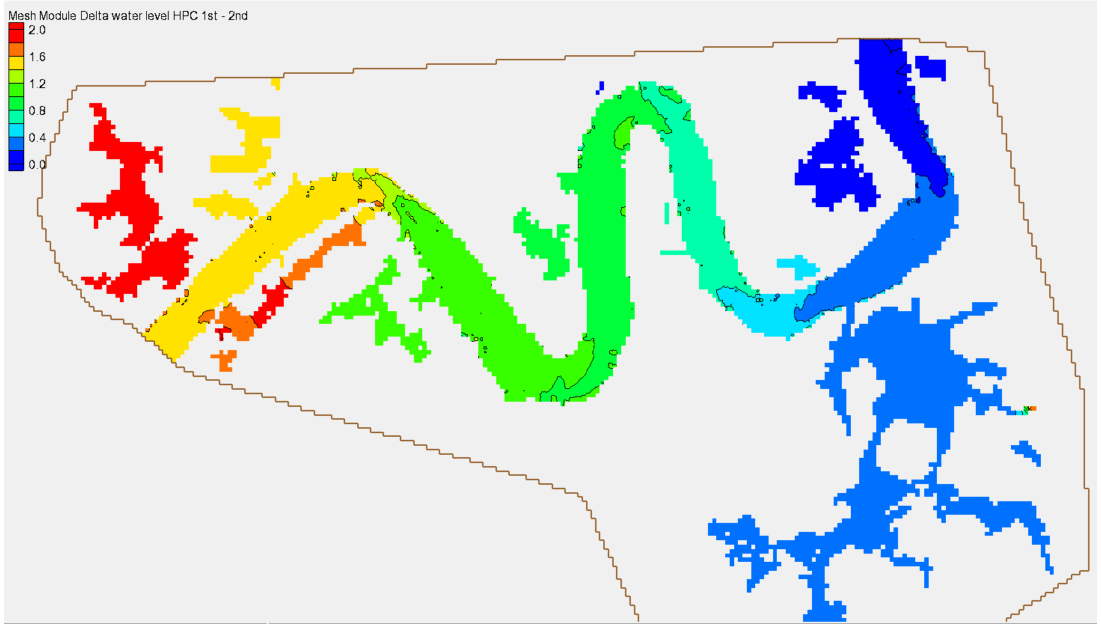
Mathematical Solution

Does 1st Order, 2nd Order Matter?

- 1st Order typically generates more energy losses and steeper water level gradients
- ~1.5 m higher in this case

Yes, it can matter

1st order ideally tested against 2nd order



Well calibrated model

TUFLOW HPC
Timestep Convergence

- TUFLOW HPC uses 4th order Runge-Kutta integrator
- Known to quickly transition to well converged
- Non-dimensional numbers must be below limits:
  - Courant number
  - Wave celerity number
  - Diffusion number
- Adaptive time-stepping
- 1st and 2nd order poor time convergence

$$N_u = \max\left(\frac{|u|\Delta t}{\Delta x}, \frac{|v|\Delta t}{\Delta y}\right) \leq 1.0$$

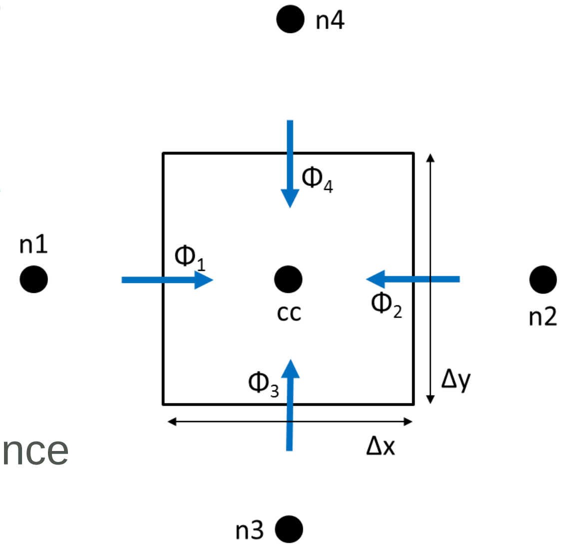
$$N_c = \max\left(\frac{\sqrt{gh}\Delta t}{\Delta x}, \frac{\sqrt{gh}\Delta t}{\Delta y}\right) \leq 1.0$$

$$N_d = \max\left(\frac{\nu_T\Delta t}{\Delta x^2}, \frac{\nu_T\Delta t}{\Delta y^2}\right) \leq 0.3$$

Adaptive Timestepping

HPC Control Numbers

- Courant number (Nu < 1.0)
- Shallow wave celerity number (Nc < 1.0)
- Diffusion (turbulence) number (Nd < 0.3)
- Explicit solution: all three at or below limits for convergence
- Δt adjusted every timestep to meet above conditions
- Δt estimated from previous timestep results
- Therefore, Δt can be too large
- So, have built in a repeat timestep feature (next slide)



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$$N_d = \max\left(\frac{\nu_T \Delta t}{\Delta x^2}, \frac{\nu_T \Delta t}{\Delta y^2}\right) \leq 0.3$$

TUFLOW BMT

TUFLOW HPC
Stability

Timestepping

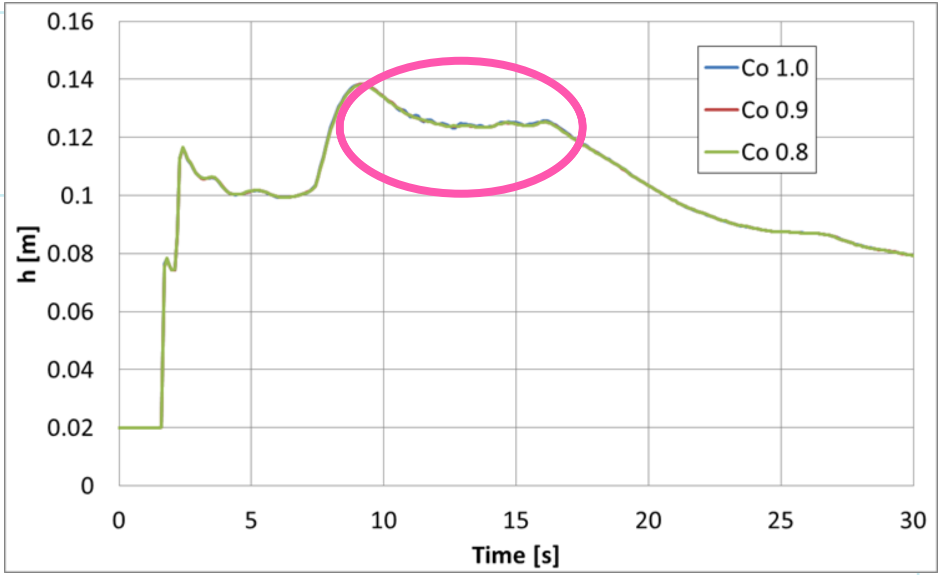
- Adaptive (default) – very stable
- Can run fixed timestep – if control number limits exceeded, solution likely to go unstable
- Nu, Nc, Nd limits may be factored down by user (e.g. Control Number Factor == 0.8)

Repeat Step Feature

- Model state at end of step is evaluated
  - If NaNs encountered, or control numbers' limits exceeded by more than 20%, step is rejected, timestep is reduced, and step is repeated
- Model fails at 10 consecutive failed repeat step attempts - exceptionally rare!
- Model state at start of each step is retained
- Repeated step messages reported in .hpc.tlf file (and on console window)

Adaptive Timestepping

HPC Control Numbers



Default limits: Nu = 1.0; Nc = 1.0; Nd = 0.3

Can underclock or overclock using "Control Number Factor =="

- Use with caution if overclocking!

May underclock where:

- Numerous repeated timesteps
- Any "noise" in maximum surfaces
- If timestepping likely to change for "What if?" scenarios
- Like to be conservative!

Underclocking by 20% increases runtimes by 20%

$$N_u = \max\left(\frac{|u|\Delta t}{\Delta x}, \frac{|v|\Delta t}{\Delta y}\right) \leq 1.0$$

$$N_c = \max\left(\frac{\sqrt{gh}\Delta t}{\Delta x}, \frac{\sqrt{gh}\Delta t}{\Delta y}\right) \leq 1.0$$

$$N_d = \max\left(\frac{\nu_T\Delta t}{\Delta x^2}, \frac{\nu_T\Delta t}{\Delta y^2}\right) \leq 0.3$$

Minimum dt

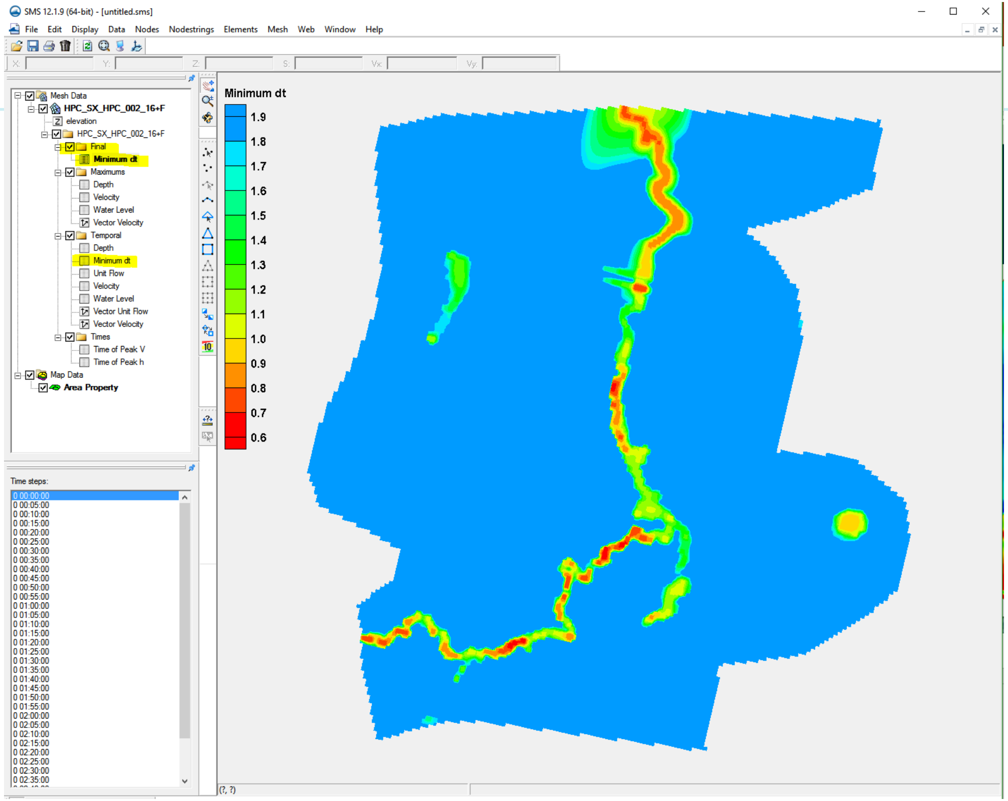
Timestep Map Output

Outputs the limiting Δt for each cell

Identifies where in the model is controlling the timestep

Highlight poor or inaccurate data

- Erroneous elevations creating very deep cells
- A cliff in the model from a breakline with wrong values
- Incorrect, and very slippery Manning's n value



Classic vs HPC

Beware of the Stability!

Classic

- Can go unstable (as we all know!)
- Due to divergence of solution (i.e. matrix solution not converging)
- Instabilities highlight bad data or poor model setup
- Forces the modeller to make good models

HPC

- VERY stable (an instability is very rare!), and zero mass error, BUT
- May hide poor data or poor model set up
- Tracked maximums may pick up a slight bounce (that's not deemed to be an instability)
- Tools provided to help quality control models
- Be thorough in reviewing results

HPC Timestepping
Good Indicator of a “Healthy” Model

Good indicator of model quality/health

Timestepping that changes steadily is good!

Causes of poor timestepping and repeat timesteps

- Rainfall (RF) histogram boundaries (this is OK)
- Poor or erroneous data
- Poor boundary setup (e.g. QT line not perpendicular to flow)
- Cell size too coarse for main waterways
- Insufficient SX cells linked to 1D structure
- And so on…
- Same culprits as for Classic, but HPC will most likely remain “stable”!!! BEWARE

Mesh Size Convergence

Mesh Size Convergence

Mesh Size Convergence

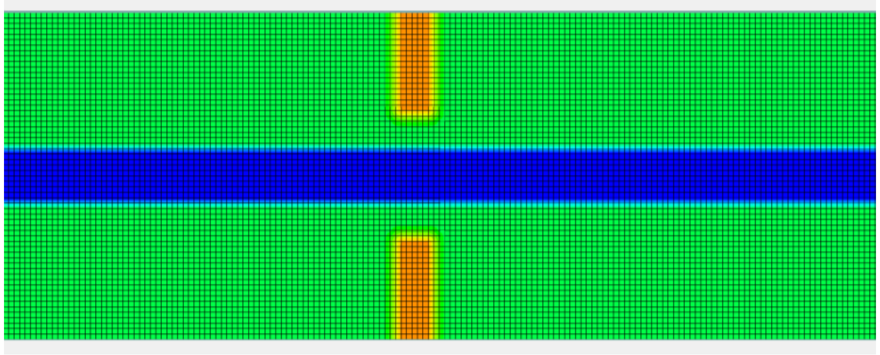
Mesh Size Convergence

Mesh Size Convergence

- IT SHOULD!
- Confidence in code and model
- Can assist with model calibration
- Helps with understanding model accuracy
- Watch out for Picasso solutions…

Kansas Uni Bridge Flume Test

- Engineered river channel
- Highway embankment and bridge piers
- Deal. Evan Christopher. “A Comparison Study of One- and Two-Dimensional Hydraulic Models for River Environments”. University of Kansas Thesis, 2017
  https://kuscholarworks.ku.edu/handle/1808/23919



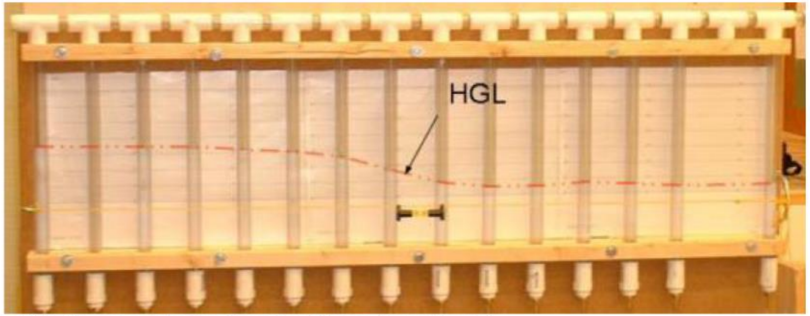
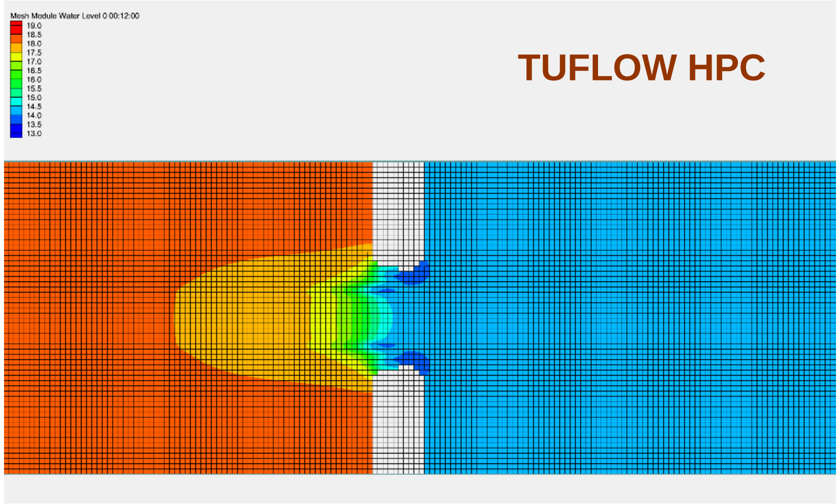


Figure 6.3: Piezometric Surface for Flume Experiment

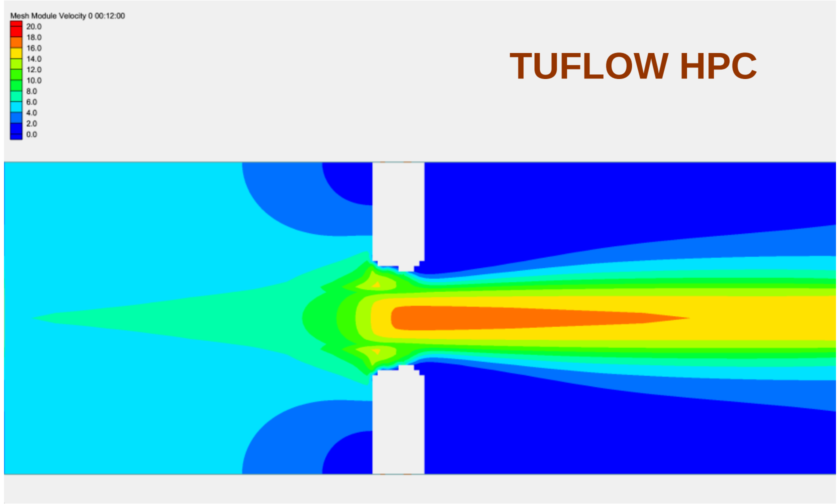
Kansas Uni Bridge Flume Test

TUFLOW HPC Results

Surface elevation (ft)



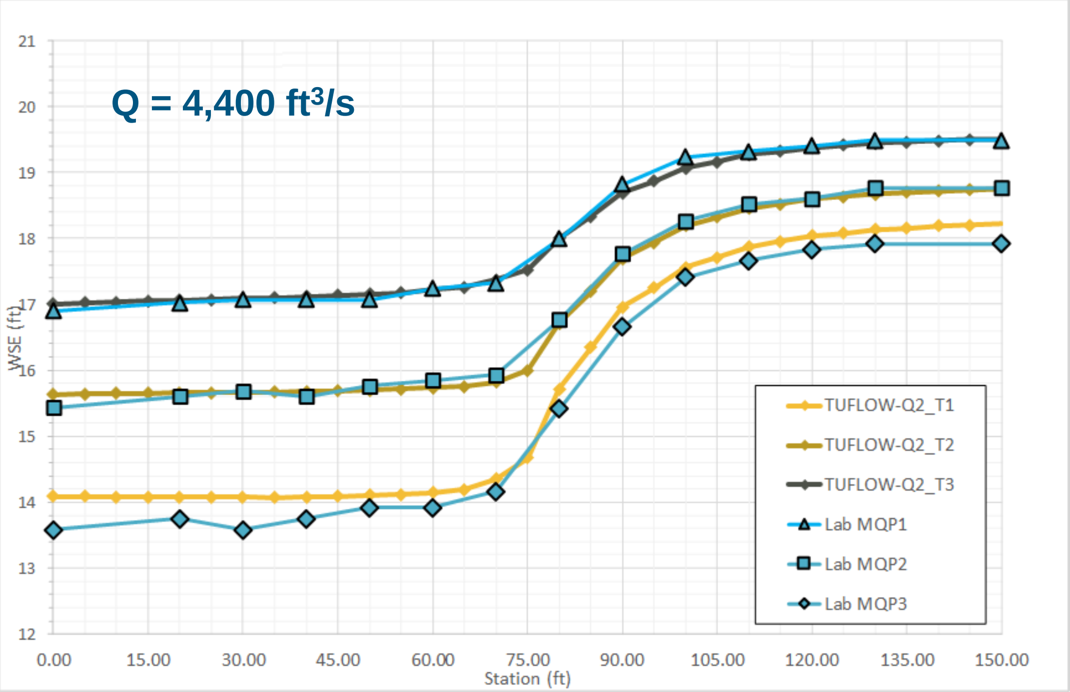
Velocity (ft/s)



Kansas Uni Bridge Flume Test

TUFLOW HPC Results

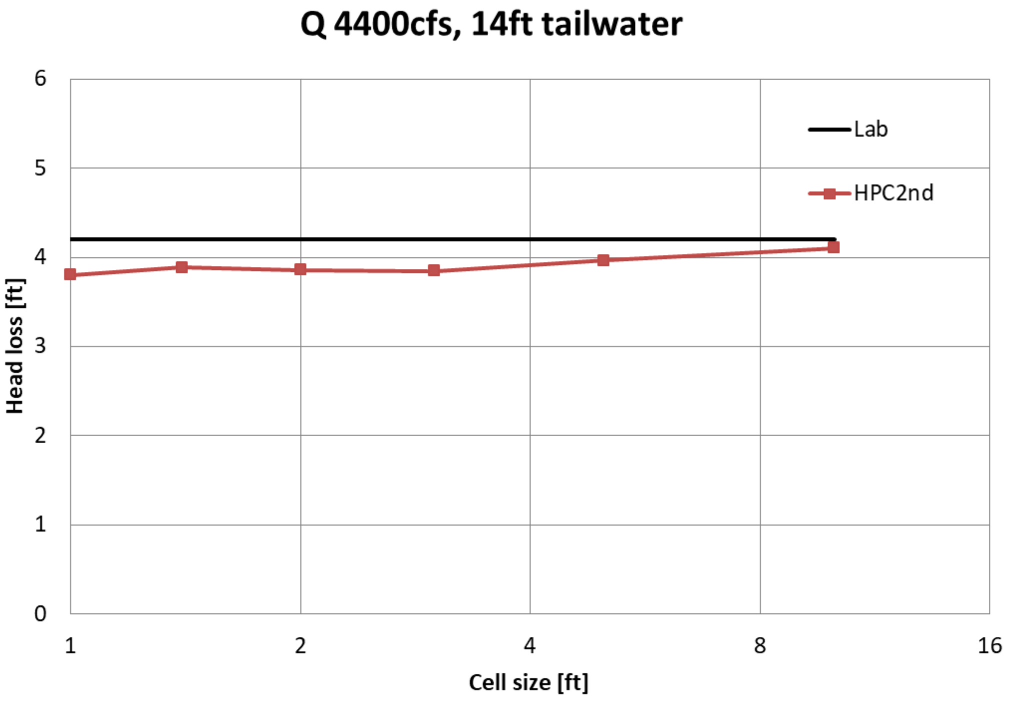
- 2^{nd} Order HPC solution
- Mannings n = 0.0233
- Bridge pier (K_p) losses as derived from Hydraulics of Bridge Waterways
- Default eddy viscosity parameters



Kansas Uni Bridge Flume Test

HPC Mesh Convergence Tests

- Head loss vs cell size for low tail-water case
- In this case, little variation for 2nd order solution



Brisbane River

Benchmark Model

- D/S water level 2.7m
- U/S Q = 9,000 m3/s
- Smagorinsky M=0.5 C=0.05
  (Default values)
- Steady flow model
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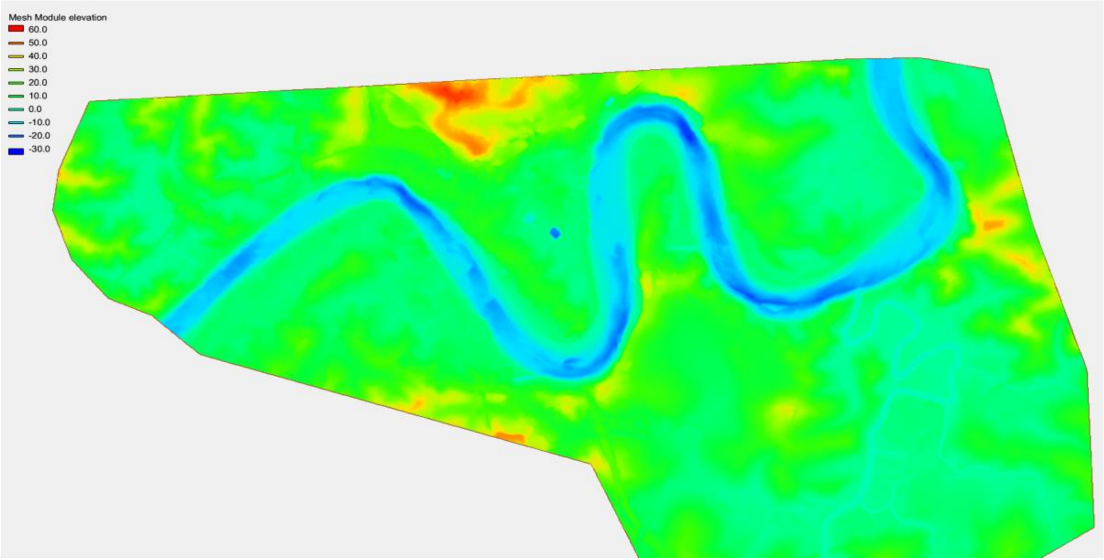


Mesh Size Convergence

Does it Matter?

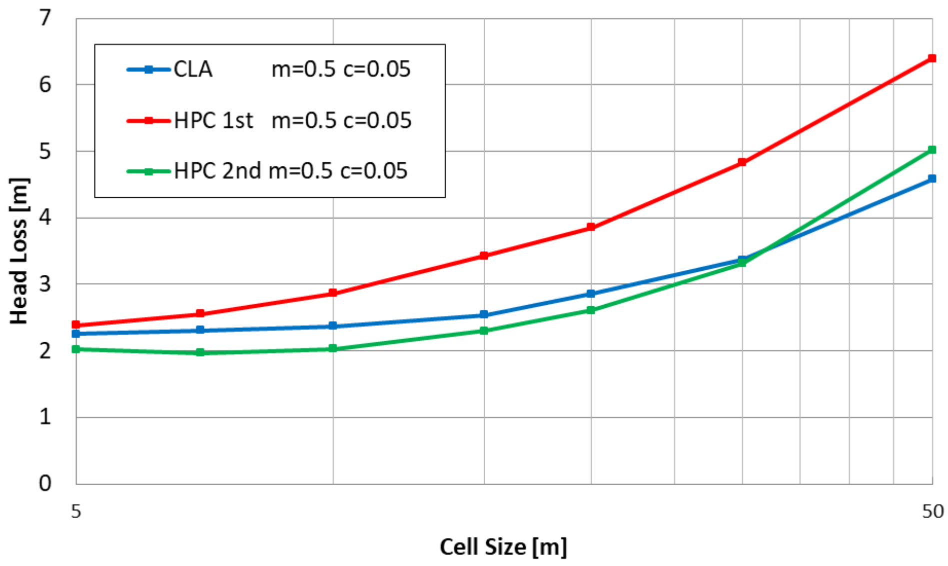
Brisbane River Sensitivity Test

- Run for different mesh resolutions, different timesteps
- Ascertain any dependencies
- Are these of importance?

1st order solution tends to show poorer convergence

Researching turbulence (eddy viscosity) representation where cell size << depth

Yes, it can matter

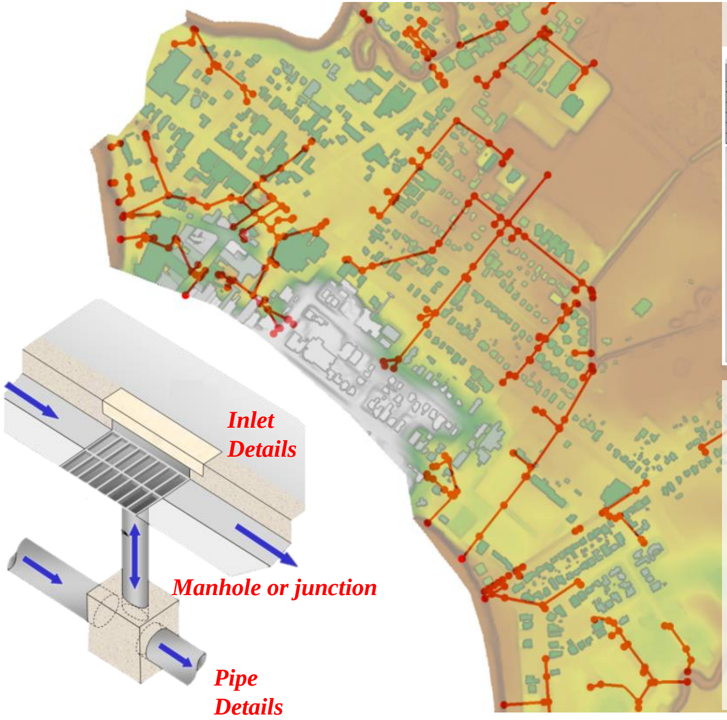


Case Study – Surfacewater Modelling Innisfail

1D Stormwater Network / 2D Overland

- Inlets
- Manholes or junctions
- Stormwater pipes
- Gates, Spillways, Weirs, Backflow control devices
- Linked to 2D overland

"Road Crossfall" option to improve flow capture at pits

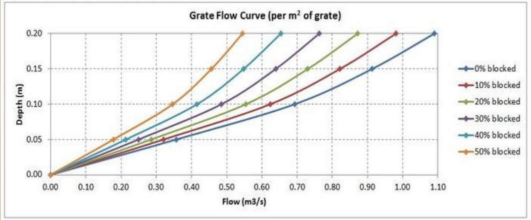


Pit Inlet depth vs flow curves

Grate Flow Curve

Water Depth (m)	Discharge (m^3/s) per m^2 of grate area					
	0% blocked	10% blocked	20% blocked	30% blocked	40% blocked	50% blocked
0.00	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.357	0.321	0.285	0.250	0.214	0.178
0.10	0.693	0.624	0.554	0.485	0.416	0.347
0.15	0.913	0.822	0.730	0.639	0.548	0.456
0.20	1.089	0.980	0.871	0.763	0.654	0.545

NOTE: Multiply table value by grate area to calculate site specific value



Manhole Energy Loss Options:

Fixed = QUDM compatible

Engelund method (default)

1) Expansion / contraction of flow
2) Changes in pipe size
3) Changes in angle at junctions
4) Change in elevation at junctions

2D Surfacewater Modelling – Innisfail

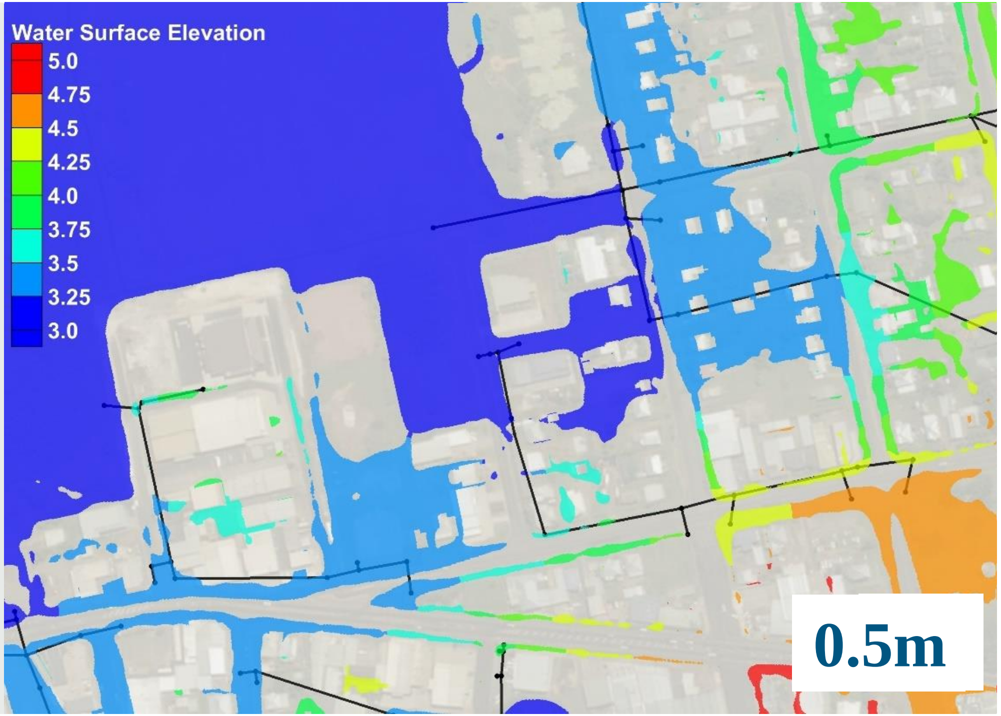
How fine can/should(!) we go?

Accurate topography data

What 2D model resolution…

How fine for urban situations?

- **20m** 7,500 cells
- **10m** 31,000 cells
- **5m** 125,000 cells
- **2m** 750,000 cells
- **1m** 3,100,000 cells
- **0.5m** 12,500,000 cells



2D Surfacewater Modelling – Innisfail

How fine can / should(!) we go?

Accurate topography data

What 2D model resolution…

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- **20m** ✗ 7,500 cells
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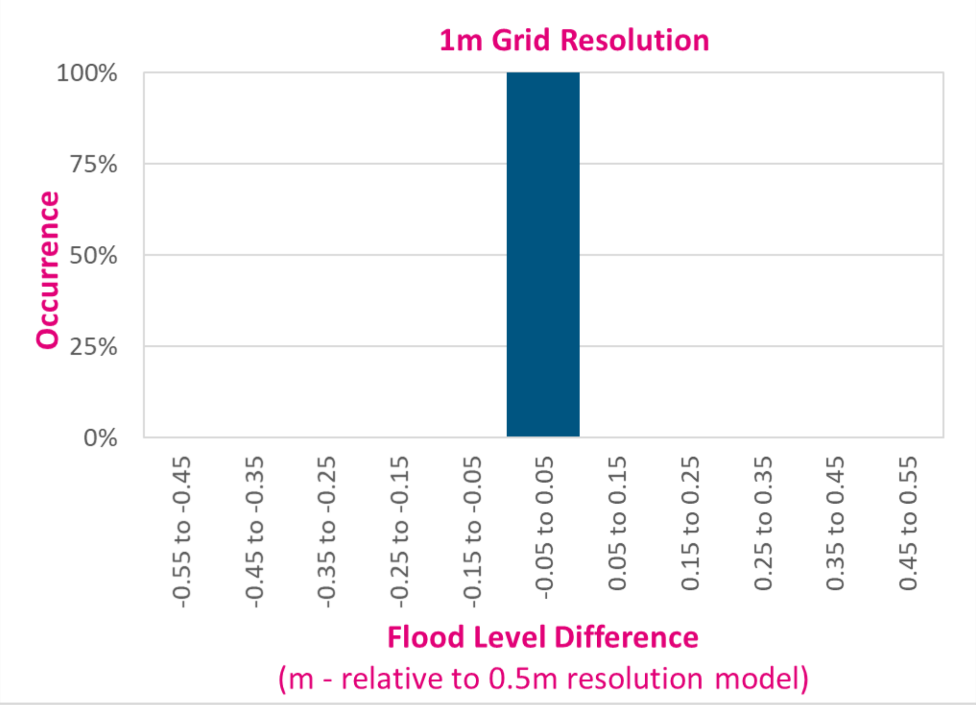
- **5m** ✗ 125,000 cells
- **2m** ✓ 750,000 cells
- **1m** ✓ 3,100,000 cells
- **0.5m** ✓ 12,500,000 cells

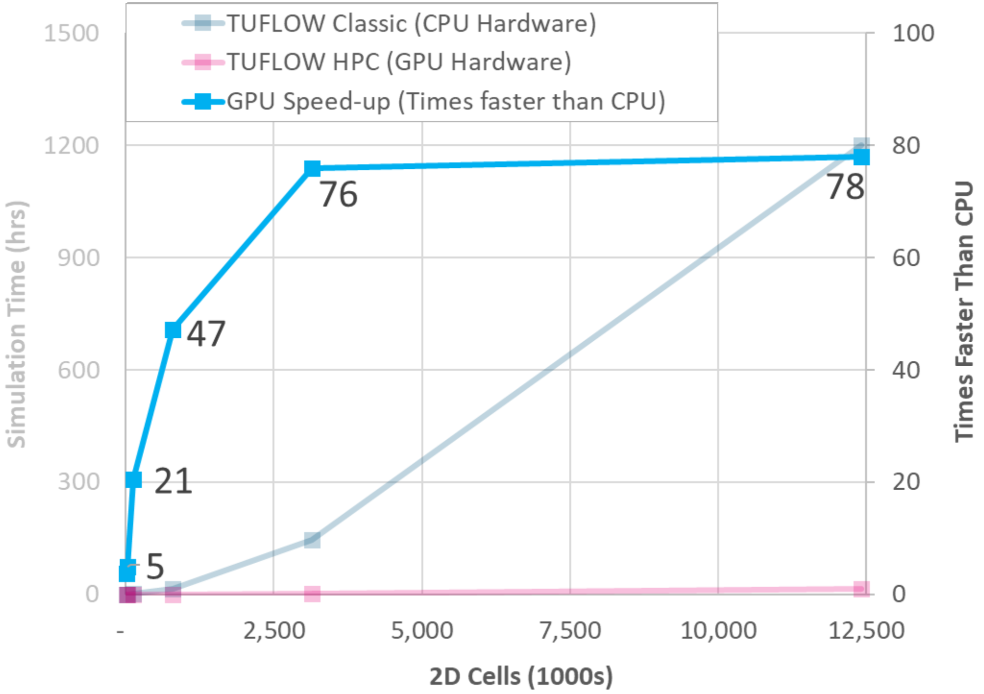


Surfacewater Modelling
How fine can we go?

CPU = 17-5960X CPU @3.00GHz
GPU = 2 x GeForce GTX 980

Solver and Hardware Options

	Classic CPU	HPC GPU
~~• 20m~~	~~0:12 hr~~	~~0:03 hr~~
~~• 10m~~	~~0:15 hr~~	~~0:03 hr~~
~~• 5m~~	~~1:32 hr~~	~~0:05 hr~~
• 2m	15:19 hr	0:20 hr
• 1m	14[illegible]0 hr ✗	1:55 hr
• 0.5m	≈48 days ✗	18.30 hr



TUFLOW HPC
Boundaries

Supported boundaries/links

- HT, HQ, HX
- QT
  (Note: A QT boundary invokes 1D linking, therefore, communication with CPU every timestep)
- RF (all forms), SA (all forms), SX

HQ boundary implementation the most different

- HPC applies slope on a cell-by-cell basis
- Classic estimates flow across HQ line and applies same water level across all cells

TUFLOW HPC

1D/2D Integration

Fully compatible with ESTRY (TUFLOW 1D)

- ESTRY now supports adaptive time-stepping to synchronise with HPC
- All 1D functionality available to HPC

Integration with External 1D Schemes

- Implemented or in progress (12D DDA, Flood Modeller 1D and XP-SWMM 1D)

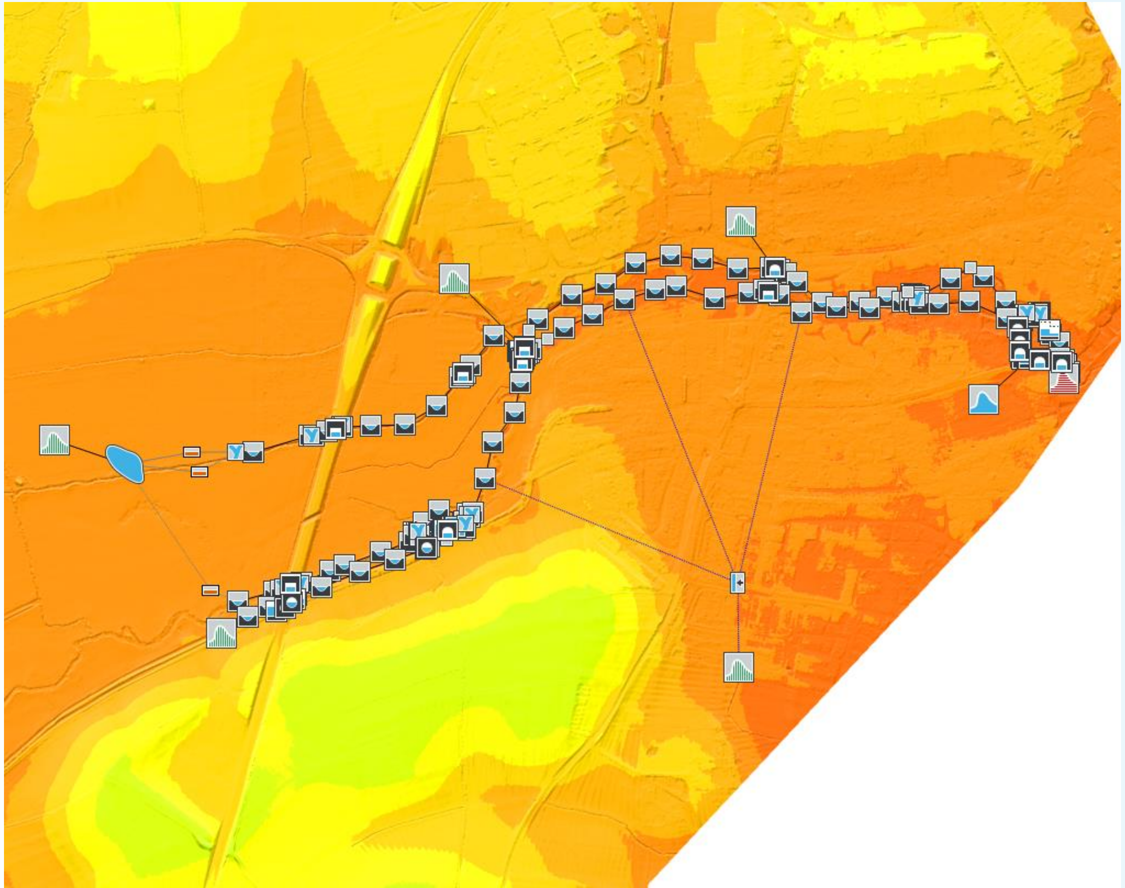
Supports all HX and SX links

- No need to change any inputs

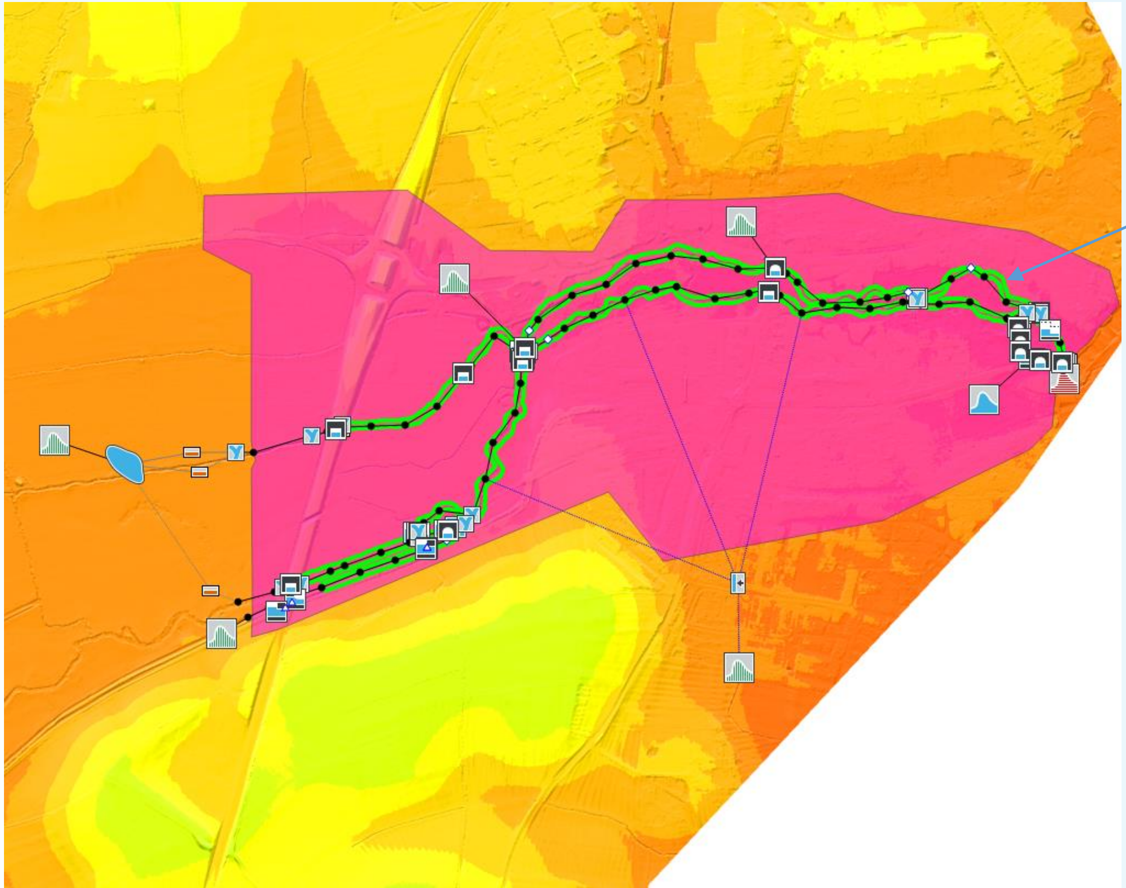
TUFLOW GPU’s Virtual Pipes feature now supported

- Can now have 1D pipe networks and virtual pipe pits in same model
- Build 2018-03-AA about to be released

Linking to TUFLOW HPC - Example

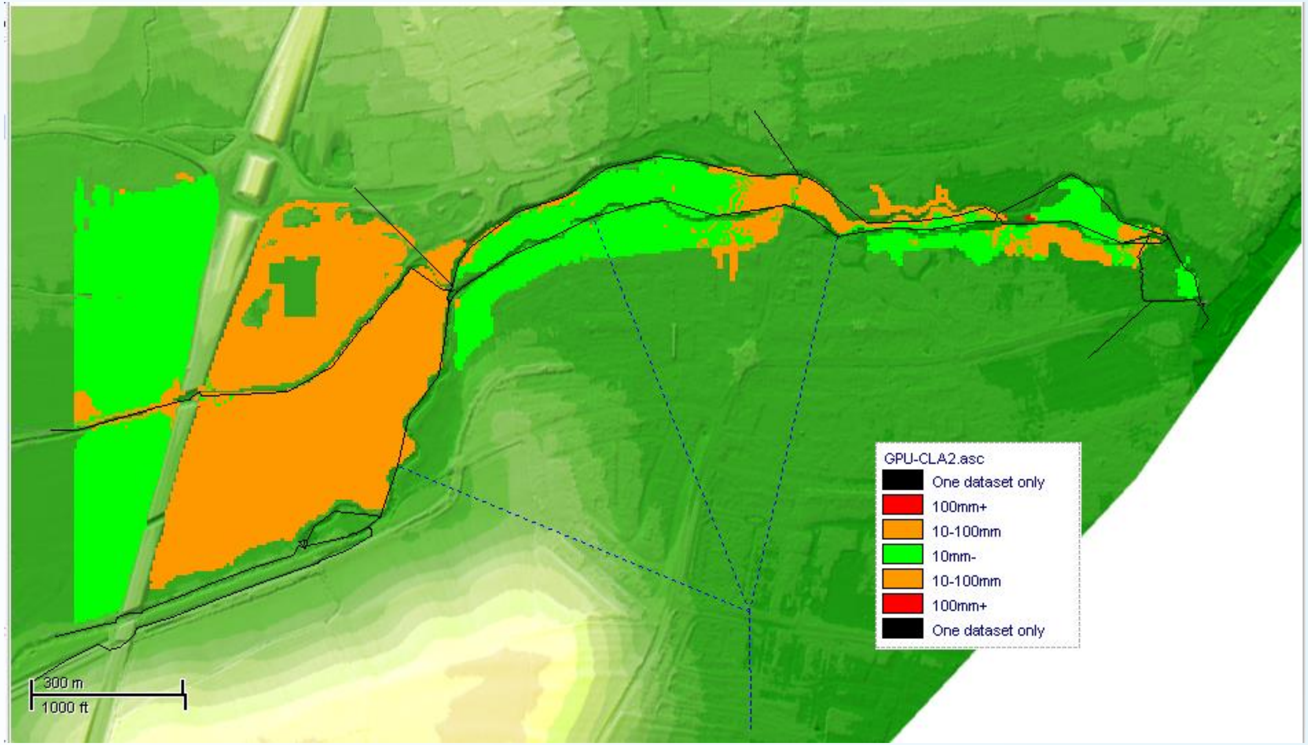


Linking to TUFLOW HPC - Example



HX links

Linking to TUFLOW HPC - Example



Linking to TUFLOW HPC - Example

- Example run times with linked Flood Modeller 1D

	With TUFLOW Classic (on CPU)	With TUFLOW HPC on CPU	With TUFLOW HPC on GPU
Ock model	137 mins	150 mins	32 mins

- Speed up

	With TUFLOW Classic (on CPU)	With TUFLOW HPC on CPU	With TUFLOW HPC on GPU
Ock model	n/a	0.9	4.3

NVIDIA GeForce GTX 1080 – £500 gaming graphics card

Do I Need to Change my Classic Model?

No (other than a couple of .tcf commands)

Can run 1D/2D Classic models using HPC 2D solver

Default for 2017 is to use Classic 2D solver

To run HPC 2D solver:

```
Solution Scheme == HPC  ! Default is Classic
```

To run on GPU Device(s) :

```
Hardware == GPU  ! Default is CPU
```

Note: HPC does not yet support all of Classic's functionality (discussed later)

But, you may need to recalibrate

All solution schemes produce different results

Compare differences, if unacceptable or poorer calibration

- Fine-tune parameters
  (e.g. Manning's n values; Form losses; Eddy viscosity)

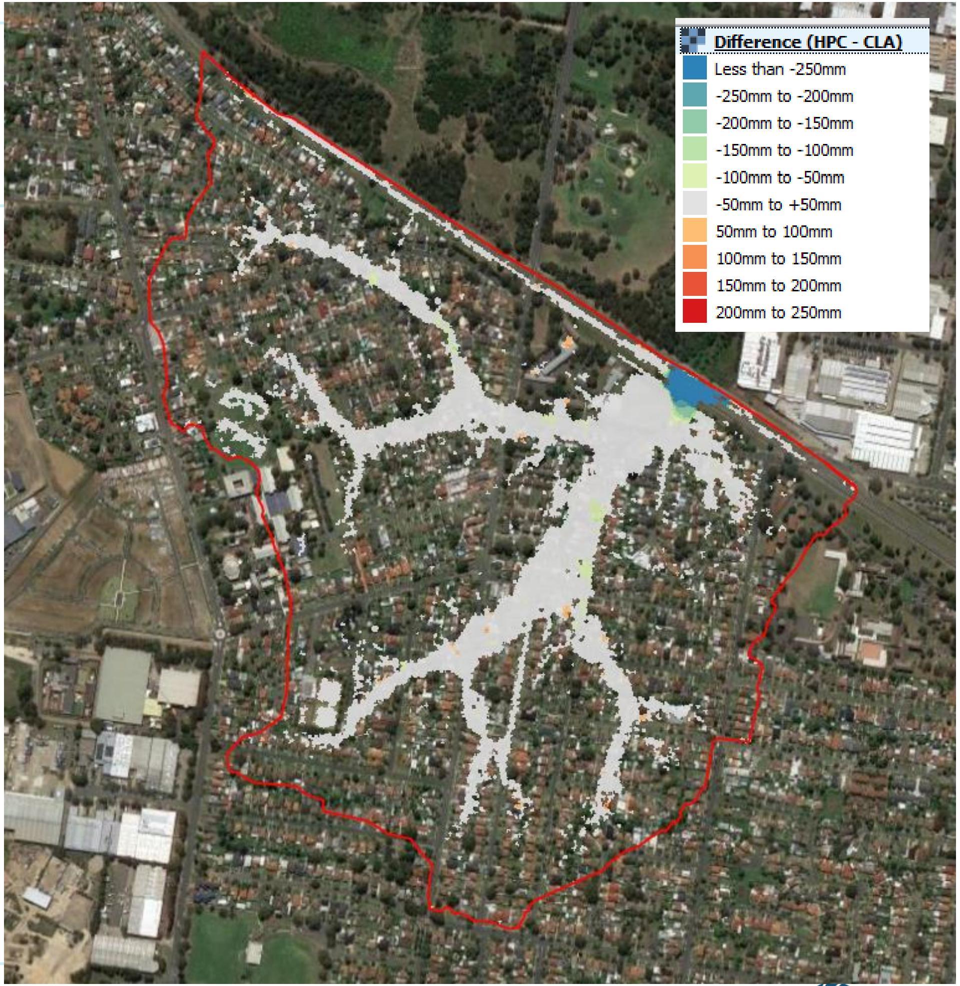
Can use Classic / HPC 2nd order to cross-check each other

If starting, or just started, a new project, try HPC

HPC vs Classic

Direct rainfall with pipe network

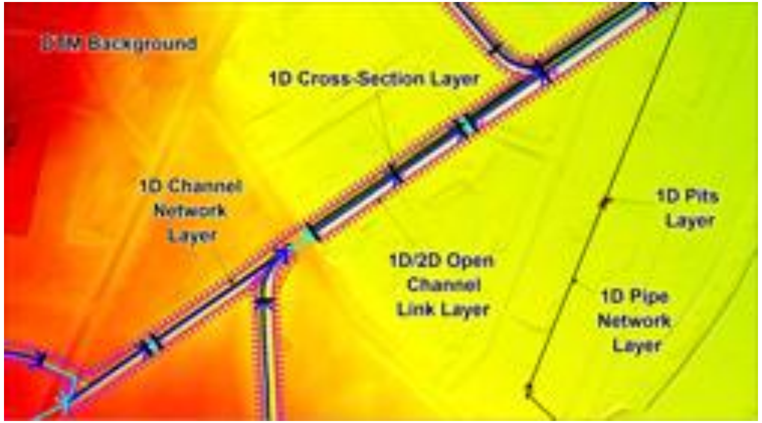
- 200,000 2D cells
- 200 1D culverts
- 150 pits

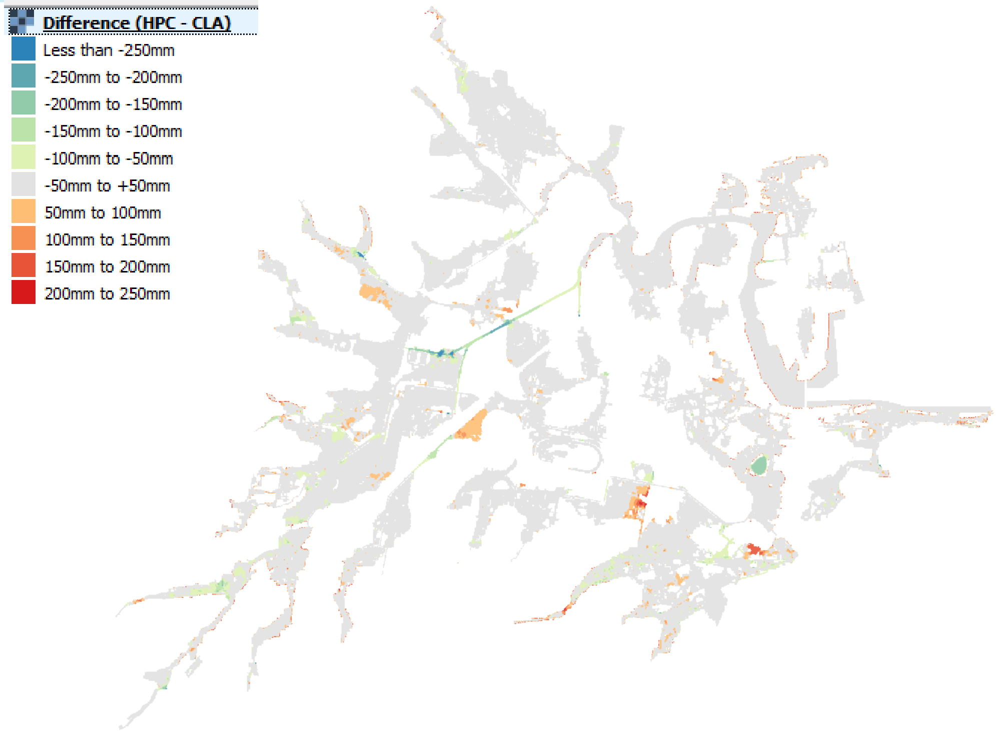


TUFLOW BMT

HPC vs Classic

- Throsby – Newcastle, Urban drainage, discrete hydrology model
- Very high in channel velocities (>5m/s)
- Very tricky to model stability wise
- Great benchmark model!





HPC vs Old GPU Solver

HPC supports cell mid-side features

- Thin breaklines (e.g. fences, levees)
- Sampling of Manning's n and materials at cell mid-sides
- Sampling of FLC and CWF at cell mid-sides

"GPU Solver == ON" invokes old TUFLOW GPU solver

- Make sure this command is replaced by commands below to run HPC
  - Solution Scheme == HPC
  - Hardware == GPU ! If you're using a GPU device

TUFLOW GPU provided, but engine will not be developed further

- No more new features for TUFLOW GPU
- Being provided for legacy reasons

TUFLOW HPC

GPU Hardware

How fast your model runs

- Compute performance (Flops), CUDA cores, clock speed

How large can your model be

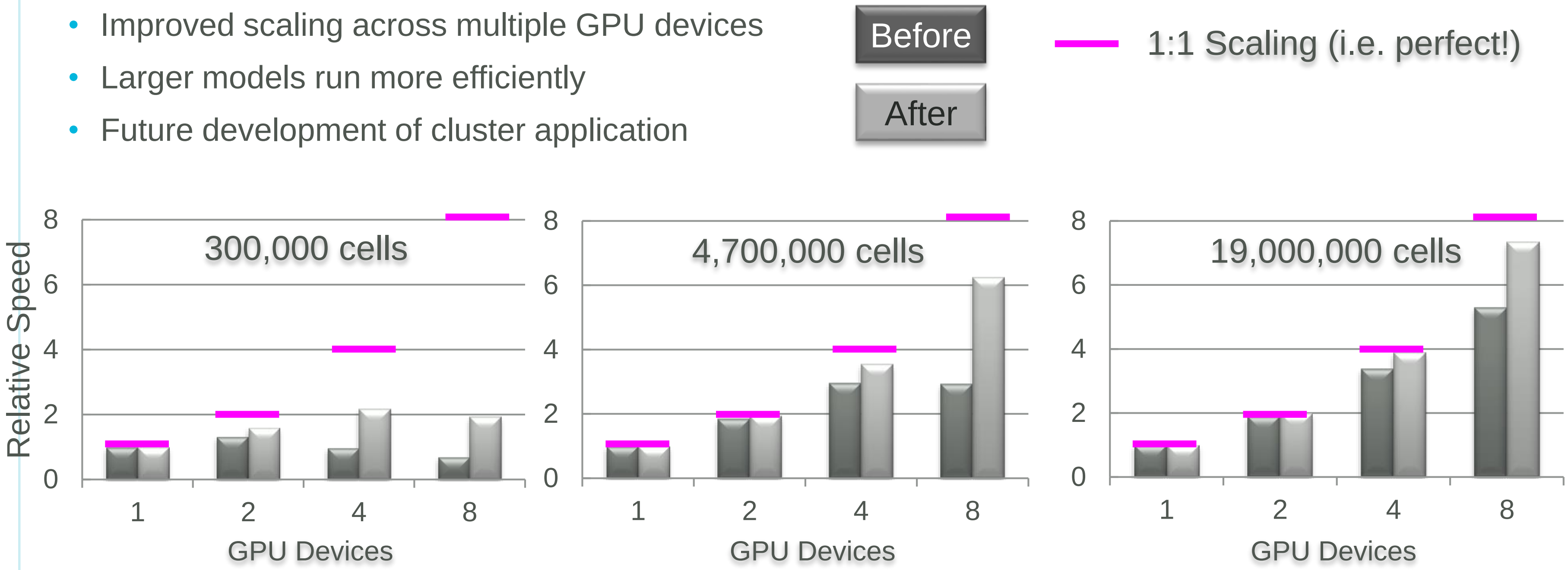
- Memory available in GPU
- Single or Double precision
- New features add more memory requirements!
  e.g. Tracking of time of maximums

Multiple GPU support

- Speed-up depends on model size, larger models scale better
- Pooled memory, allows running of large model
- NVIDIA DGX-1, 8 x Tesla V100 (5,120 cores each) USD$149,000

TUFLOW HPC
Improved Multi-GPU Card Performance

- Improved scaling across multiple GPU devices
- Larger models run more efficiently
- Future development of cluster application



TUFLOW HPC

What it doesn't do… (yet)

- Traditional FCs (Read GIS FC ==)
- Multiple 2D Domains
  (Prioritising nested grid feature)
- Evacuation routes and other specialised outputs
- Reporting Locations underway
- Others…

Over the coming year aiming to include all/nearly all functionality

TUFLOW HPC
Conclusions

2^{nd} order excellent mesh size and timestep convergence

Consistent comparisons with Classic models (on-going)

Performing strongly in wide range of applications

- Flume models with cell-sizes less than 1 cm
- Surface water applications
- Large, deep, fast flowing river systems

Very strong uptake in the Australian market

- Now preferred over Classic

Papers and 2012 UK 2D Benchmark Tests

- Visit https://www.tuflow.com/Library.aspx

UK Advanced Training Courses

Next Two Weeks, Leeds and London

Advanced TUFLOW HPC and IUD Training

- 25 & 26 April (Leeds) – places available
- 30 April & 1 May (London) – places available, nearly full

Details www.tuflow.com Training Page

- https://www.tuflow.com/Training.aspx?ubt
- Or email training@tuflow.com