How to Benchmark your Hydraulic Solver?

Bill Syme
Greg Collecutt

How to Benchmark your Hydraulic Solver?
Today's Webinar

Why we need to benchmark hydraulic solvers?

What should we benchmark?

How do we benchmark?

How to Benchmark your Hydraulic Solver?

Why we need to Benchmark?

How to Benchmark your Hydraulic Solver?
Why we need to Benchmark?

Our modelling informs decision makers
(Government, Authorities, Emergency Managers)

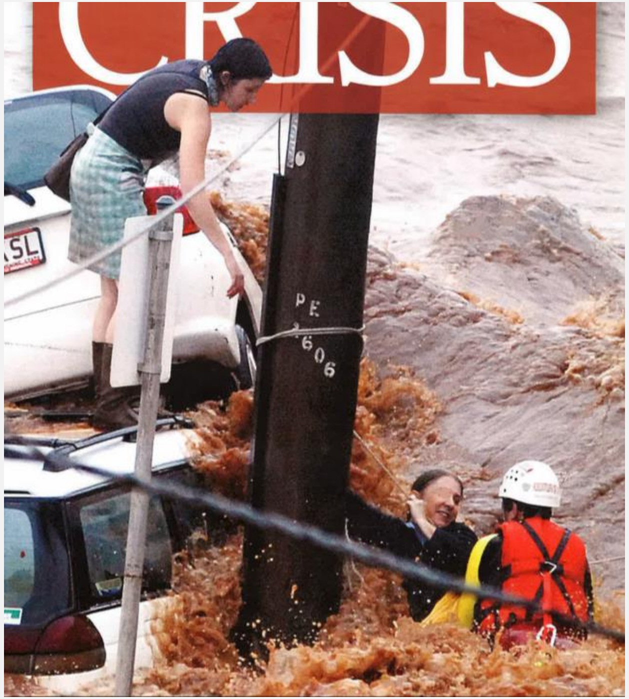
- Risk metrics
  - Risk to people, infrastructure, the economy
  - Understand what measures reduce the risk
- Predicts "what-if" impacts for planning
- Helps emergency management during an event

Affects infrastructure costs ($$$$)

You'll

- Become a much better, more confident modeller
- Improve workflow efficiency
- Enjoy your modelling more ☺

Modelling accuracy directly impacts peoples' lives



The Toowoomba Chronicle

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Why we need to Benchmark?
Uncertainties Everywhere

Input Data

- Terrain and bathymetric elevations
- Land-use (surface material)

Parameters

- Manning's n; Energy losses; Infiltration

Boundaries

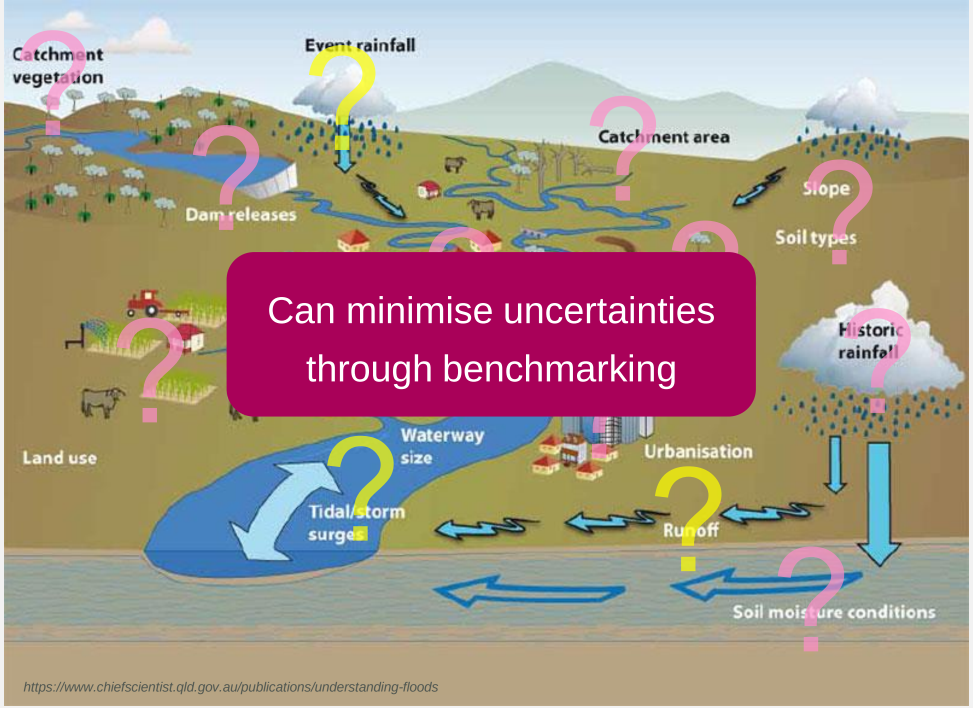
- Flows; Rainfall; Water Levels

Model Setup

- Cell size; Structures; Boundary locations

Numerical (Solver) Computations

- Solution is not exact



https://www.chiefscientist.qld.gov.au/publications/understanding-floods

Can minimise uncertainties through benchmarking

Why we need to Benchmark?
Hydraulic Models are not 100% right!

Is the numerical solution appropriate?

- Solver solutions are stripped down versions of the physically derived fluid flow equations
- Does the solution accurately reproduce the physics you're modelling?
- Does the solution have any dependencies? Do the results change due to changes in the model's
  - Cell sizes, Cell shapes, Cell orientations
  - Timestepping

Today's Webinar

Is the model reproducing reality (calibration) using standard parameters?

- Model calibration will struggle if
  - The solution is inaccurate or has dependencies
  - Input data is inaccurate – **GIGO – Garbage In, Garbage Out**
- Uncalibrated models rely on
  - The solution being accurate and no dependencies
  - Accurate input data – **GIGO – Garbage In, Garbage Out**

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How to Benchmark your Hydraulic Solver?

What should we Benchmark?

What should we Benchmark?
Fluid Flow Equations come in Different Forms

Spatial Dimension

- 1D / 2D / 3D

Common Forms

- Kinematic wave (bed resistance, e.g. Manning's)
- Diffusive wave (+ gravity)
- Dynamic wave
  - Without turbulence (+ inertia) – Slow moving (low energy) hydraulics
  - With turbulence (+ turbulence) – Flood hydraulics
  - Complete dynamic wave (+ pressure + Coriolis) – Coastal hydraulics
- Complete fluid flow equations (Navier-Stokes) – CFD

Solution Approaches

- Finite Element, Finite Difference, Finite Volume, ….
- 1^{st} order, 2^{nd} order, …. in time and space

What should we Benchmark?
Depends on the Flow

Low energy flows

- Slow moving water; backwaters
- Sub-critical flow (downstream controlled)
- Inertia and turbulence not important
- ➔ **Storage dominated**
- ➔ **Mass balance equation rules**

High energy flows

- Fast moving water
- Complex flow patterns, hydraulic jumps
- Super or sub-critical flow
- ➔ **Conveyance dominated**
- ➔ **Momentum equation rules**

1990 Flood Newcastle. Courtesy David Gibbins, Newcastle City Council.

1990 Flood Newcastle. Courtesy David Gibbins, Newcastle City Council.

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What should we Benchmark?
Depends on the Flow

Learn to appreciate what physical terms are important

How Velocity changes over time | Inertia Term | Gravity | Bed Resistance | Turbulence (Eddy Viscosity) | Other Forces

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial h}{\partial y} + \frac{gvn^2\sqrt{u^2+v^2}}{H^{4/3}} - u\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) = F_y$$

1990 Flood Newcastle. Courtesy David Gibbins, Newcastle City Council.

How Velocity changes over time | Inertia Term | Gravity | Bed Resistance | Turbulence (Eddy Viscosity) | Other Forces

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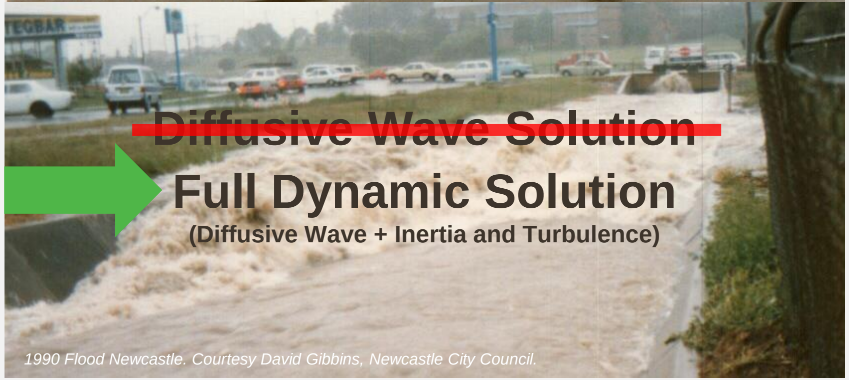

1990 Flood Newcastle. Courtesy David Gibbins, Newcastle City Council.

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What should we Benchmark?
Energy Dissipation

Flowing water dissipates its energy as heat

Bed friction (e.g. Manning's equation)

Turbulence (diffusion of momentum)

- Occurs strongly at
  - Bends, rock ledges
  - Constrictions
- 1D: can't model turbulence
- 2D: depends on the solver
  - Pseudo-2D (1D over a 2D mesh) ✗
  - Without turbulence ✗
  - 1st order spatial (numerically diffusive) ✗
  - 2nd order spatial with sub-grid turbulence ✓

1D can't model turbulence
(energy loss coefficients needed at structures, bends)

2D may not model all turbulence
Vertical circulations (eg. sharp bends)
Sub-grid obstructions (eg. piers)

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What should we Benchmark?
Solution Dependencies

Cell size, shape, orientation

- What happens if you change or rotate your mesh?

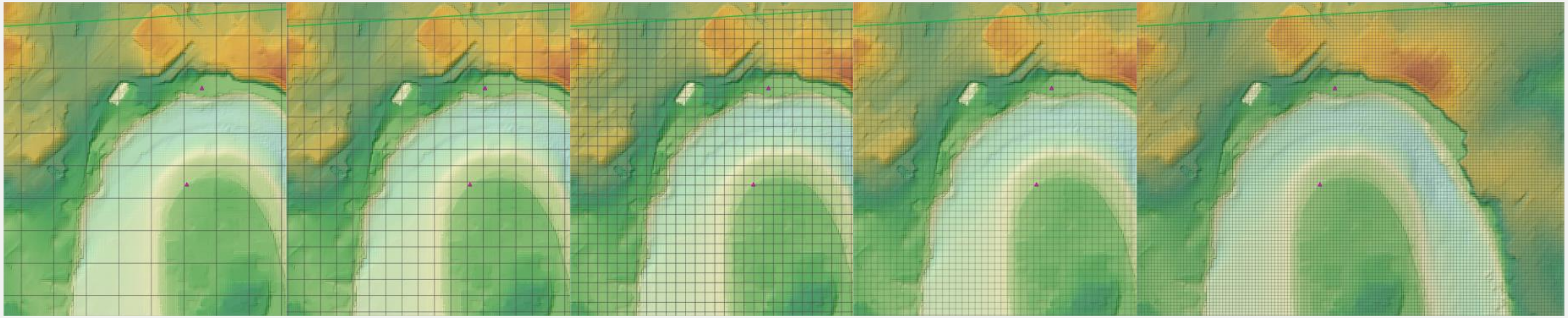
Timestepping

- What happens if you change your timestepping?

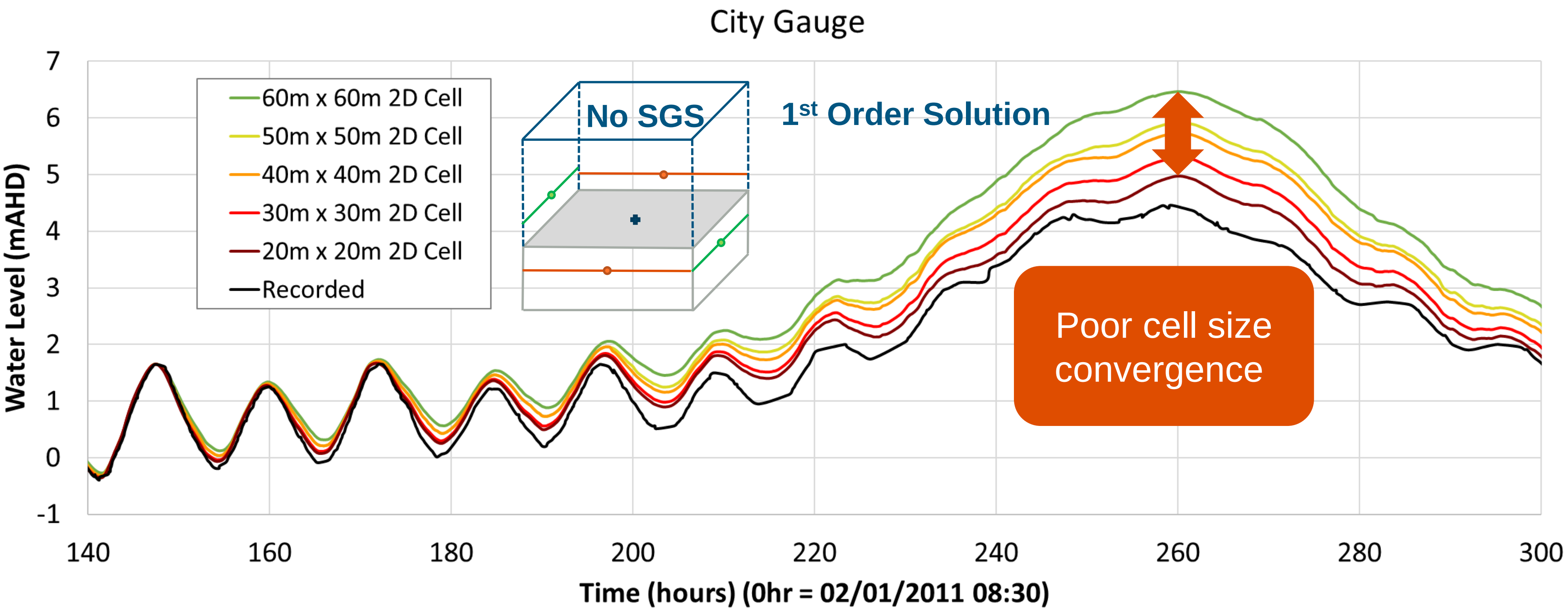
Numerical solution

- What happens if we change the solution?

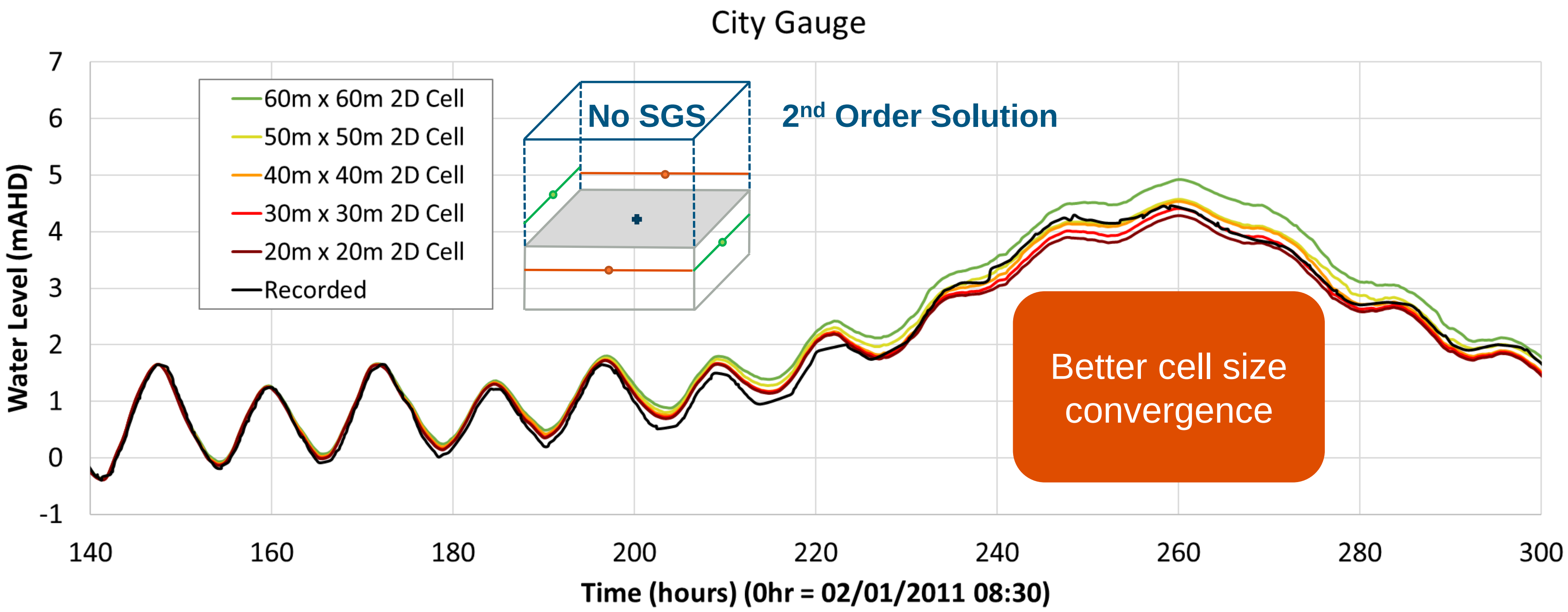
What should we do?
➔ Sensitivity test



What should we Benchmark?
Solution Dependencies – 1st Order Solution



What should we Benchmark?
Solution Dependencies – 2nd Order Solution



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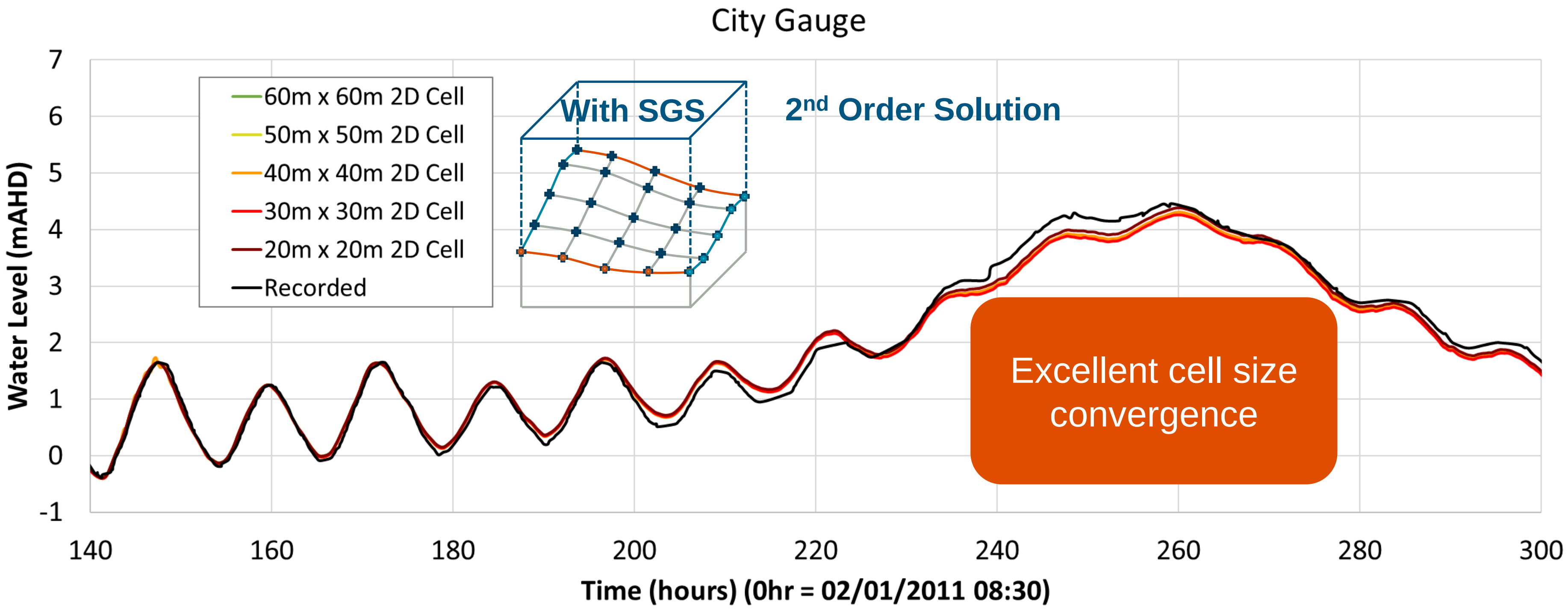
What should we Benchmark?
Solution Dependencies – 2nd Order Solution with SGS



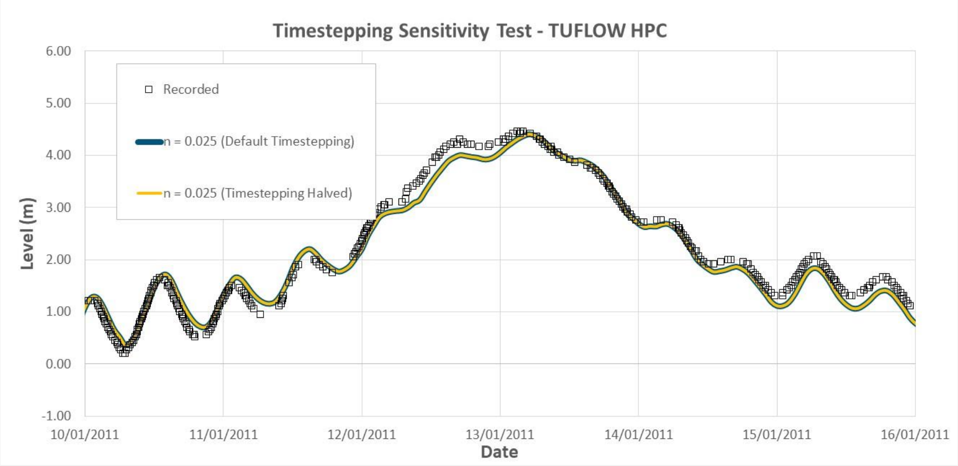
What should we Benchmark?
Solution Dependencies – Timestepping

Why?

- Characteristic of solution
- Occurrence of instabilities

What to do?

- Halve the timestepping and compare
  - Should give consistent, near identical results
  - If not, keep reducing timestepping until consistent results occur



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What should we Benchmark or be Checking? Summary

What?	Why?
Bed friction / Bend losses	Fundamental – industry standard parameters should always be used
Mass balance	Fundamental – zero or near zero mass error
Inertia terms	Important for higher energy flows: super elevation, hydraulic shocks
2D Eddy viscosity (Sub-grid turbulence)	Required for 2nd order solvers modelling higher energy flows, especially where: • primary flow paths resolved in 2D • velocity outputs (hazard, risk, bed shear) are important
Spatial interpolation 1st order vs 2nd order	Fundamental Related to cell size dependencies
Structures – weirs, bridges, etc	Fundamental – must reproduce structure flow equations
Cell size dependency	Quantify by sensitivity testing – rework cell sizes if needed
Timestep convergence	Quantify by sensitivity testing – can affect transient models (depends on solution)

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How to Benchmark your Hydraulic Solver?

How to Benchmark?

How to Benchmark?
Bed Friction

All 1D, 2D, 3D modelling software must be able to reproduce bed friction

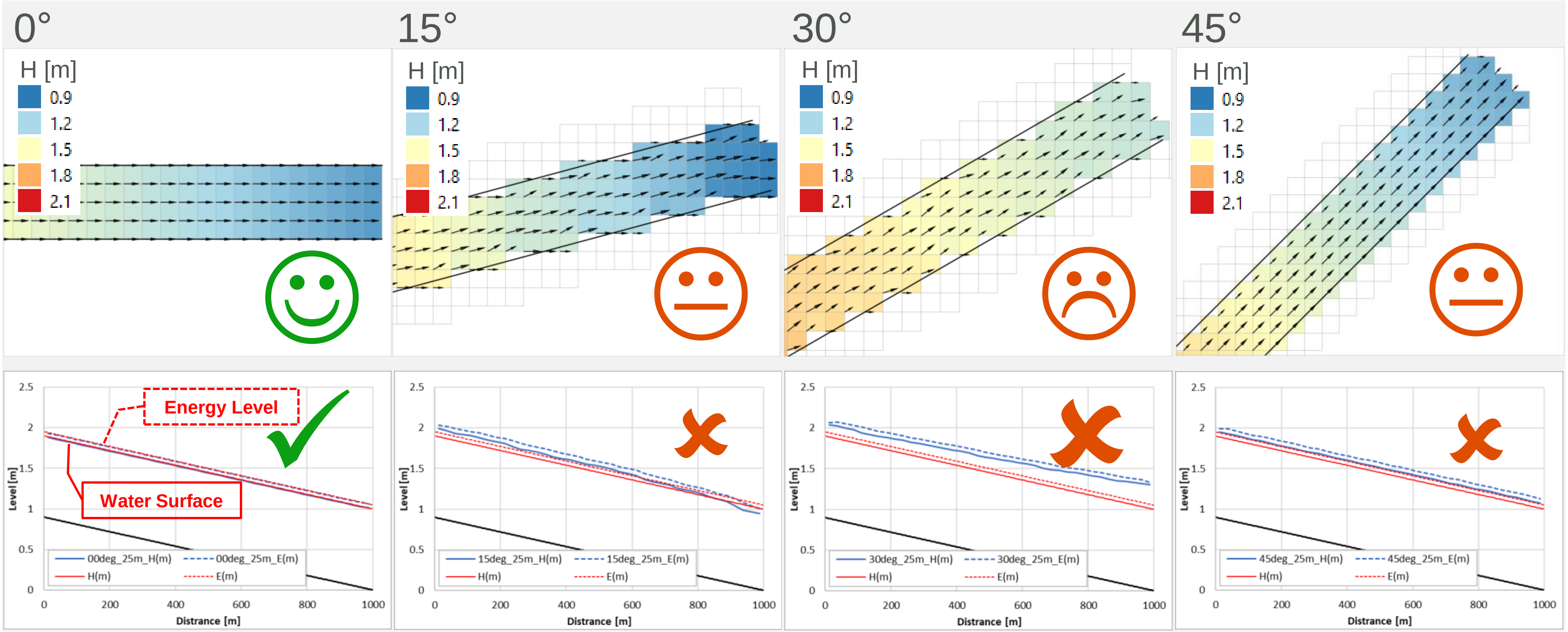
How do you test this?

- Create a simple model of a rectangular channel of fixed slope and constant flow (upstream boundary)
- Choose either a fixed elevation or a stage-discharge boundary condition (downstream boundary)
- Run model to steady-state solution and check depth against hand-calculation

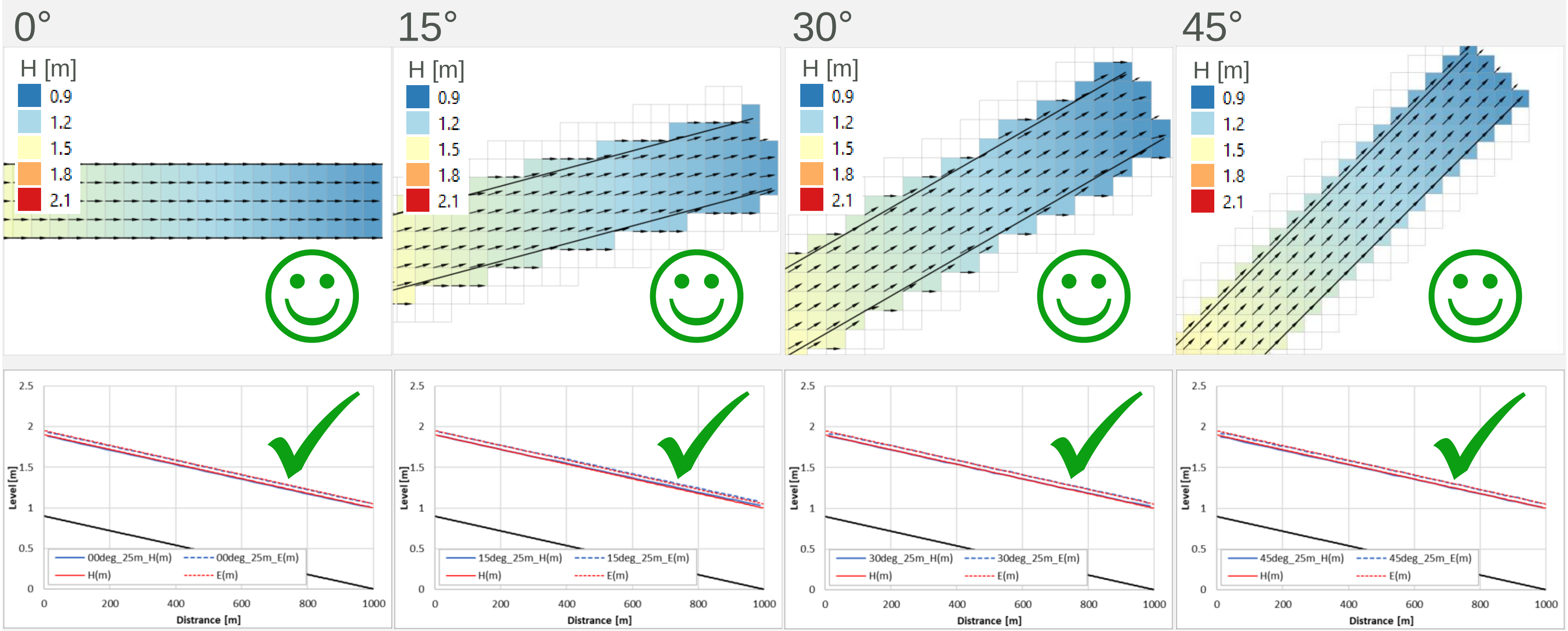
Have you thought about?

- Does the solver offer different (Manning's or Chezy or Ks Roughness) bed friction types?
- Does the solver use resistance radius or hydraulic radius (i.e. depth or Area/Perimeter)?
- Does the solver get the right answer for both sub-critical and super-critical flow?
- For 2D cases, does the element size matter?
- For 2D cases with fixed-grid meshes, does the grid orientation matter?
- For 2D cases with flexible meshes, does the element shapes/orientations matter?

How to Benchmark?
Bed Friction / Fixed Grid Orientation (No SGS)



How to Benchmark?
Bed Friction / Fixed Grid Orientation (With SGS)



How to Benchmark?
Mass Balance

All 1D, 2D, 3D modelling software must reasonably conserve volume

How do you test this?

- Create a simple model with one inlet and one outlet boundary
- For steady state solutions, only consider that Qout = Qin
- For transient solutions, volume balance (Qout + Qfinal = Qin + Qinitial) should apply at all times

Have you thought about?

- For solvers using finite difference and/or implicit or semi-implicit methods, some volume error is tolerable, and may depend on solver settings (including model timestep for transient solutions)
- For solvers using explicit finite volume, the volume error should be very small (effectively zero)
- Is it possible to get a solution from your solver, without it producing warnings, that is really wrong?

How to Benchmark?
Inertia terms

Inertia terms are essential for higher-energy flows with superelevation or shocks

How do you test this?

- Cases with non-uniform flow velocities along a primary path
- Cases with hydraulic jumps (super-critical to sub-critical flow transitions)
- Cases with super-elevation

Have you thought about?

- Choice of solution scheme
- Settings/parameters for solution scheme
- Element size, and timestep for transient schemes
- Eddy viscosity settings

How to Benchmark?
Inertia terms

Cases with non-uniform flow velocities along a primary path

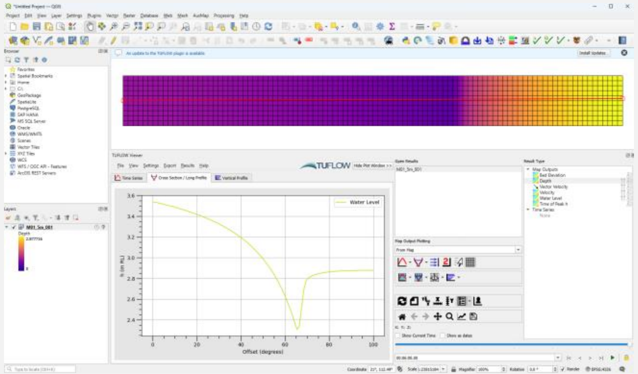
Internet search “W5-105/TR2A” for Environment Agency 1D Benchmarking suite

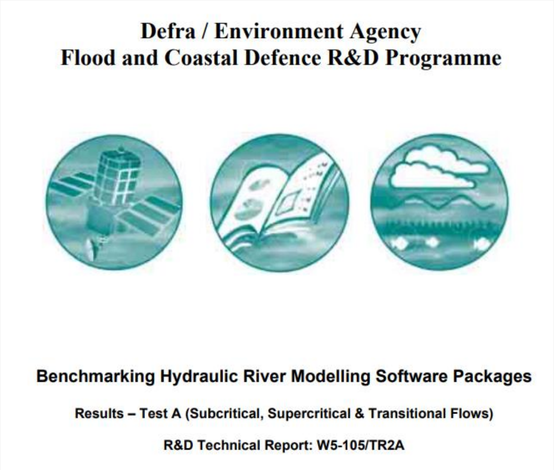
https://assets.publishing.service.gov.uk/media/5a7ce168ed915d7c849adcc5/scho0305bixp-e-e.pdf

Designed for benchmarking 1D solvers

Can be used in 2D by creating pseudo-1D cases

$$\frac{\partial h}{\partial x} = \frac{-\frac{\partial z}{\partial x} - \frac{n^2|u|u}{R_h^{4/3}}}{1 - \frac{u^2}{gh}} \qquad u = \frac{Q}{hb}$$




Defra / Environment Agency
Flood and Coastal Defence R&D Programme

Benchmarking Hydraulic River Modelling Software Packages

Results – Test A (Subcritical, Supercritical & Transitional Flows)

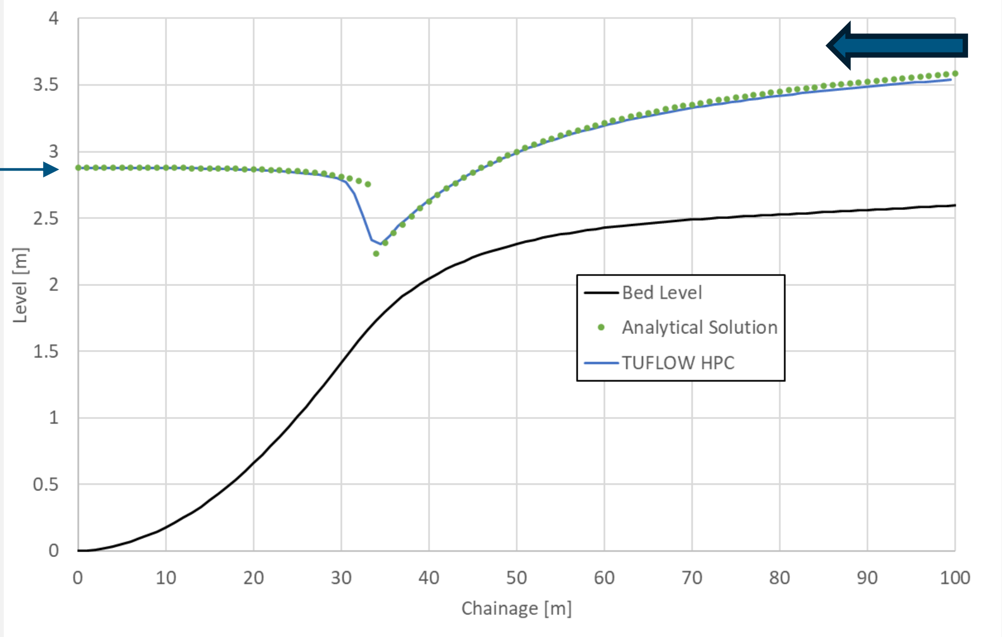
R&D Technical Report: W5-105/TR2A

How to Benchmark?
Inertia terms

Test A part 4 Subcritical – supercritical – subcritical

Downstream BC
h = 2.879 m

Channel width 10 m
Manning's 0.03
2D Cell size 1 m



Upstream BC
Q = 20 m^3/s

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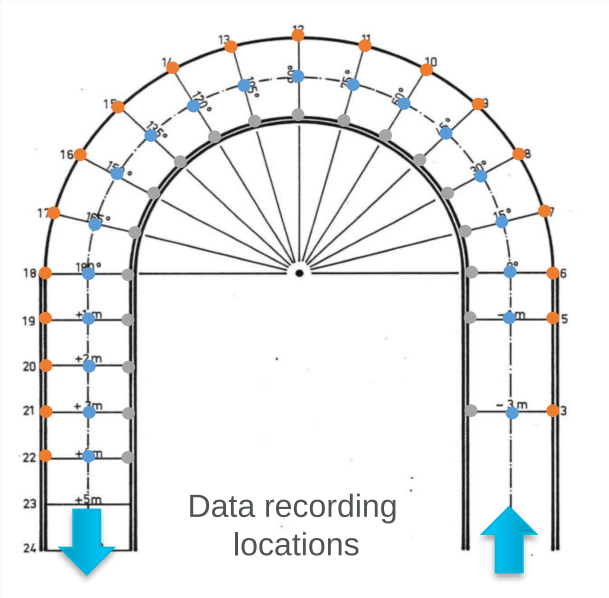
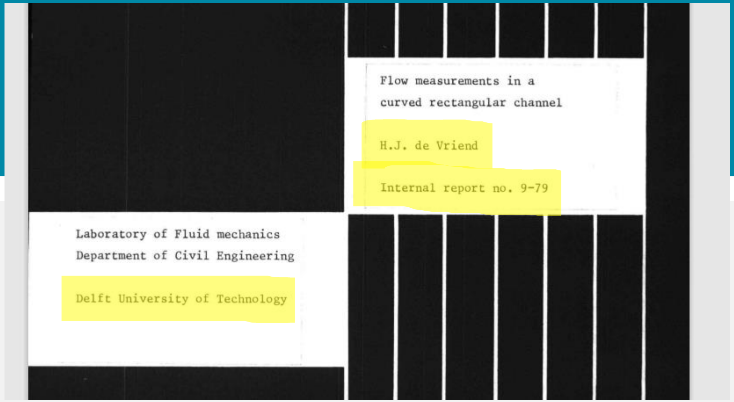
How to Benchmark?
Inertia terms

Cases with super-elevation



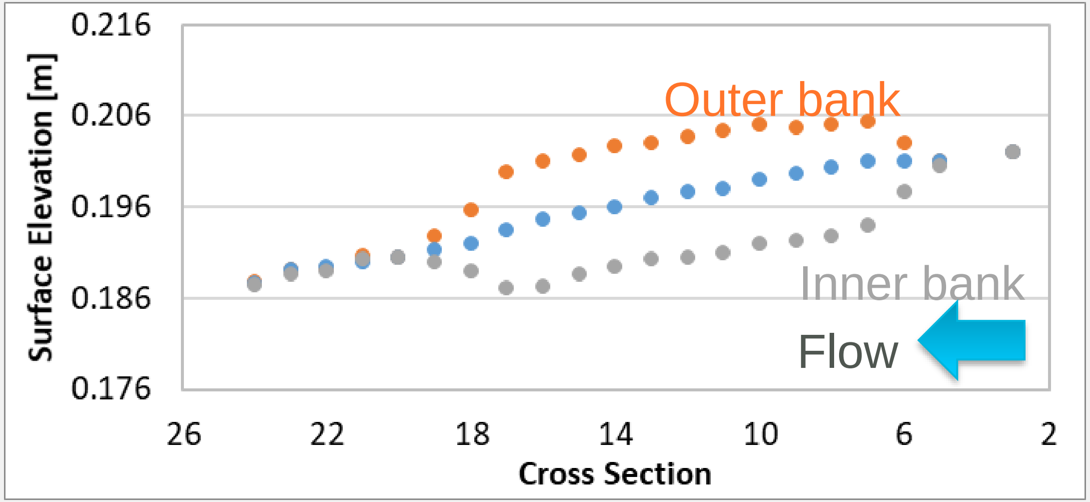

Flow measurements in a curved rectangular channel

H.J. de Vriend

Internal report no. 9-79

Laboratory of Fluid mechanics
Department of Civil Engineering

Delft University of Technology



How to Benchmark?
Inertia terms – Flexible Mesh

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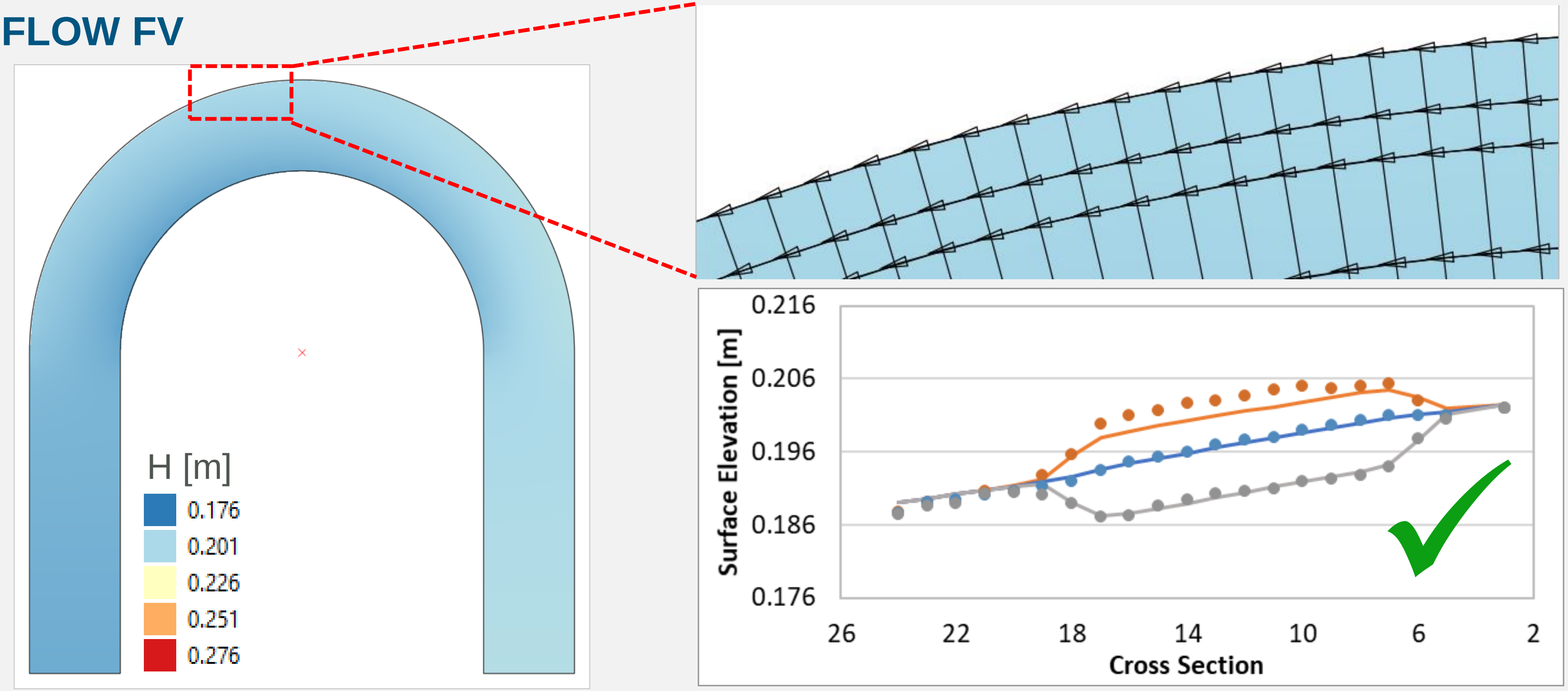
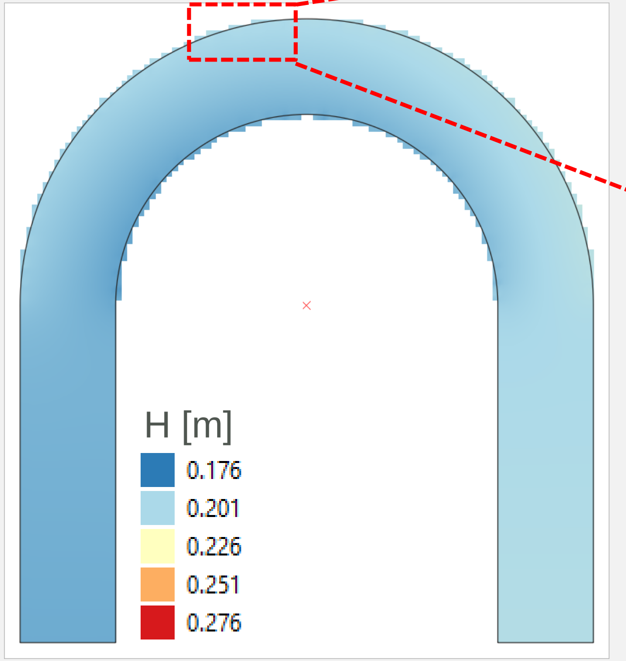
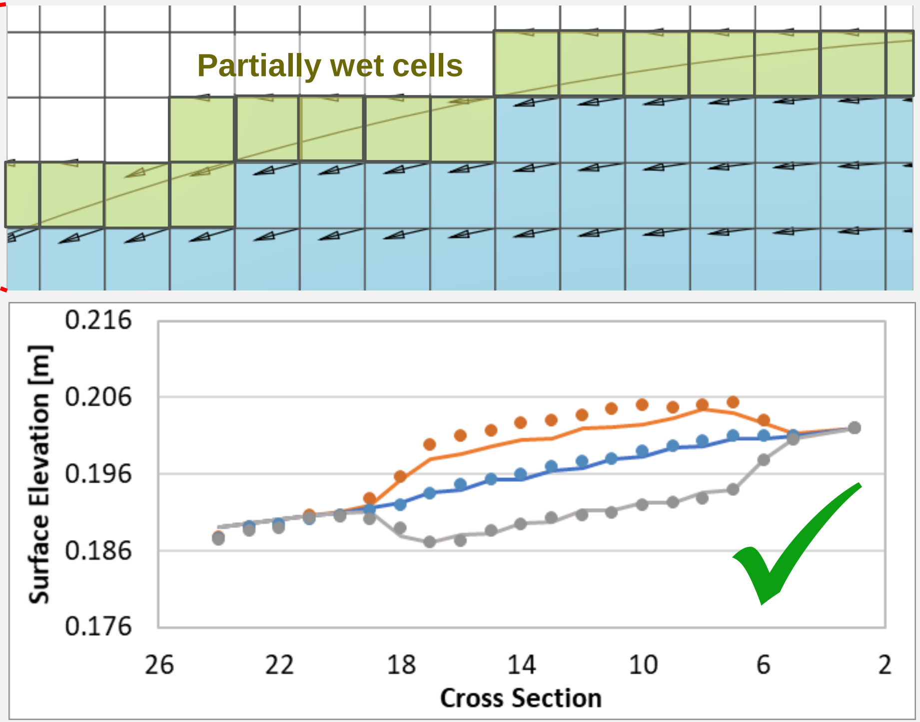


How to Benchmark?
Inertia terms – Fixed Grid with SGS

TUFLOW HPC with SGS

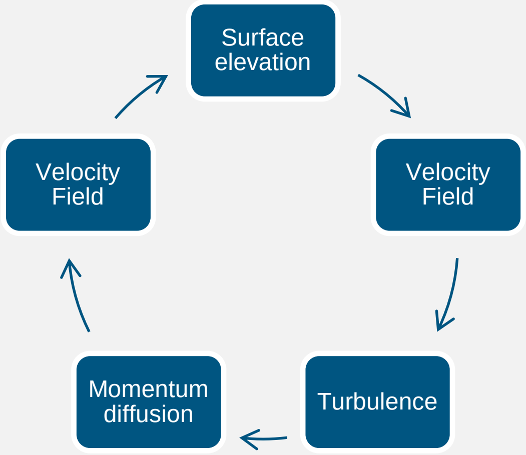




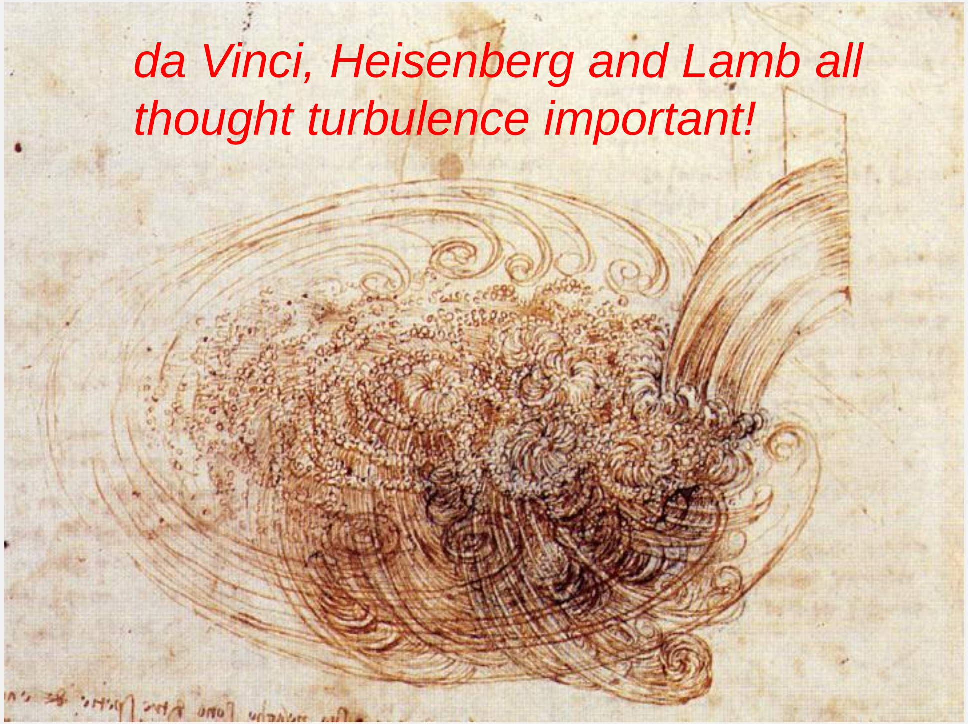
How to Benchmark?
Eddy Viscosity (Sub-Grid Turbulence)

Turbulence causes

- almost infinite flow detail
- momentum diffusivity



da Vinci, Heisenberg and Lamb all thought turbulence important!



How to Benchmark?
Eddy Viscosity

Eddy viscosity is required in 2D models for improved predictions of energy loss and velocity patterns around tight bends and flow restrictions

How do you test this?

- Energy loss around a right-angled channel bend
- Velocity pattern downstream of a river groyne

Have you thought about?

- Cell size sensitivity
- Does your solver use 1st or 2nd order spatial interpolation?

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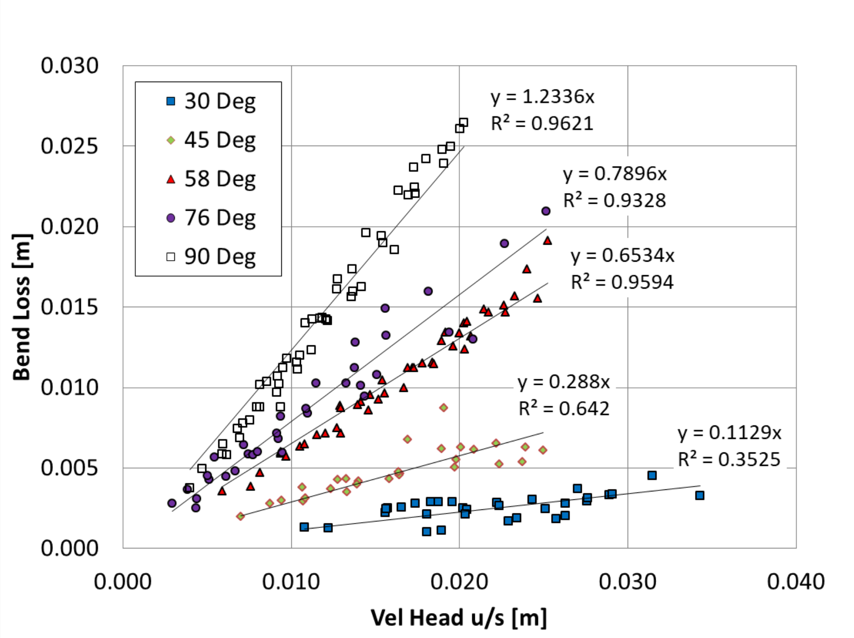
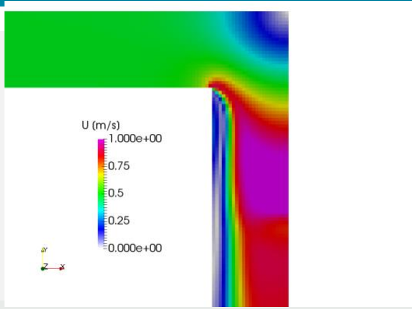
How to Benchmark?
Eddy Viscosity

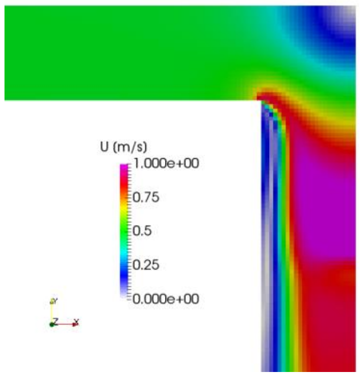
Right-angled bend

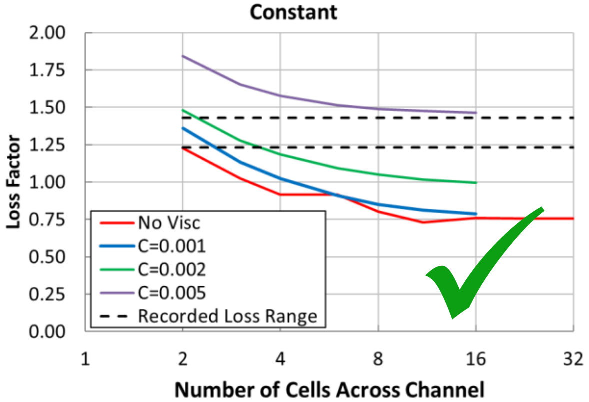


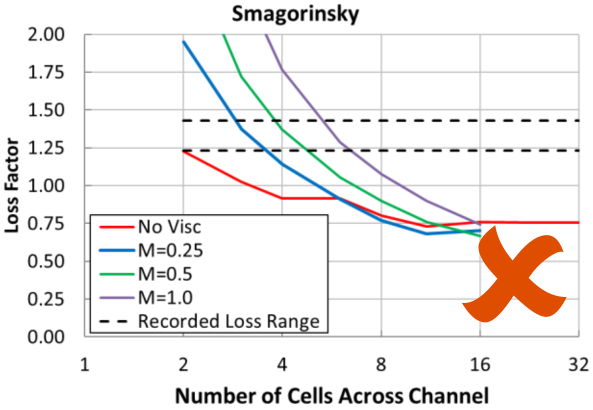


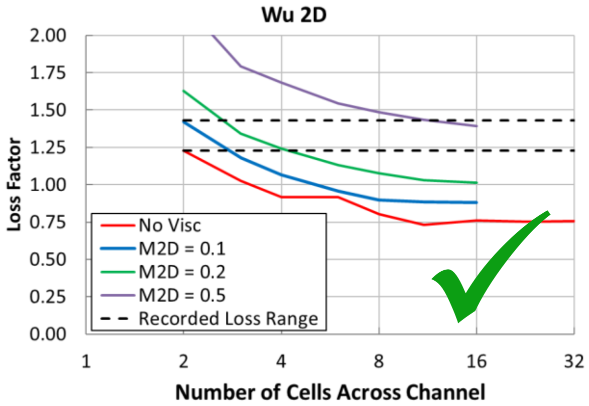
- Malone, T, Parr, D. (2008). Bend Losses in Rectangular Culverts, Kansas Department of Transport (http://ntl.bts.gov/lib/30000/30900/30935/KU-05-5_Final_Report.pdf)
- Excellent correlation between head loss and upstream velocity head
- 90 deg bend loss factor 1.23

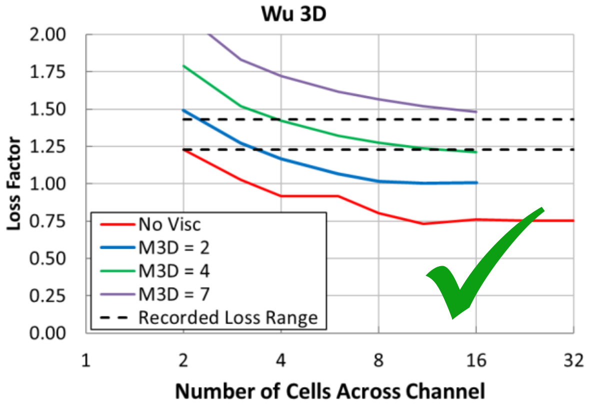
How to Benchmark?
Eddy Viscosity

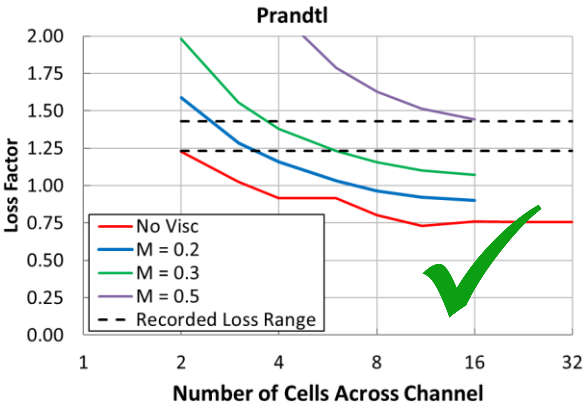












How to Benchmark?
Eddy Viscosity

Velocity pattern downstream of a river groyne

N. Rajaratnam and B. Nwachukwu, "Flow Near Groyne-Dike Structures," Journal of Hydraulic Division, Vol. 109, No. HY3, 1983, pp. 463-480. doi:10.1061/(ASCE)0733-9429(1983)109:3(463)

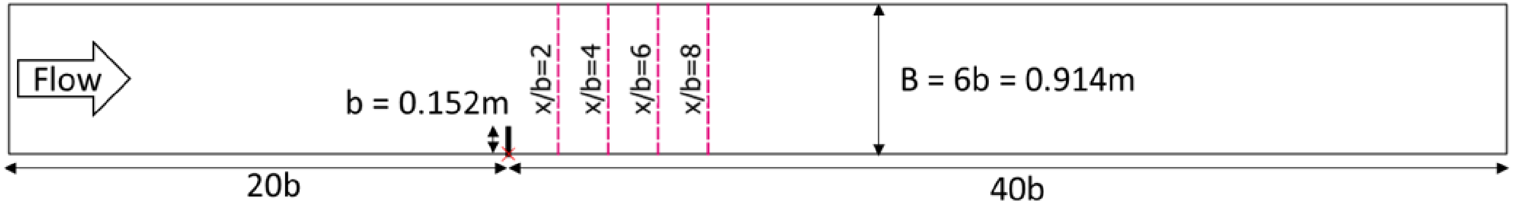
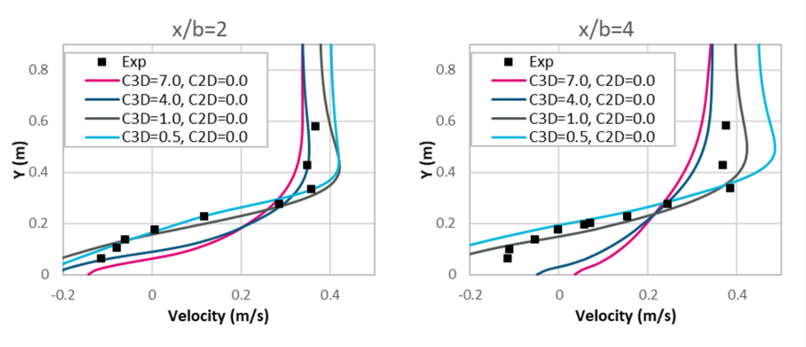


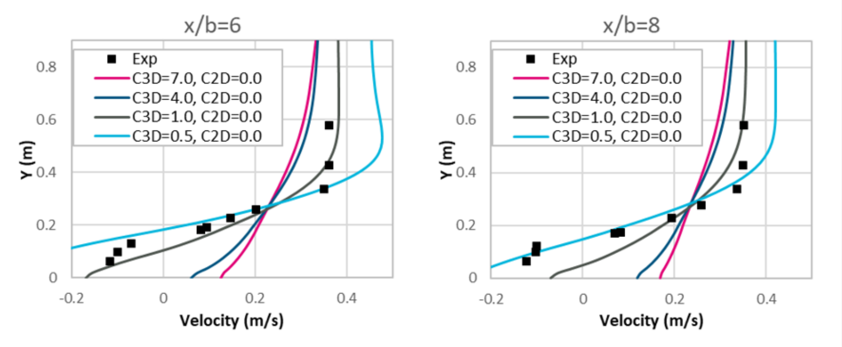
Figure 2-1 Plan view of the experimental flume

How to Benchmark?
Eddy Viscosity

Velocity pattern downstream of a river groyne

TUFLOW HPC + Wu Eddy Viscosity





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How to Benchmark?
Spatial Interpolation

Significant differences (flood levels) between 1st and 2nd order spatial interpolation

How do you test this?

- Investigate energy losses as a function of element size in a case with non-uniform velocity field
  - 1st order interpolation will display linear convergence
  - 2nd order interpolation will display quadratic convergence

Have you thought about?

- A good 2nd order spatial interpolation will generate chaotic solutions in absence of eddy viscosity and with low bed friction. These should be treated with caution.

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How to Benchmark?
Spatial Interpolation

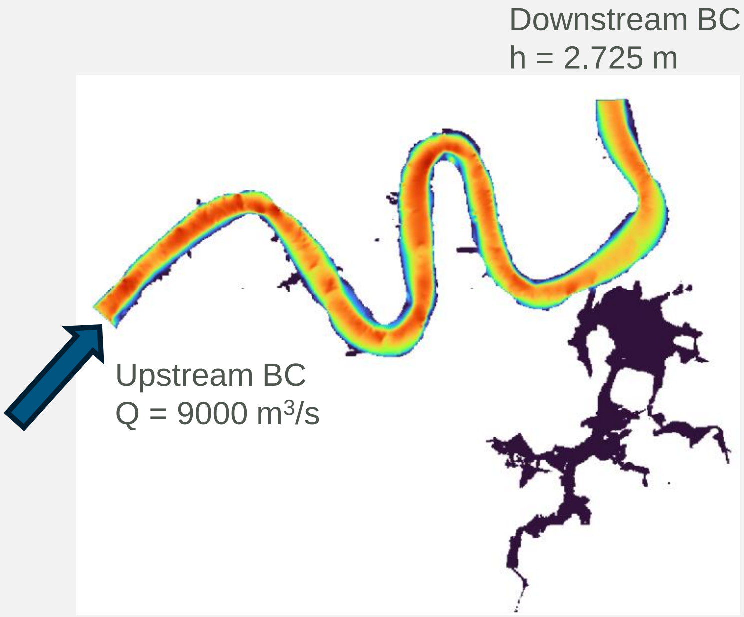
Brisbane river steady state flow

- Real world case
- Complex bathymetry
- Complex flow path at various angles with respect to grid

Investigate predicted upstream elevation as function of model cell size

Note: issues with 1st order interpolation exist for:

- 1D solvers
- 2D flexible mesh solvers
- 2D fixed grid solvers
- 3D solvers (including CFD)



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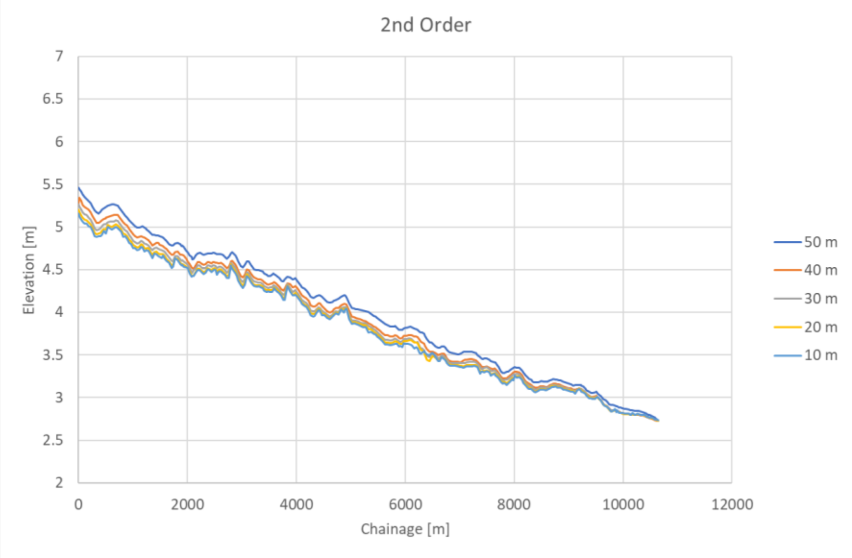
How to Benchmark?
Spatial Interpolation

Long-profiles of water surface elevation for various cell sizes



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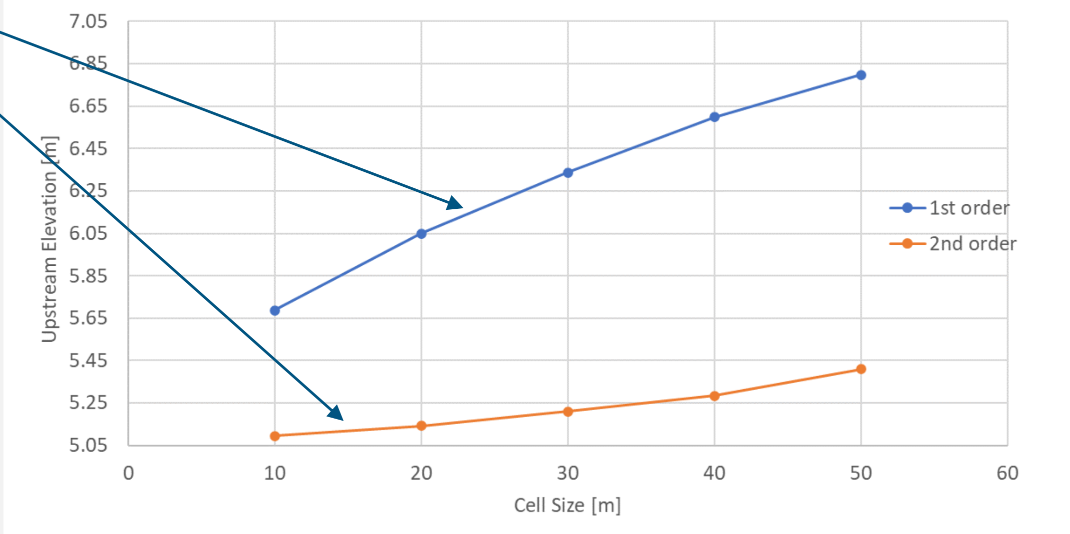
How to Benchmark?
Spatial Interpolation

1st order error not quite linear due to breakout onto flood plains

2nd order error close to quadratic

NOTE: The losses in 1st order can be so large that:

- Eddy viscosity not required
- Zero or unrealistically low Manning's number to achieve calibration



How to Benchmark?
Structures

Weirs and bridges use sub-models – have you checked these?

How do you test these?

- Create simple test cases, and compare results with hand-calculations

Have you thought about?

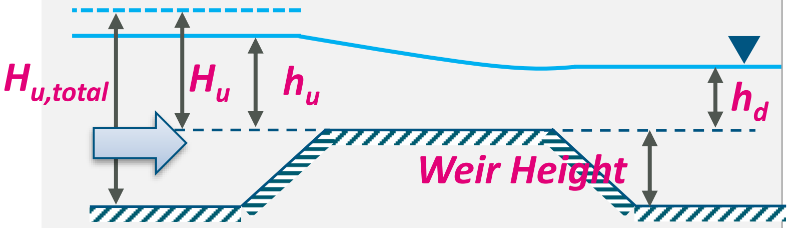
- With a structure represented in a 2D model using a fixed grid solver, what happens when the structure is not aligned with the grid?

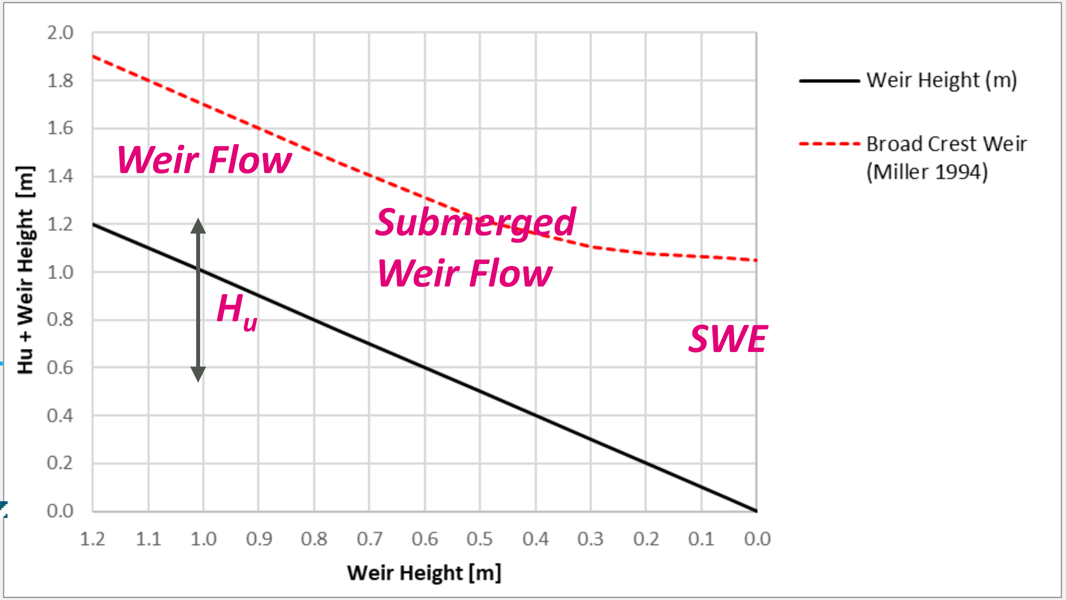
How to Benchmark?
Structures – 2D Weir Flow

Hu vs Weir height

$$Q = \frac{2}{3} C_d C_{sf} W \sqrt{2g} H_u^{3/2}$$

$$C_{sf} = [1 - (H_u/h_d)^a]^b$$

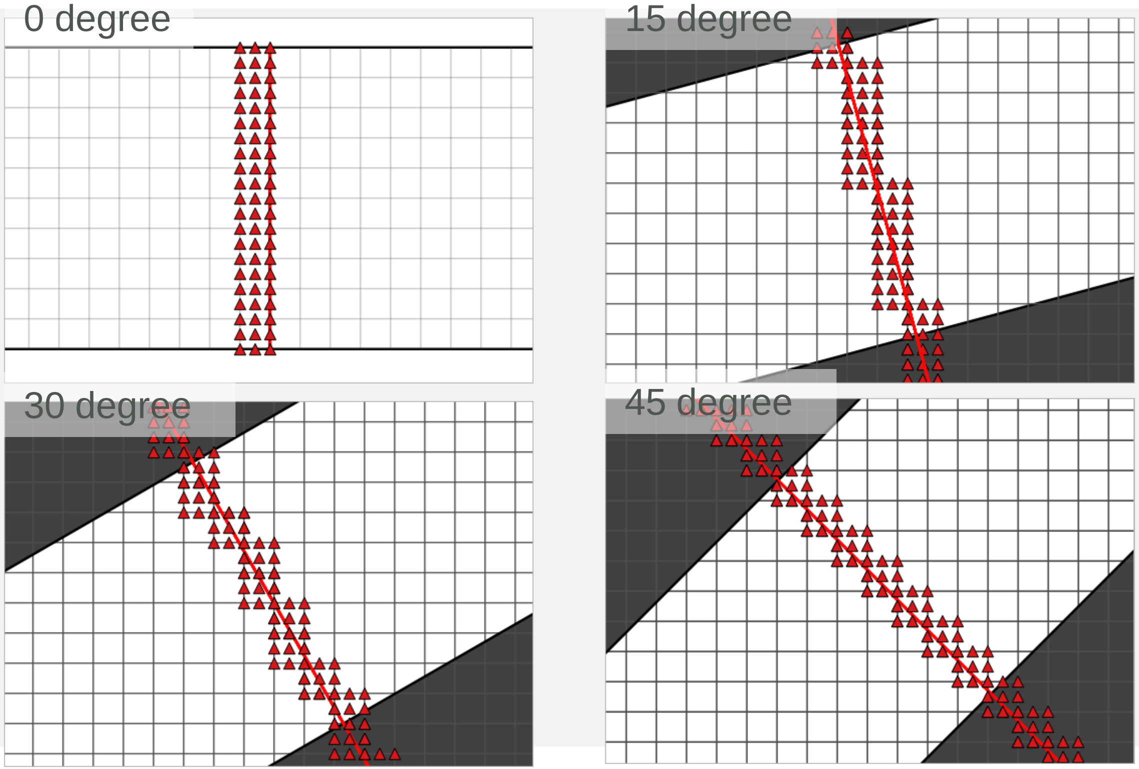




How to Benchmark?
Structures – 2D Weir Flow

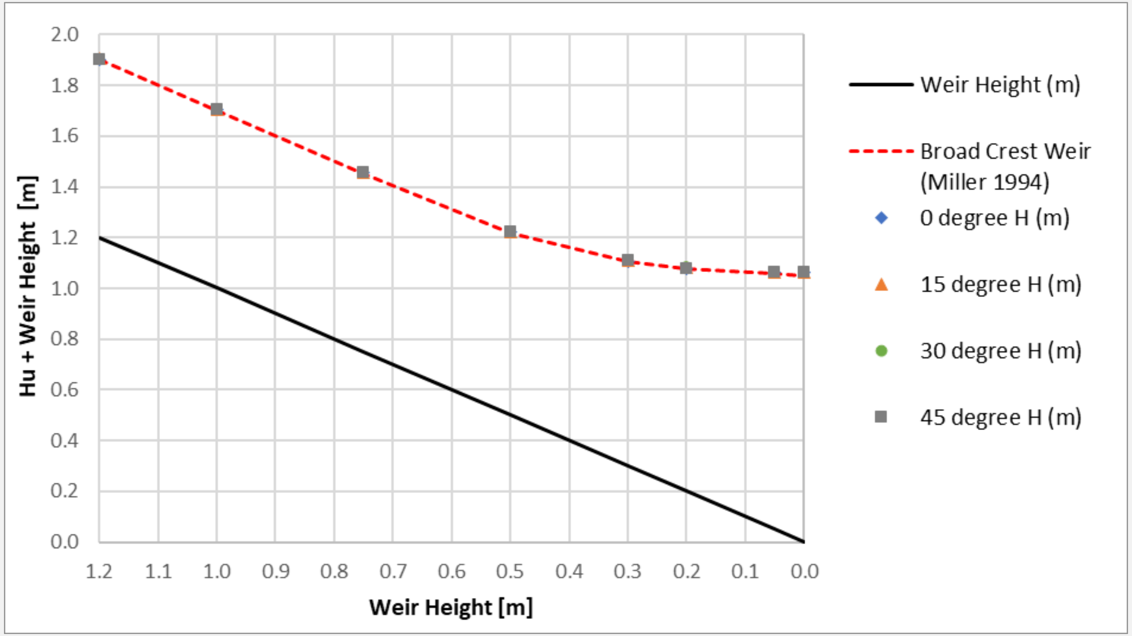
Rotated Mesh

- 0, 15, 30, 45 degree rotations



How to Benchmark?
Structures – 2D Weir Flow

Rotated Mesh Thin/Thick Breakline



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How Wrong is Your Flood Model?

www.tuflow.com/library/webinars/#jul2019_how_wrong

2D Cell Size Selection for Accurate Hydraulic Modelling

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Modelling Energy Losses at Structures

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1D, 2D, 3D Hydraulic Modelling of Bridges

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Maximising Hydraulic Model Accuracy

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Hydraulic Model Calibration to Historic Events

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Operational Structure Modelling

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The Future of 2D Modelling

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Is Direct Rainfall (Rain-on-Grid) Accurate?

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Urban Pipe Network Modelling

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Flood Modelling 101

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