Urban Water Interfaces (UWI)
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Beyond shallow water flow: Navier-Stokes simulations with OpenFOAM

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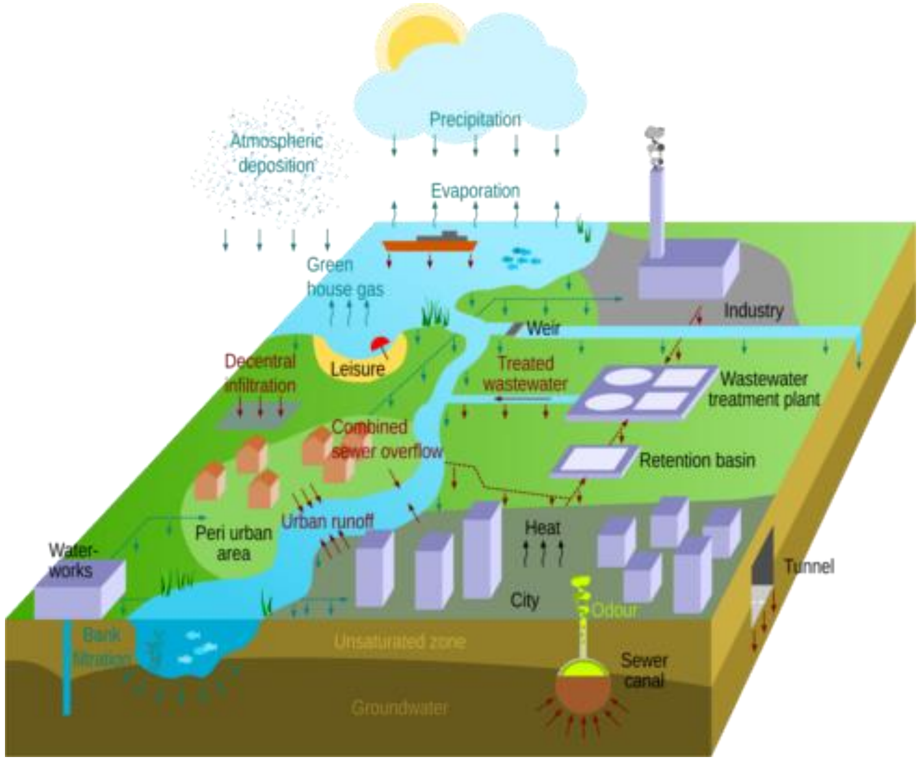
Simulations have been performed on the supercomputers of Norddeutscher Verbund für Hoch- und Höchstleitungsrechnen (HLRN), Berlin



Özgen, Hinkelmann (2014)

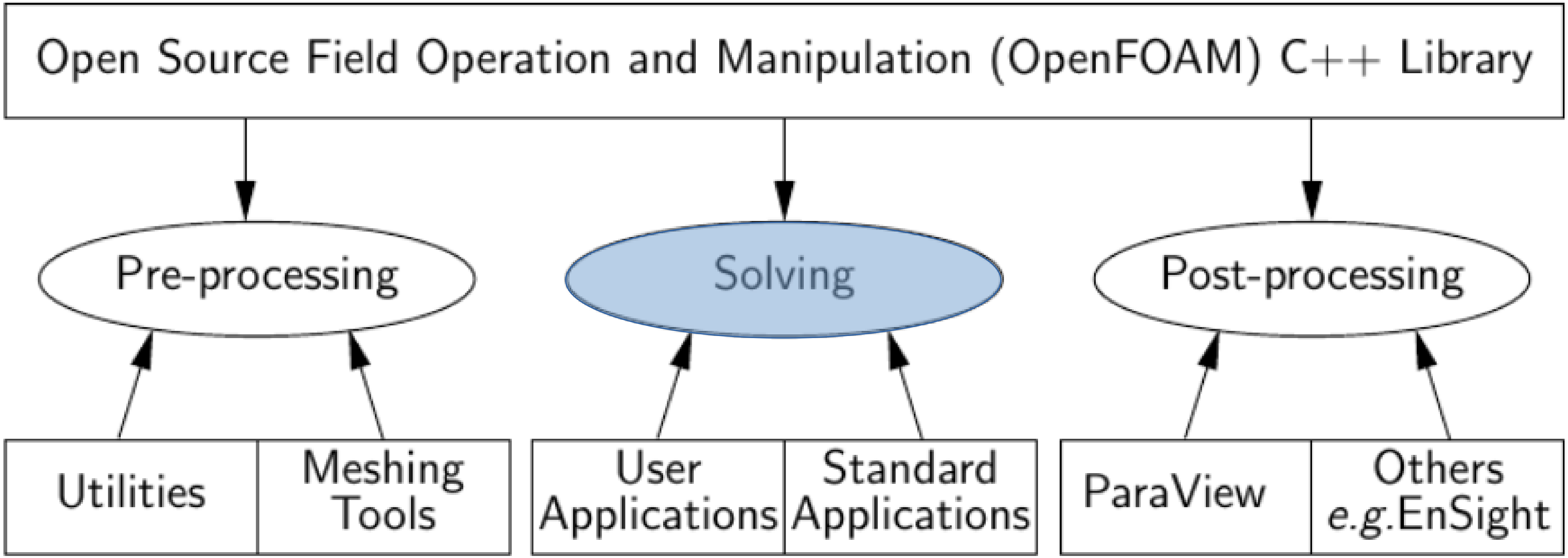
Motivation

- Hydrostatic pressure distribution not always given → depth-averaged Navier-Stokes equations not valid
- Examples
  - Hydraulic jumps
  - In front of and behind hill structures

→Solution: Three-dimensional CFD simulations

Model concepts

Version: 2.4.0



Greenshields, 2015

Governing equations – surface water (interFoam)

- Two immiscible, viscous fluids with indicator fraction α $0\ (\text{air}) < \alpha < 1(\text{water})$
- **Interface-convection equation (Volume of Fluid-equation)**

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{U}) + \nabla \cdot ((1-\alpha) U_r \alpha) = 0$$

- **Mass conservation**

$$\nabla \cdot \vec{U} = 0$$

- **Momentum conservation**

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla\, prgh + \nabla \cdot (\mu \nabla \vec{U}) + (\nabla \vec{U}) \cdot \nabla \mu - \vec{g} \cdot \vec{x} \nabla \rho$$

- **prgh as numerical value**

$$prgh = p - \rho g h$$

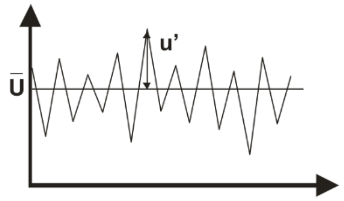
- **Material properties**

$$\rho = \alpha \rho_w + \rho_a (1-\alpha) \qquad \mu = \alpha \mu_w + \mu_a (1-\alpha)$$

Turbulence modelling

Reynolds averaged simulations (RANS)

- Description of mean flow properties of a flow using Reynolds-averaged form of Navier-Stokes equations
- Temporal averaging of velocities



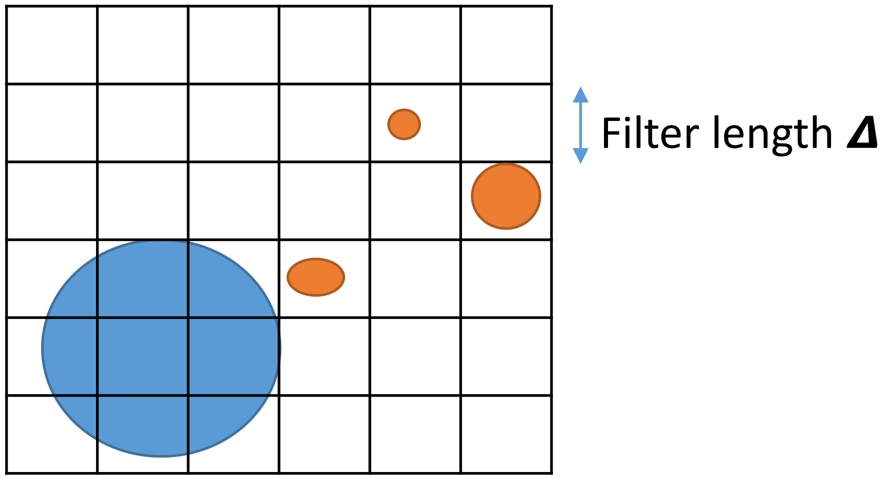
Jovanovic (2016)

- Two additional transport equations
- First transported variable: in general turbulent kinetic energy k, second transported variable depending on chosen model, here:
  - Standard k-ε (ε – turbulent dissipation)
  - Standard k-ω (ω – specific dissipation)
  - SST k-ω (ω – specific dissipation, SST – Shear Stress Transport)
  - Constant turbulent viscosity

Turbulence modelling

Large Eddy Simulations (LES)

- Large eddies resolved explicitly (small cell sizes)
- Small eddies accounted for by subgrid scale model (SGS, here: Smagorinsky model)
- Small eddies are selected with filter of length ***Δ***



OpenFOAM – discretisation methods and solvers

Discretisation schemes

- Finite-Volume-Method in space
- Finite-Differences-Method in time

Pressure-velocity coupling

– PIMPLE (PISO-SIMPLE, based on PISO (outer correction) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) (inner-correction loop)

Advection schemes

- Total Variation Diminishing scheme (interGamma) (Jasak, 1996) combined with Flux Corrected Transport approach MULES (Multidimensional Limiter for Explicit Solutions) (Damian, 2013)

Solvers

- Preconditioned Conjugate Gradient methods
- Multigrid methods

High performance computing

- Shared and distributed memory parallel computing

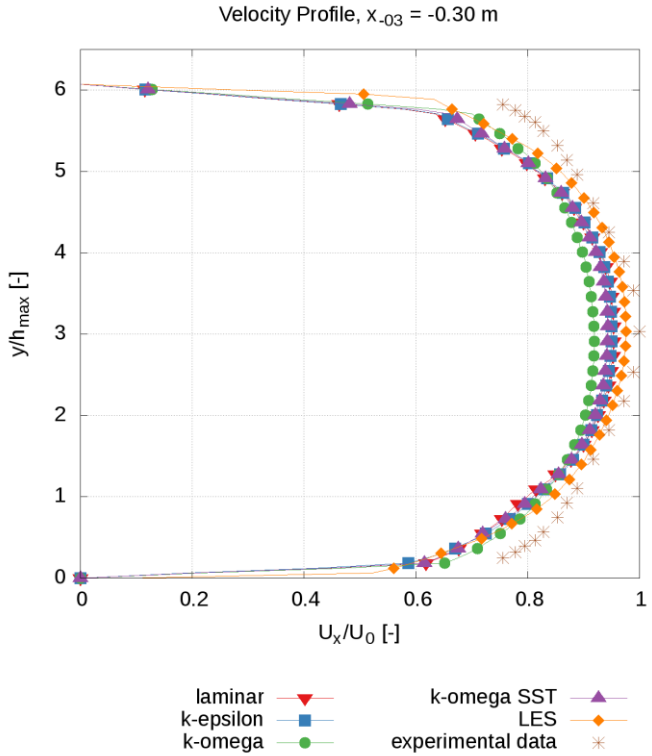
Example 1

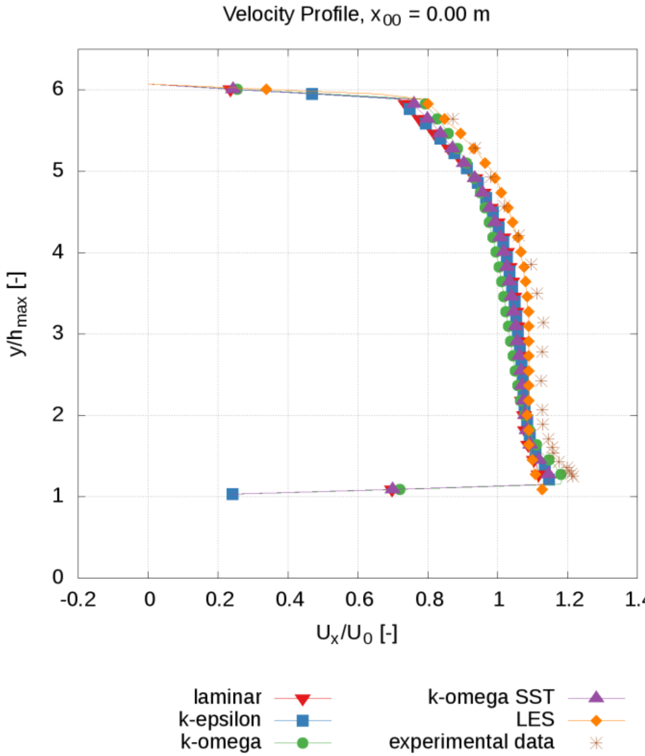
Validation cases – Flow over a ground sill

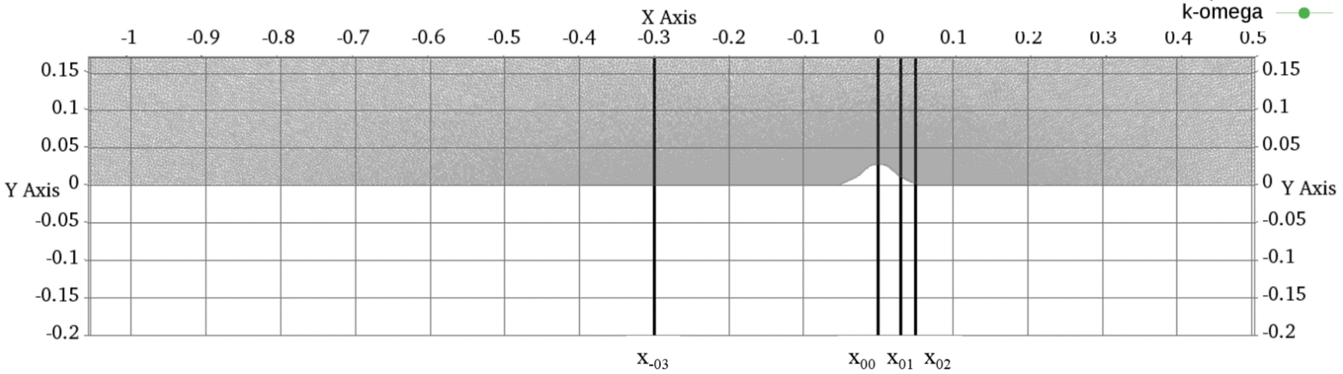
Validation of single-phase flow

Model setup:

- Mean velocity: 2.147 m/s
- Polynomial shaped hill: Δz_{max} = 0.028 m
- Channel height: 0.17 m
- Comparison at 4 locations to experimental results by Almeida et al. (1993)
- Meshes: 12,106 cells (laminar and RANS), 89,294 (LES)

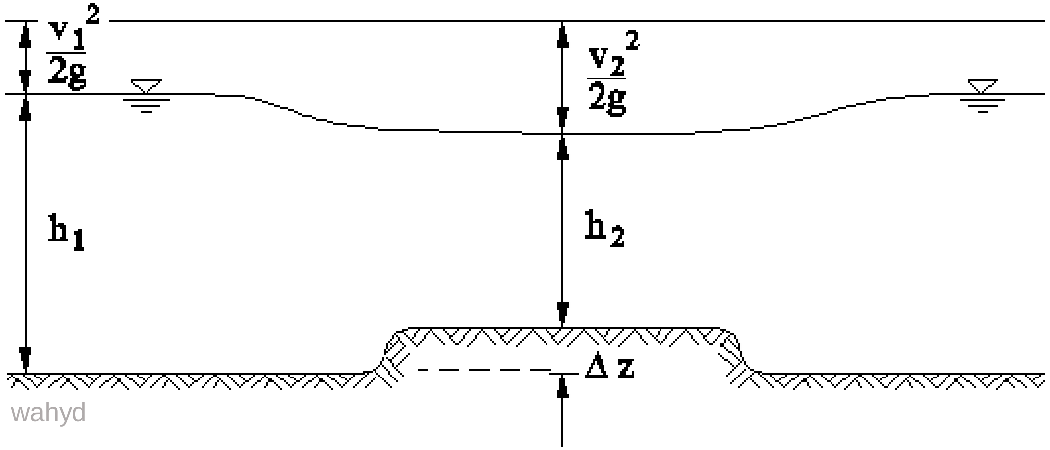






Flow over a ground sill, two phases

Model setup: Subcritical flow



	Case 1	Case 2	Case 3
h_1	1 m	1 m	3 m
v_1	1 m/s	1.25 m/s	3 m/s
Δz	0.2 m	0.2 m	0.2 m
Δh, analytical	3.6 cm	7.0 cm	11.3 cm
Δh, numerical, k-ε turbulence model	**4.2 cm**	**9.0 cm**	**14 cm**

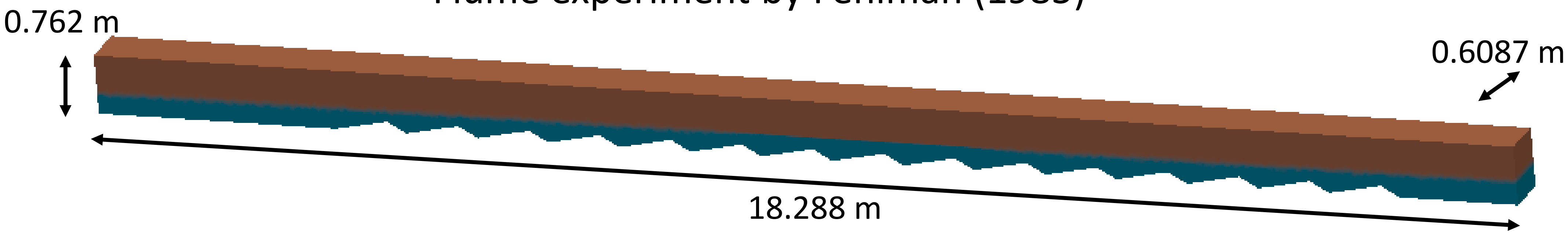
Δh: Analytical solution (continuity and Bernoulli equation)

Example 2

Natural system - Streambed with ripples

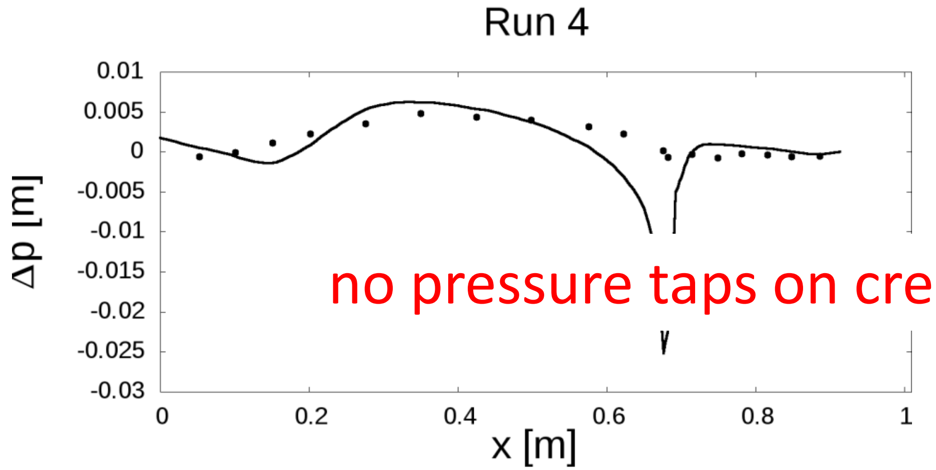
Free-surface flow and transport over streambeds with ripples - Validation hydraulics

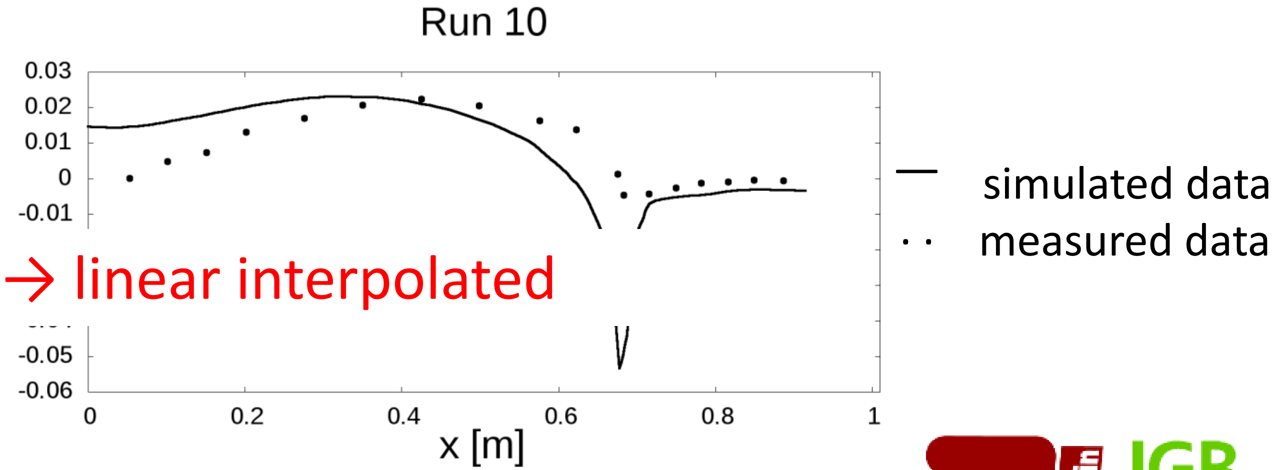
Flume experiment by Fehlman (1985)



– Ensure reliable pressure distribution of two-phase model with 3D mesh:

piezometric pressure heads on bed form minus piezometric head at dune crest





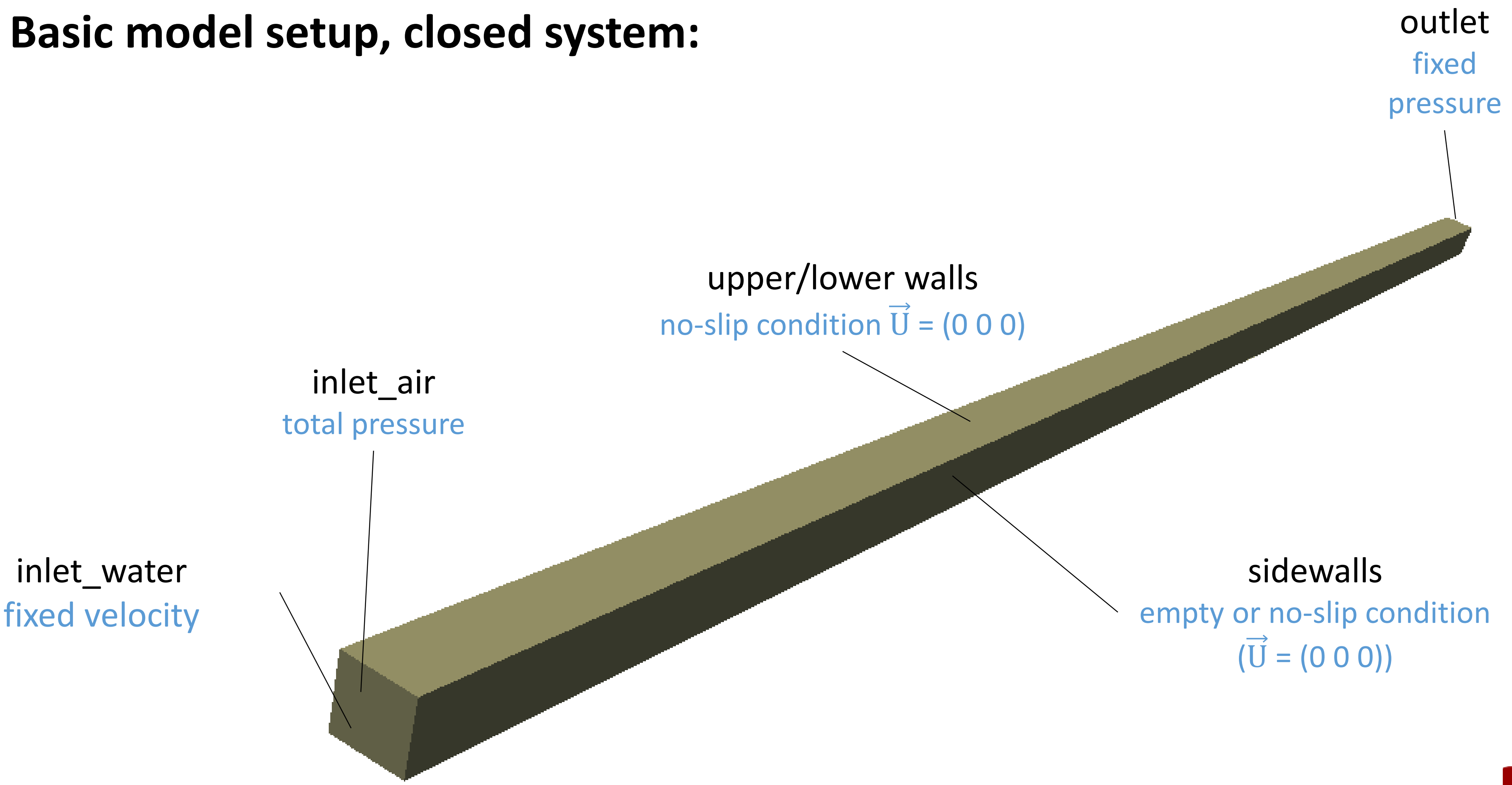
no pressure taps on crest → linear interpolated

Example 3

Technical system – Complex sewer system

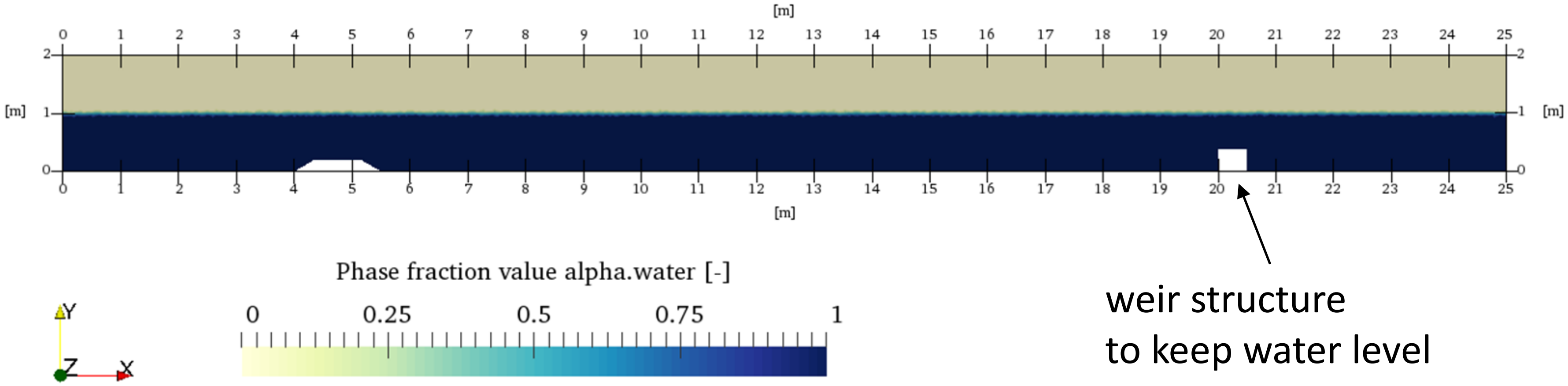
Free-surface flow in sewer systems

Basic model setup, closed system:



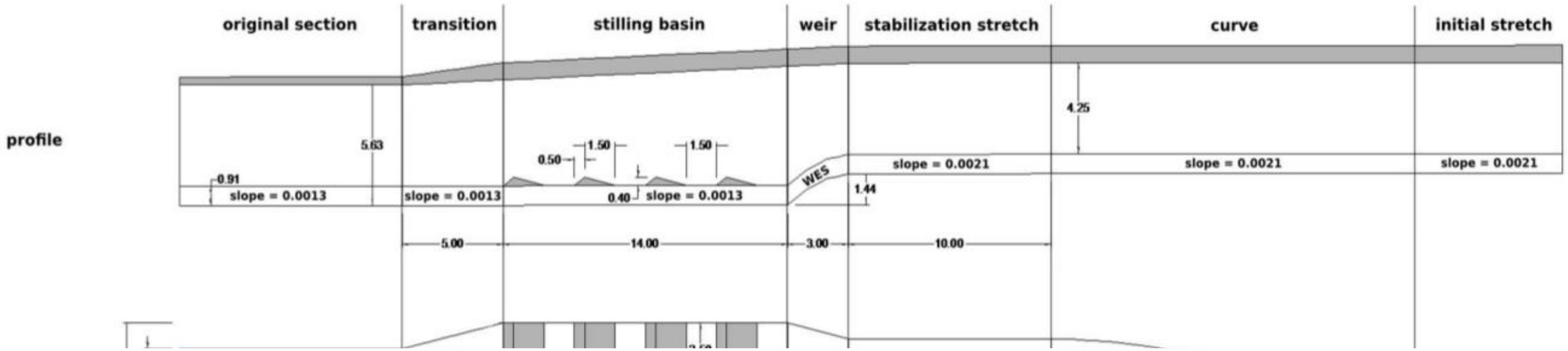
Free-surface flow in sewer systems

– Closed model setup causes high sensitivity of simulation results regarding boundary conditions
  - → Small errors imposed at inlet and/or outlet lead to instability of simulations (which do not occur if atmopheric top boundary is chosen)
  - → Difficulties in finding stable set of boundary conditions

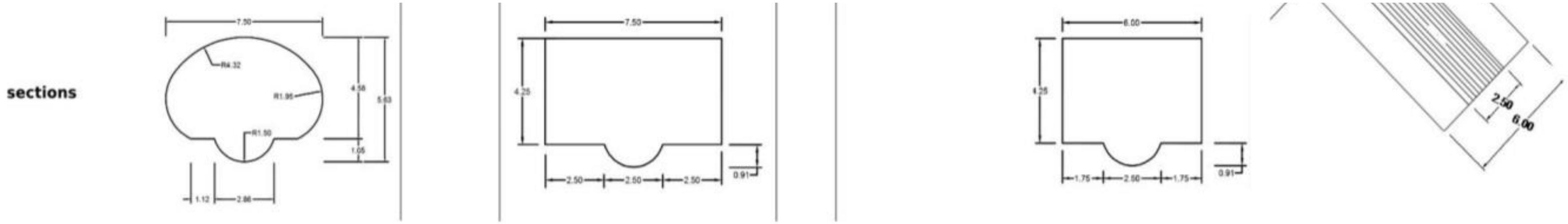


Free-surface flow in sewer systems

Sewer stretch, Valencia, Data and Mesh by Bayòn-Barrachina (2015)



„As the [system] operates in an open air regime and in order to help the model to maintain the mass balance throughout its boundaries, an atmosphere patch is imposed to the domain top. This kind of boundary condition allows the flow to freely enter and leave the domain and not using it has proved to cause severe mass conservation problems.“ Bayòn-Barrachina (2015)



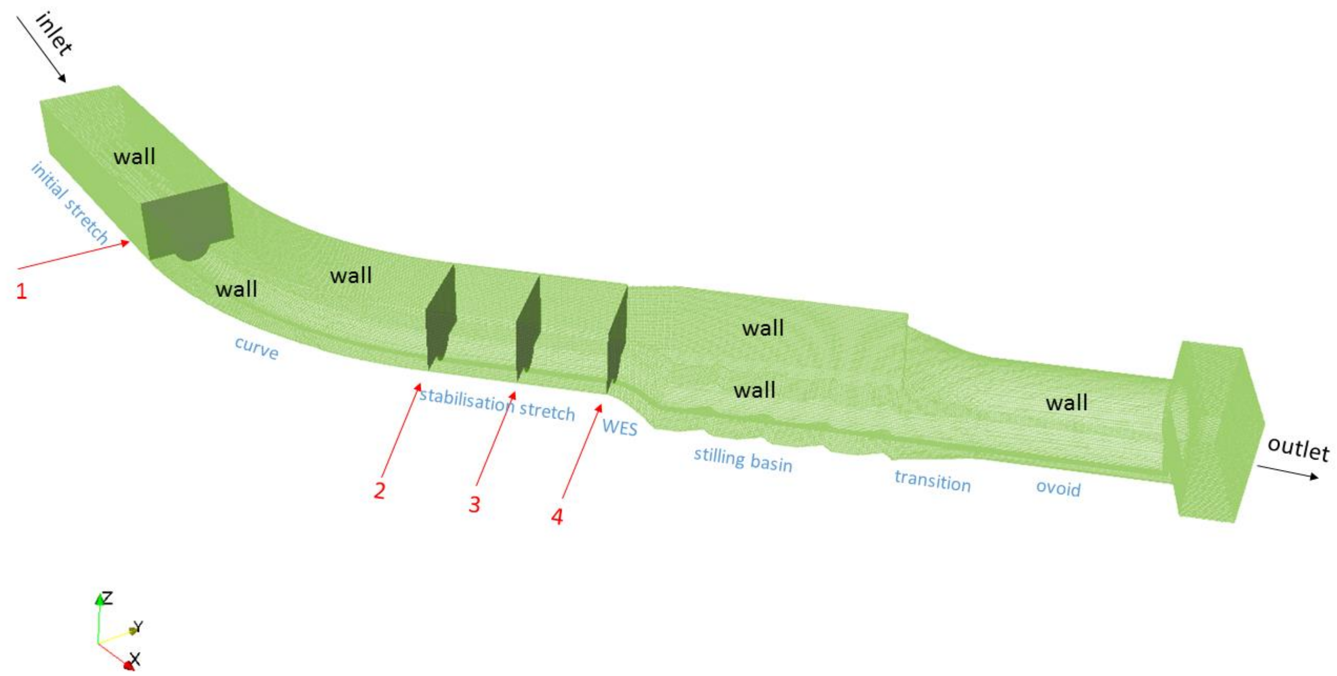
Bayòn-Barrachina (2015)

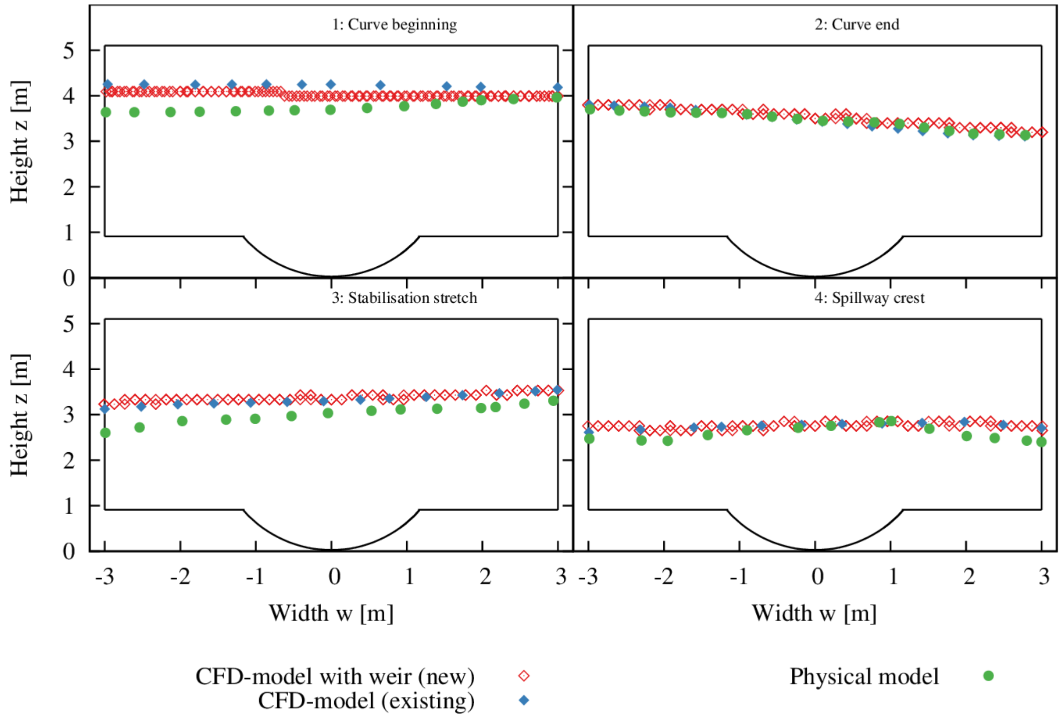
Free-surface flow in sewer systems

Sewer stretch, Valencia, Data and Mesh by Bayòn-Barrachina (2015)

- Mesh: 3,029,223 structured elements

Free-surface flow in sewer systems





Take-home messages

Validation cases

- Different turbulence models show good accuracy
- Water phase behaviour is represented appropriately

Natural (streambed) and technical (sewer) system

- Simulation results describe water phase behaviour correctly
- Simulations are stable concerning initially dry conditions, changing flow conditions, high filling ratios and complex geometries

→ CFD simulations can be used to describe systems in which a hydrostatic pressure distribution is not given

Thank you for your attention!