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Development and application of a three-dimensional urban flooding model

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Introduction of Fluidity CFD software

- Developed by **Applied Modeling and Computation Group** (AMCG) at Imperial College London;
- **Open source, general purpose, multi-phase** CFD code, can be obtained from http://fluidityproject.github.io/;
- Numerically solving the **Navier-Stokes** and accompanying field equations;
- Arbitrary **unstructured** finite element meshes in one, two and three dimensions;
- **Adaptive mesh in parallel**;
- A wide range of finite element/control volume element choices including **mixed formulations**.

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Research motivations -- why 3D modeling?

- More **detailed** information (vertical velocity, forces, etc.);
- **Applicable** when shallow water assumptions become invalid;
- **Better representation** of the physical process of flooding.

Contents of this presentation

- Governing equations and boundary conditions;
- Validation of the model results;
- Application in real urban flooding events;
- Future work.

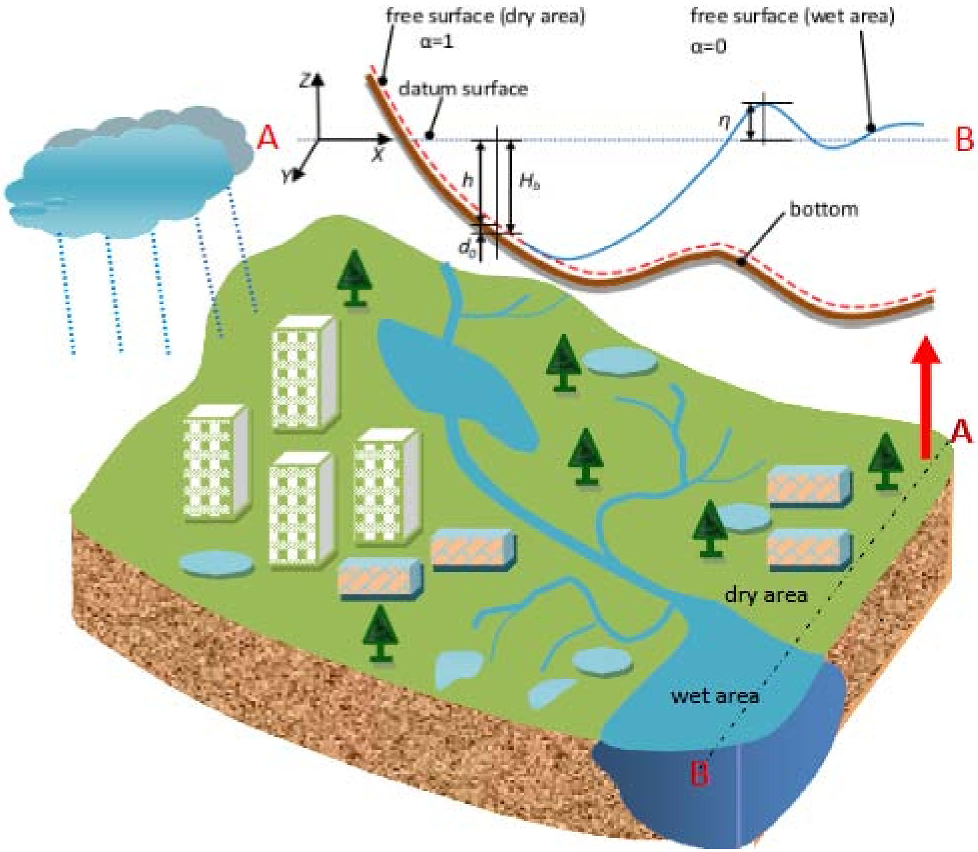
Governing Equations

The 3D non-hydrostatic Navier-Stokes equations with the Boussinesq Approximation:

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

$$\rho_0(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u}) - \nabla \cdot \mu \nabla \vec{u} + \nabla p = -\rho g \vec{k}$$

Wetting and Drying



Boundary conditions

- **The combined kinematic free-surface boundary condition:**

$$\vec{n} \cdot \vec{k}\frac{\partial \eta}{\partial t} = \vec{n} \cdot \vec{u} \qquad \textbf{on } \Gamma_s \textbf{ .}$$

- **Bottom stress parameterization (Manning-Strickler formulation):**

$$\vec{n} \cdot \mu \nabla \vec{u} = n_m^2 g \frac{|\vec{u}|\, \vec{u}}{d^{1/3}},$$

In dry areas, a large value of n_m is needed :

$$n_m|_{\Gamma_{dry}} = n_m + max\left(0, \frac{d_{min} - d}{d_0} \times n'_m\right), \quad d_0 \leq d \leq d_{min},$$

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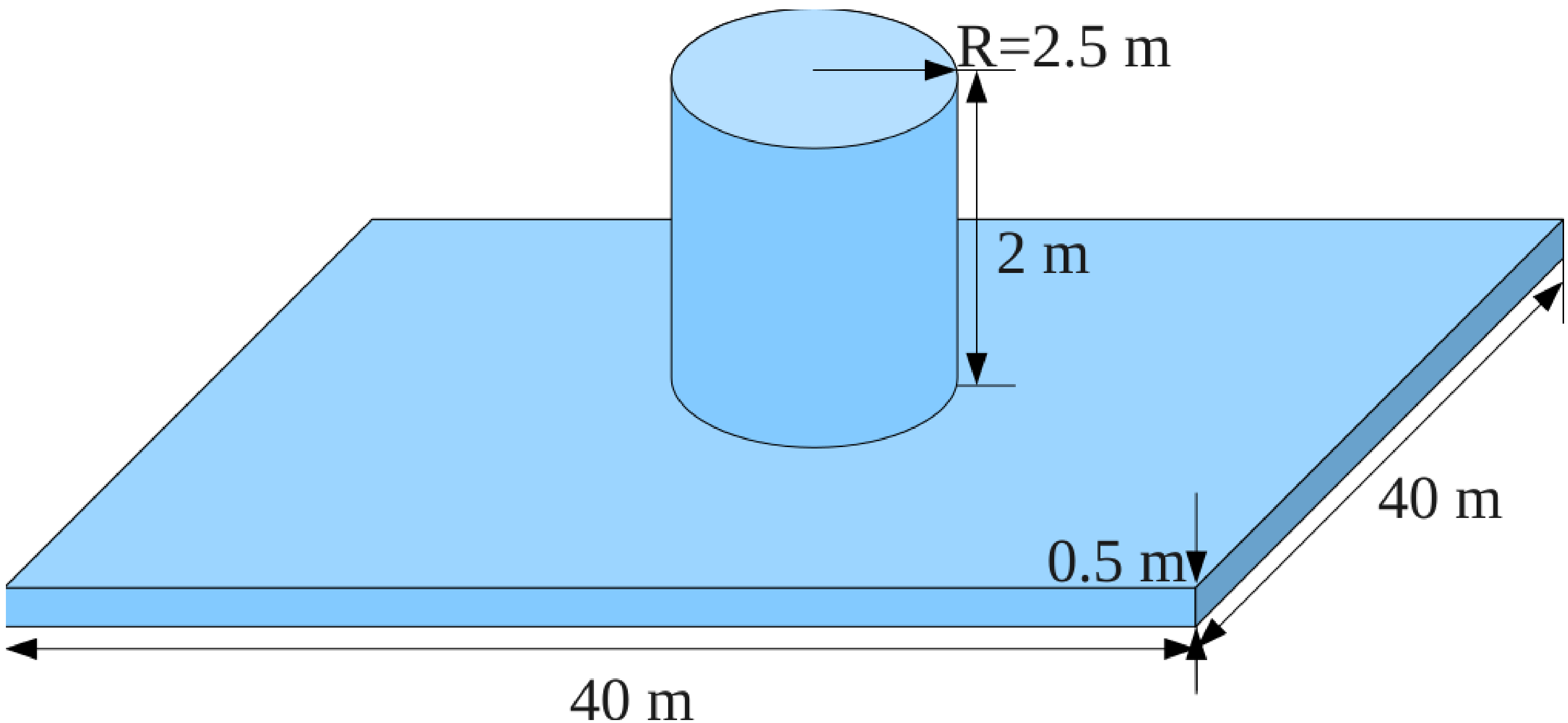
Validation of the 3D flooding model

- **Circular dam break case — compared with 2D modeling results**

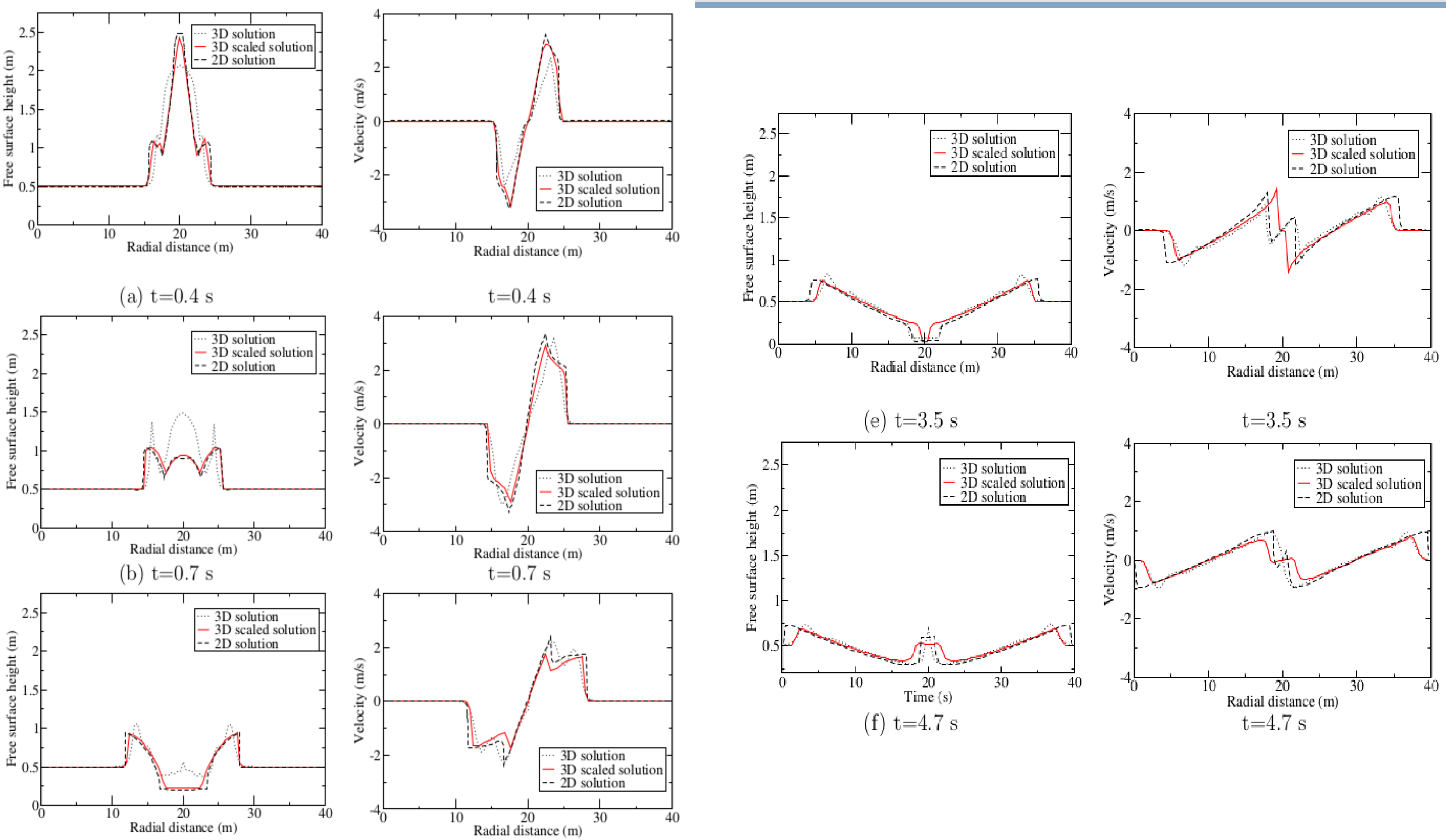
- **L-shape channel flow — compared with experimental data**

Circular dam-break case



movie of H=2.5 m   movie of H=0.025 m

Circular case: comparison with 2D models

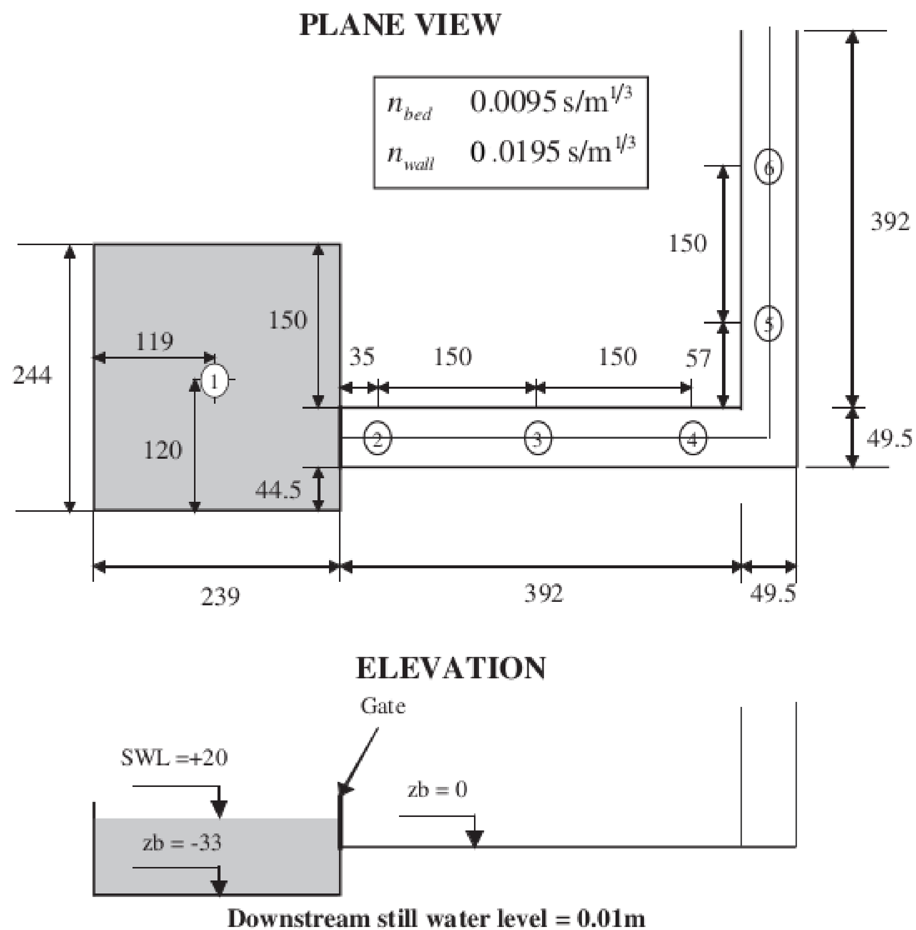


(a) t=0.4 s
t=0.4 s
(b) t=0.7 s
t=0.7 s
(c) t=1.4 s
t=1.4 s
(e) t=3.5 s
t=3.5 s
(f) t=4.7 s
t=4.7 s

L- shape dam break case

Layout of the case, dimensions in cm (cited from Liang et al. 2004[1])

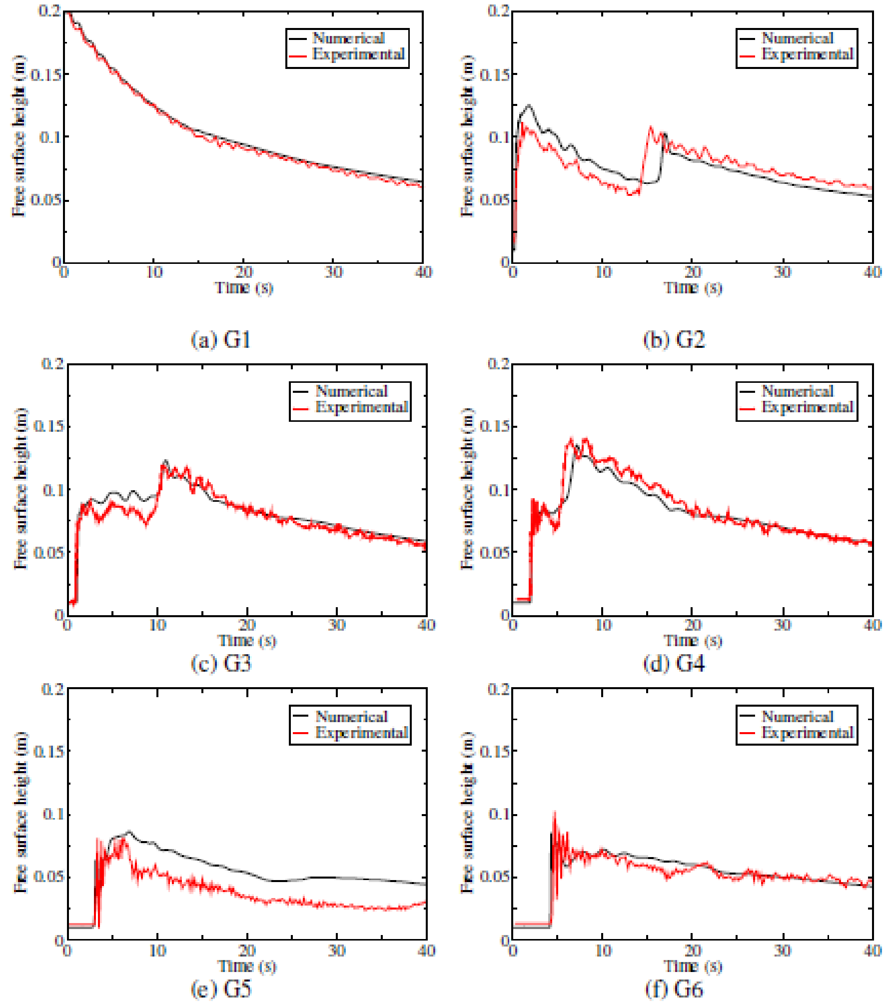
movie



[1] Q. Liang, A. Borthwick, and G. Stelling. Simulation of dam-and dyke-break hydrodynamics on dynamically adaptive quadtree grids. International journal for numerical methods in fluids, 46(2):127–162, 2004.

Validation

Comparison of 3D modelling results with experimental data



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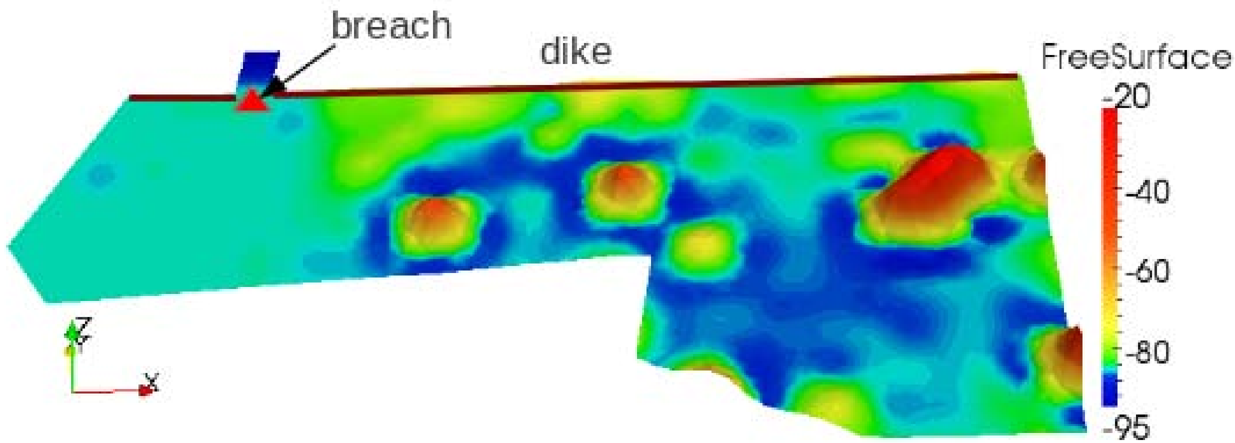
Application in real urban flooding events

- **A flooding case in a 5.5km×2.5km realistic domain**

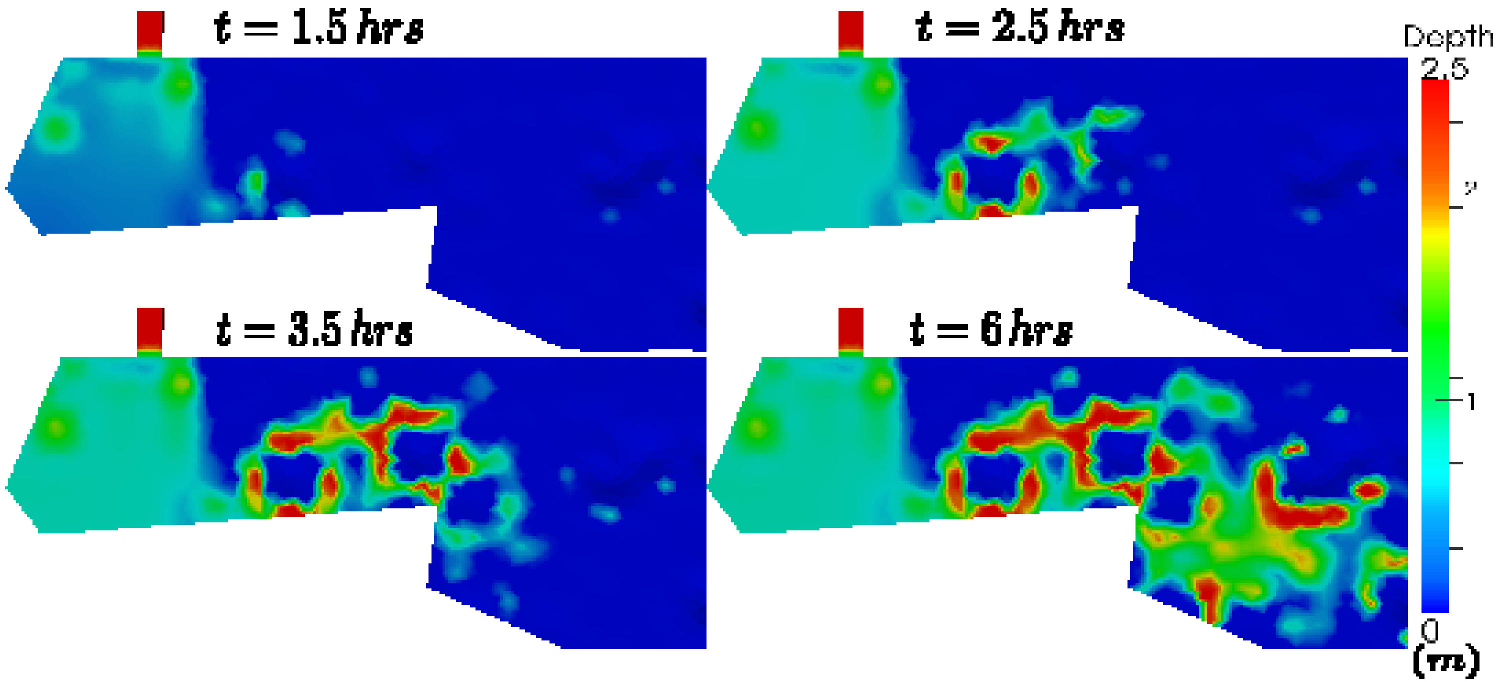
- **A flooding event within Glasgow city**

Flooding in a 5.5km×2.5km domain

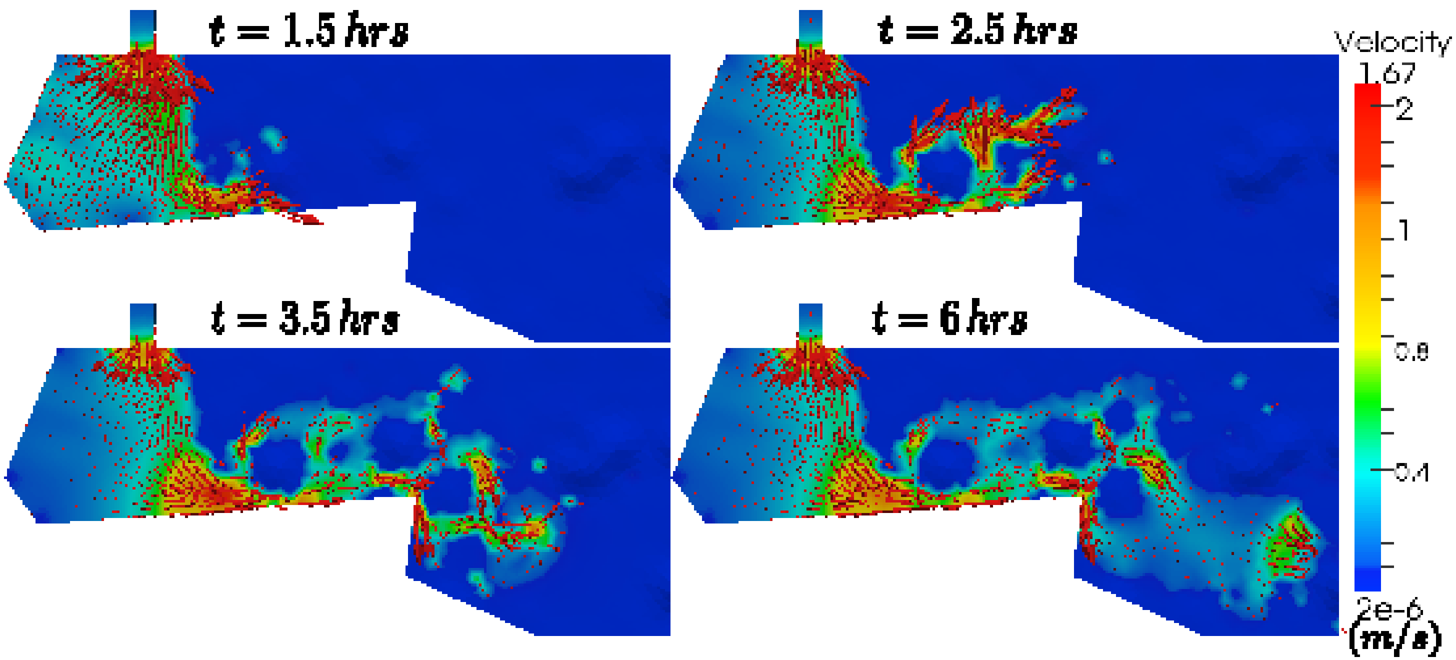


movie

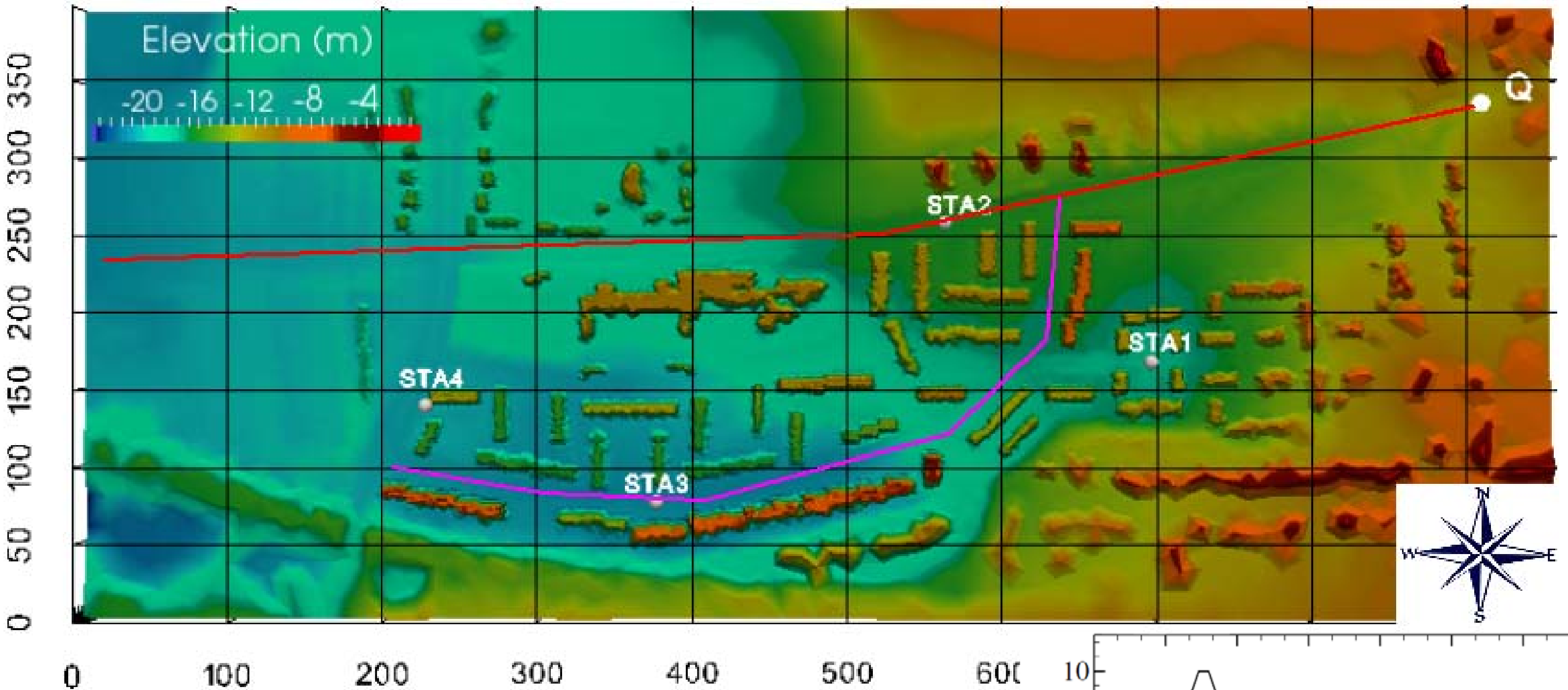
Water depth

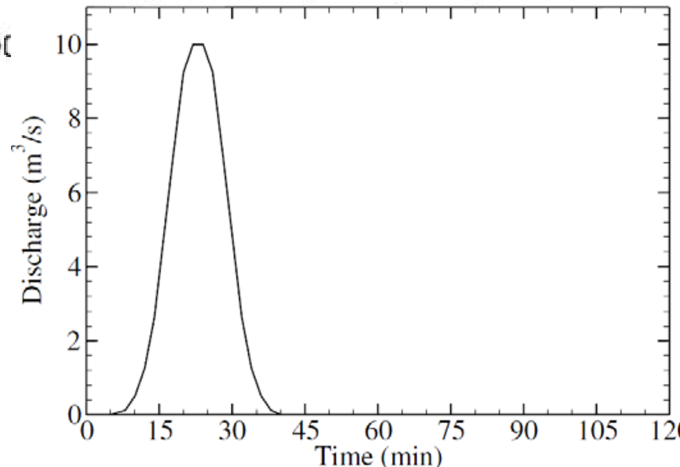


Velocity

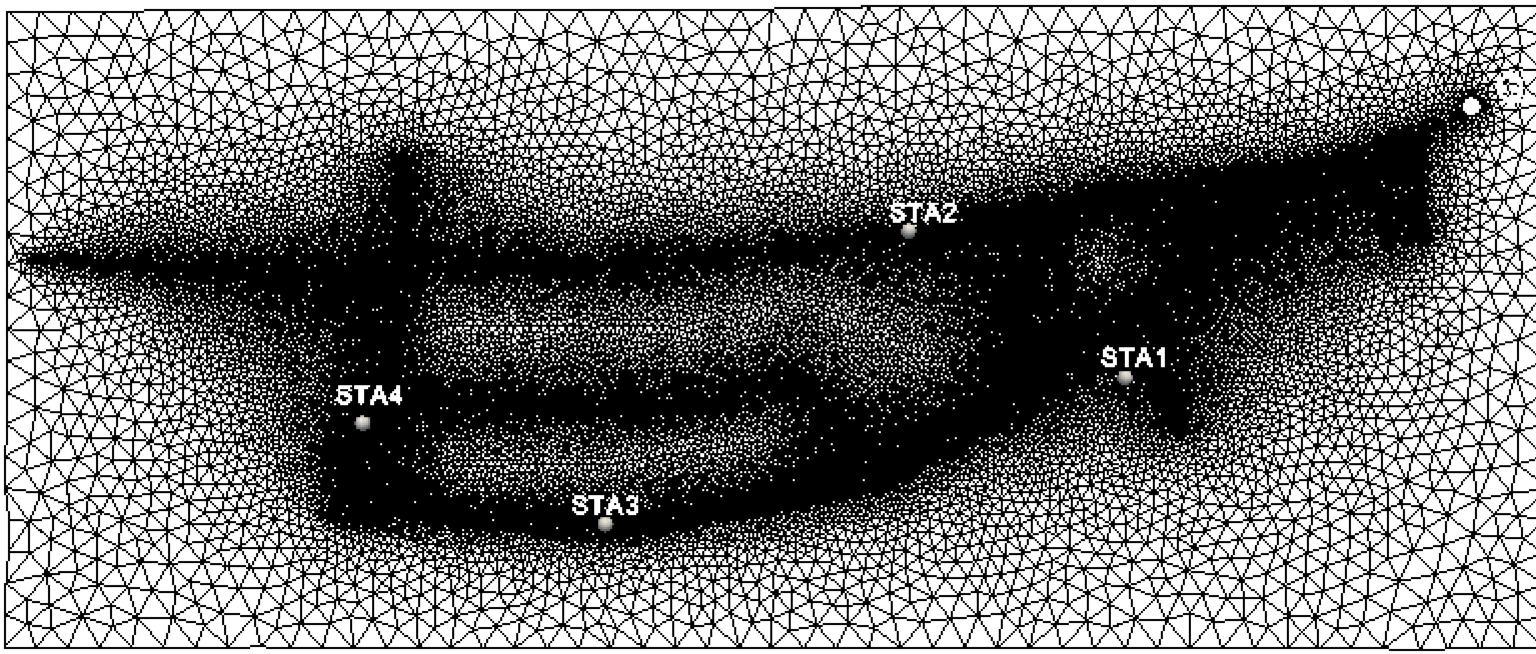


Topography and discharge of inflow – Glasgow case





Multi-scale mesh (plain view)



[Movie of velocity]   [Movie of depth]

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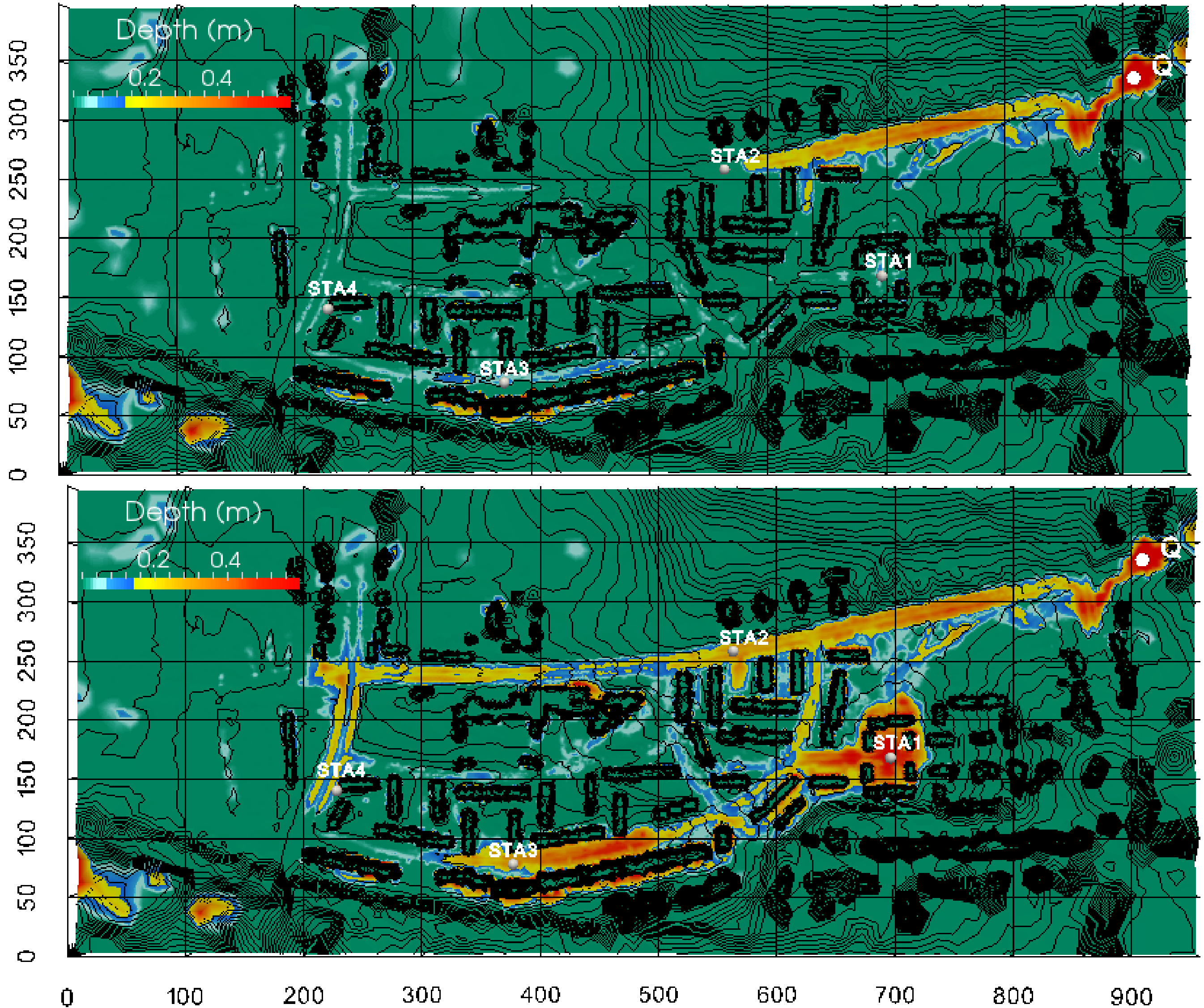
Water depth

t=20min

t=30min



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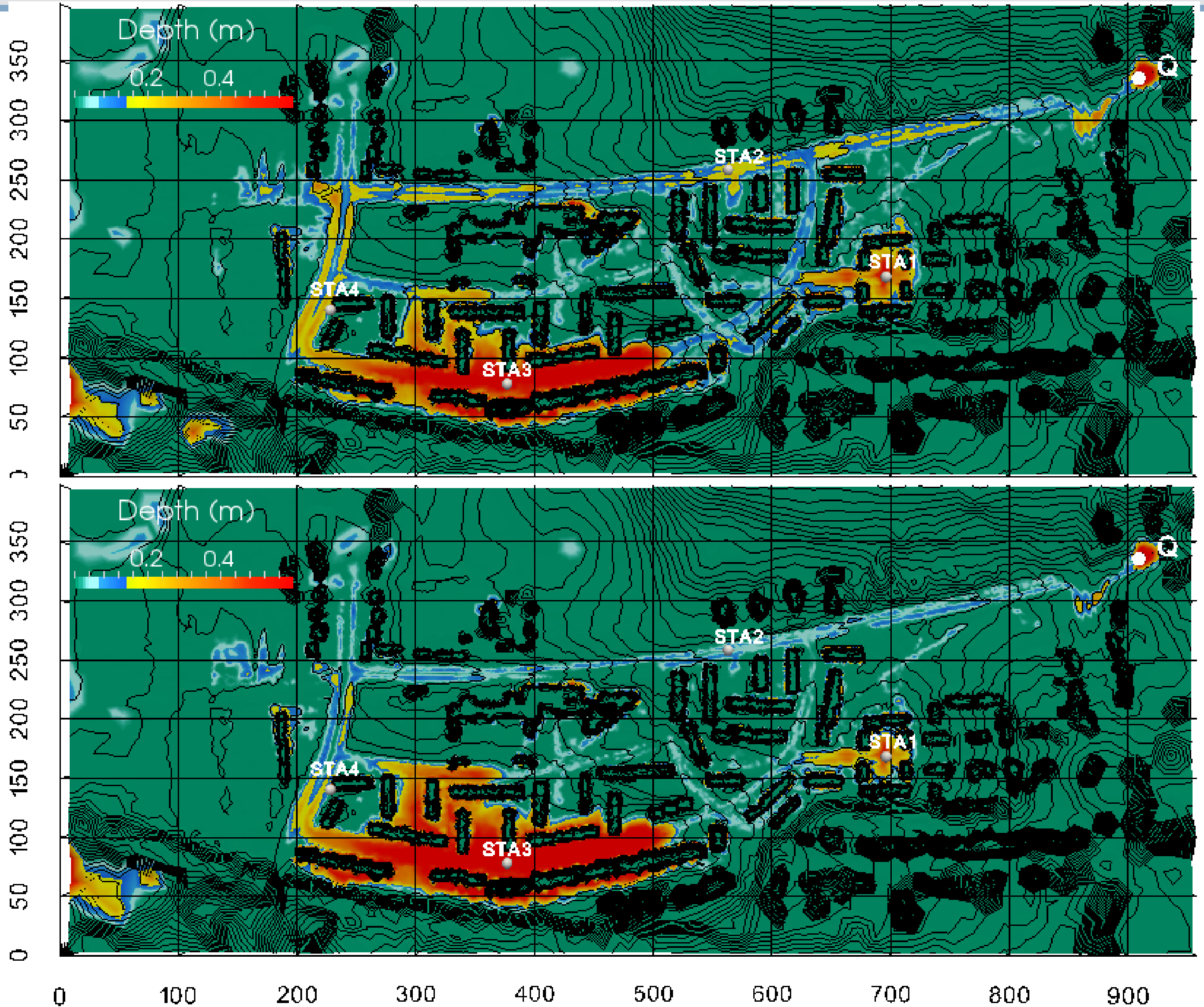
Water depth

t=40min

t=60min



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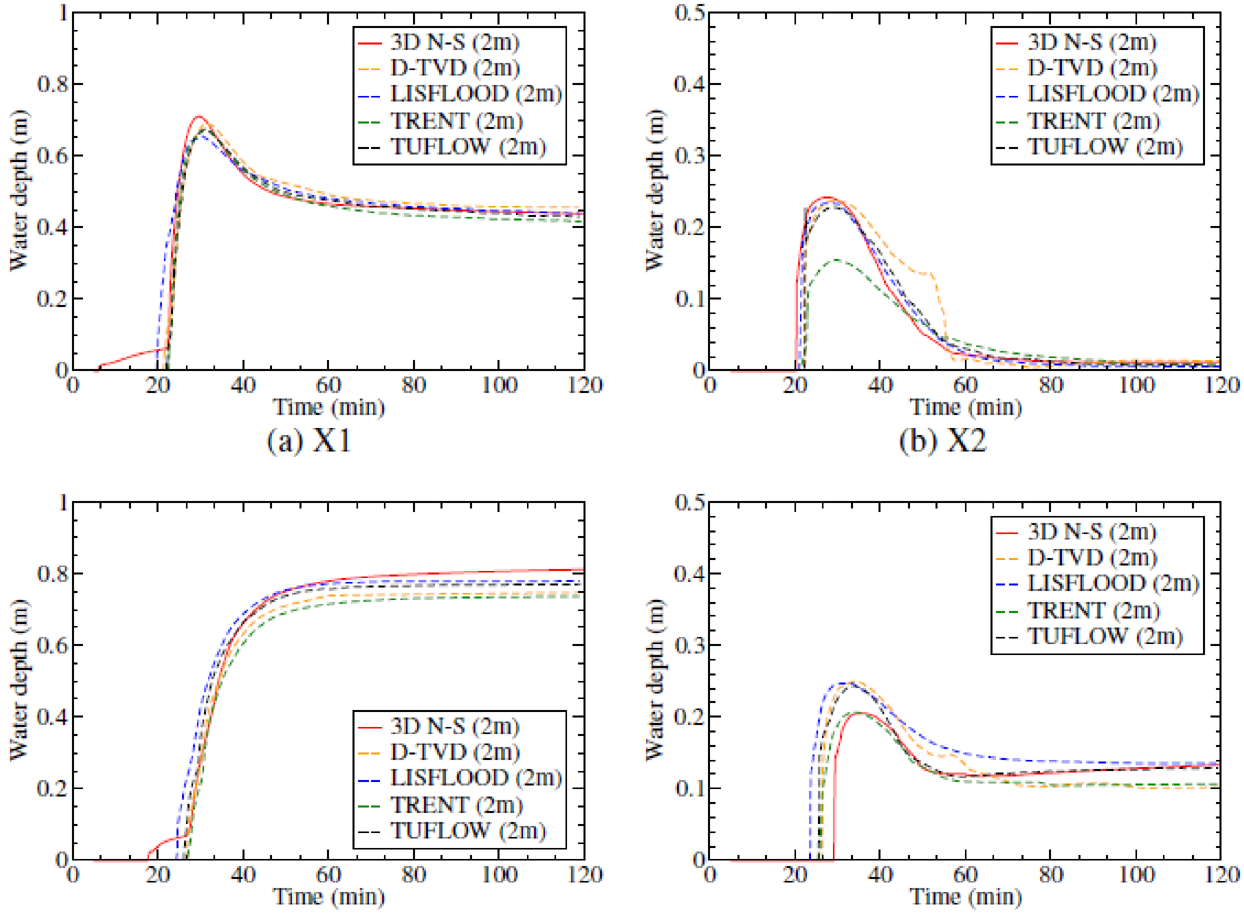
Comparison with four 2D models[2]



(a) X1 (b) X2

(c) X3 (d) X4

[2] Hunter N.M. and Bates P.D., et al. Benchmarking 2D hydraulic models for urban flooding. Proceedings of the ICE-Water Management, 2008; 161(1):13-30.

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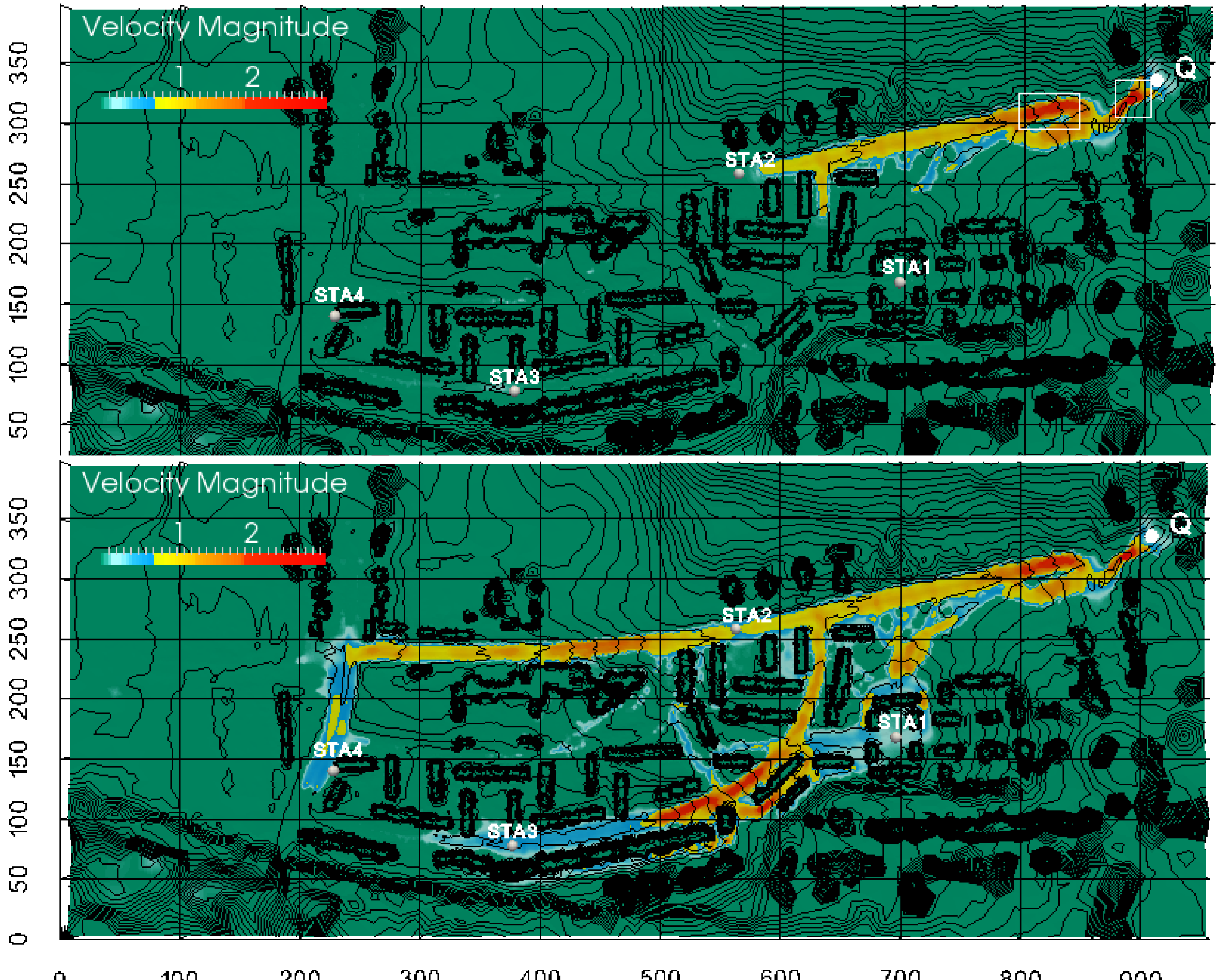
Velocity

t=20min

t=30min



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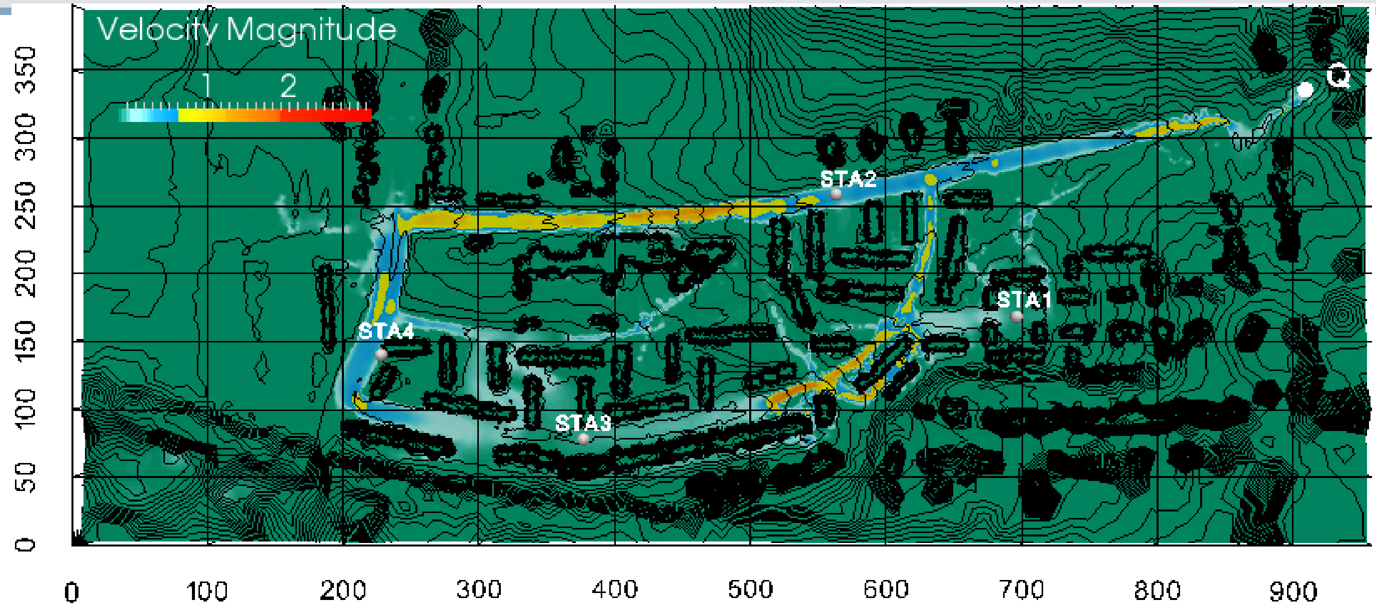
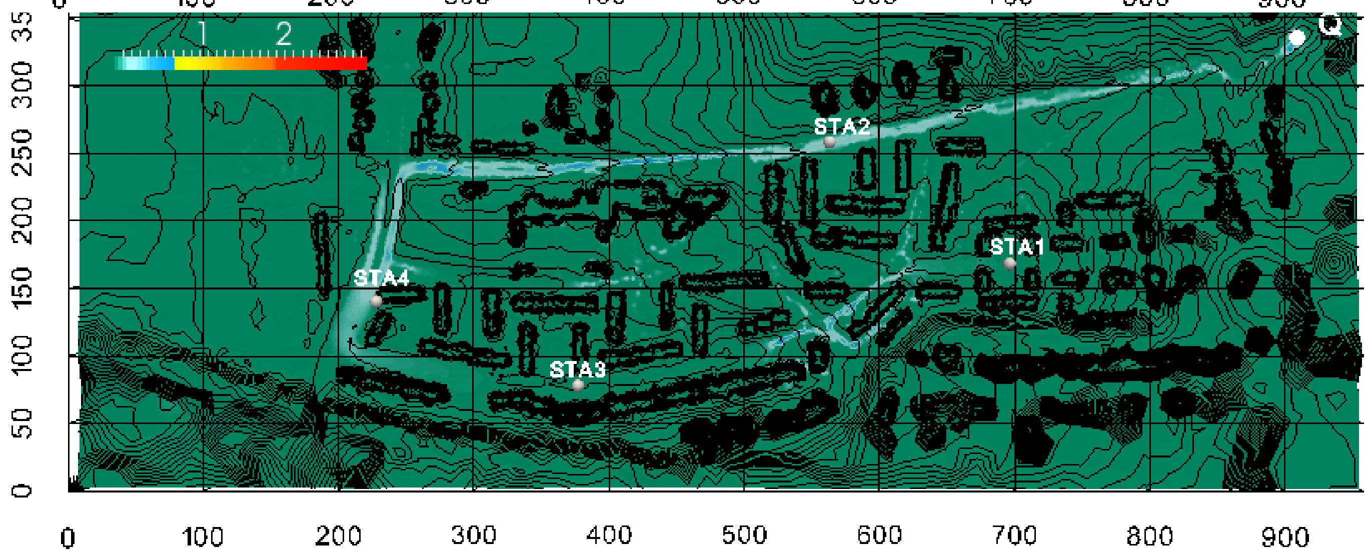
Velocity

t=40min



t=60min



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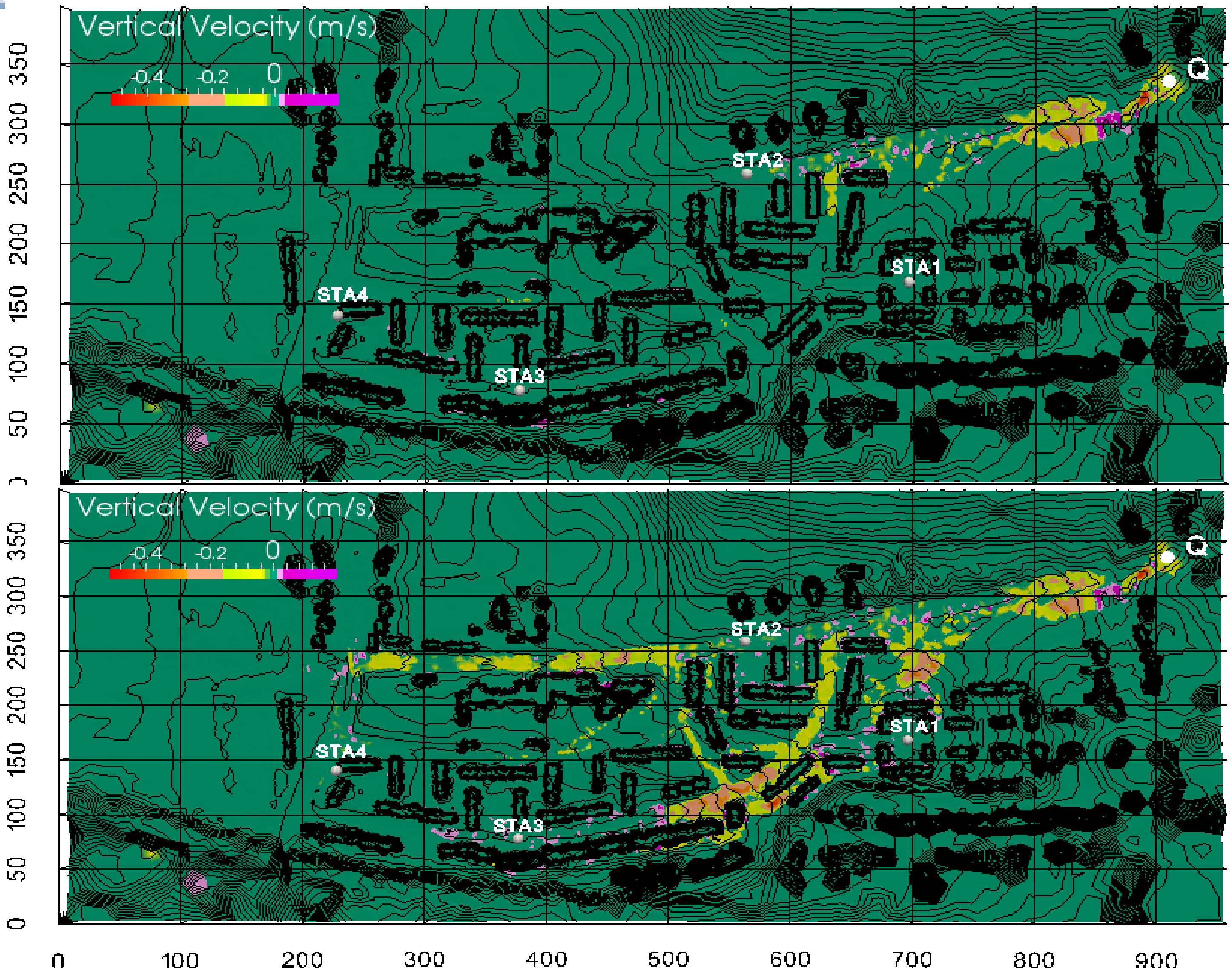
Vertical motion

t=20min

t=30min



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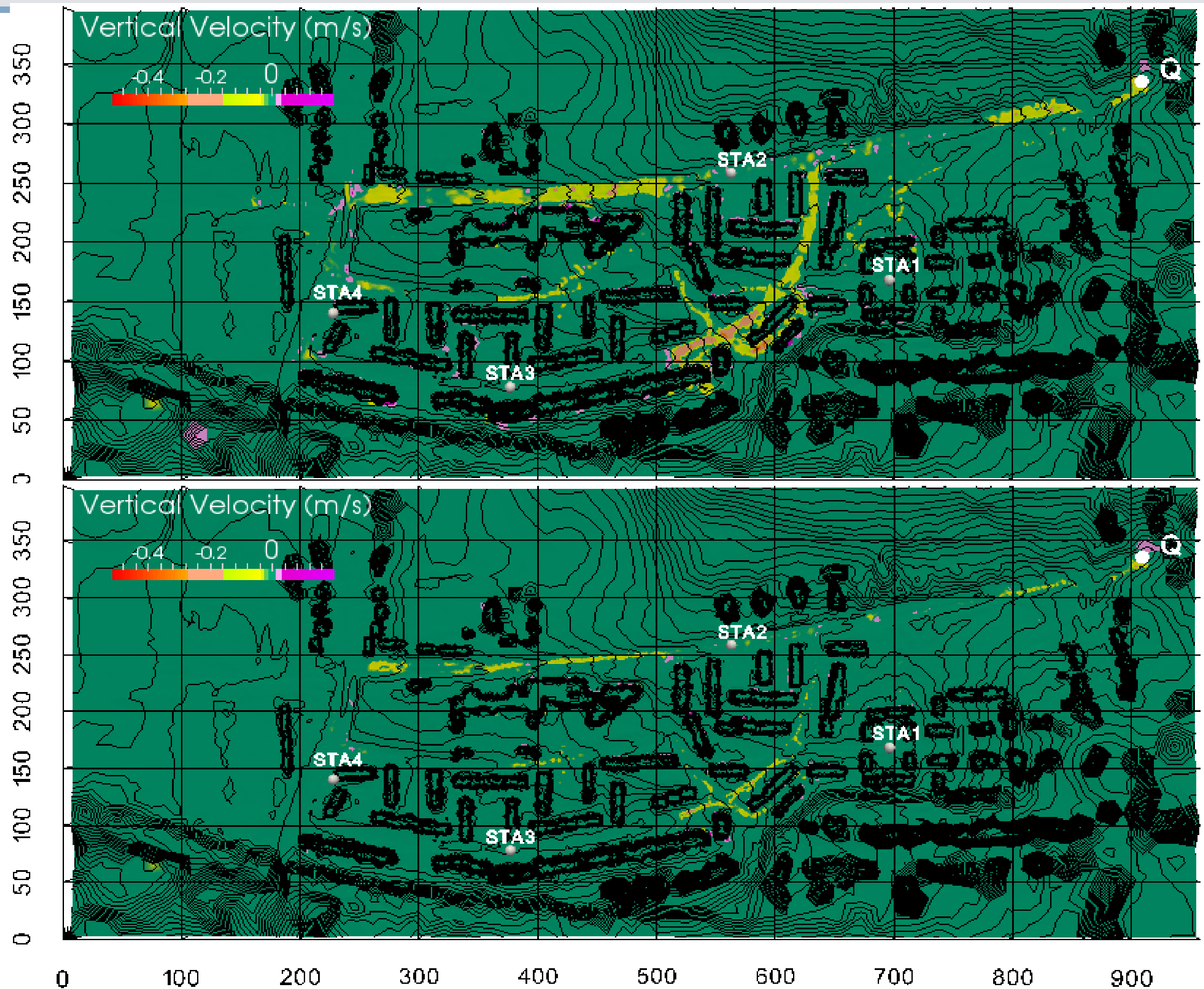
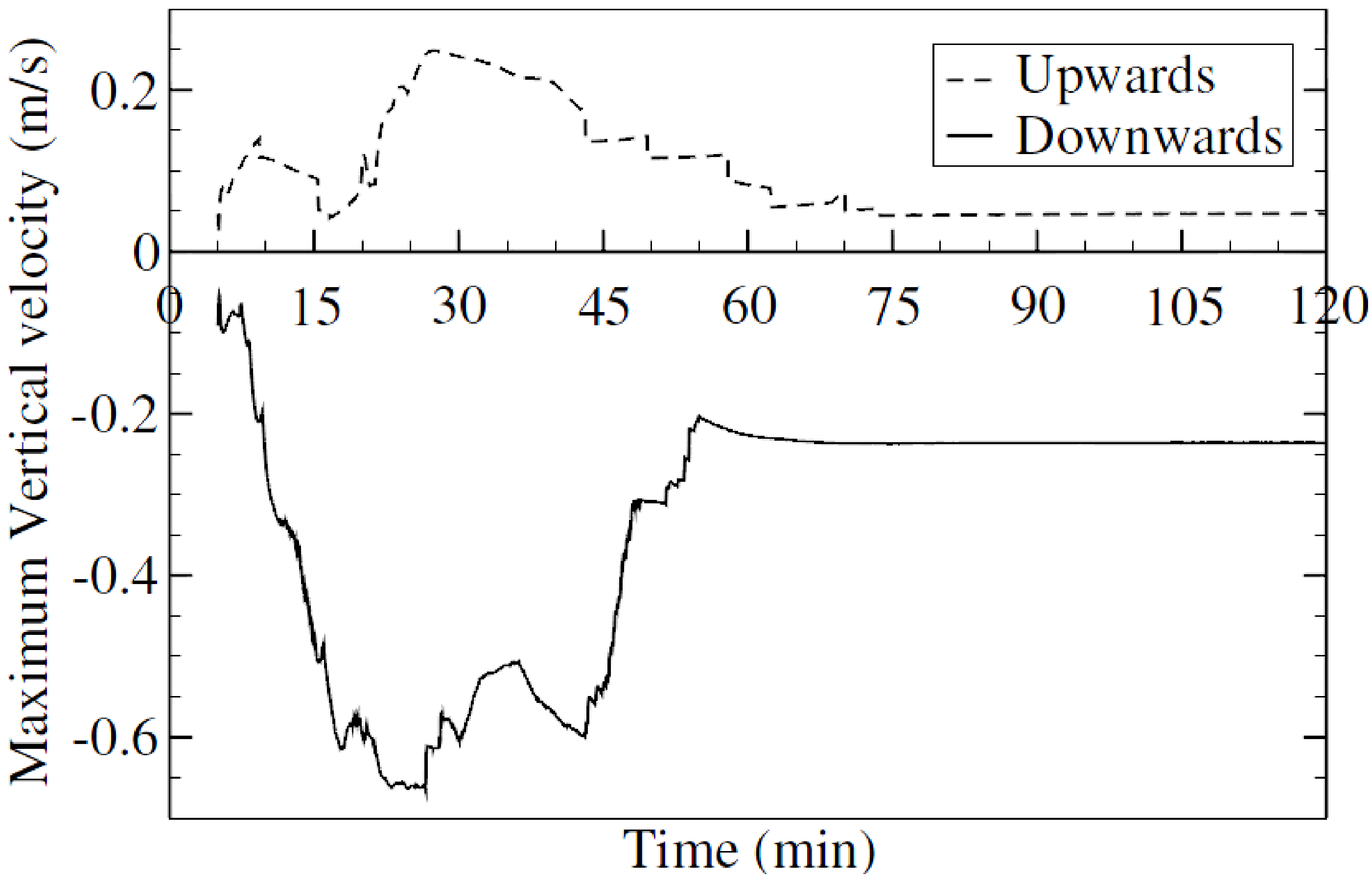
t=40min

t=60min



Statistic maximum vertical velocity component in the whole domain



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Future work

- **Coupled modeling** of surface flow in 3D (Fluidity) and drainage pipe flow in 1D (SWMM);
- Implementation of **Adaptive Mesh technique** to the proposed 3D flooding model.

Thank you