Modelling Extreme Flood Events and Associated Processes

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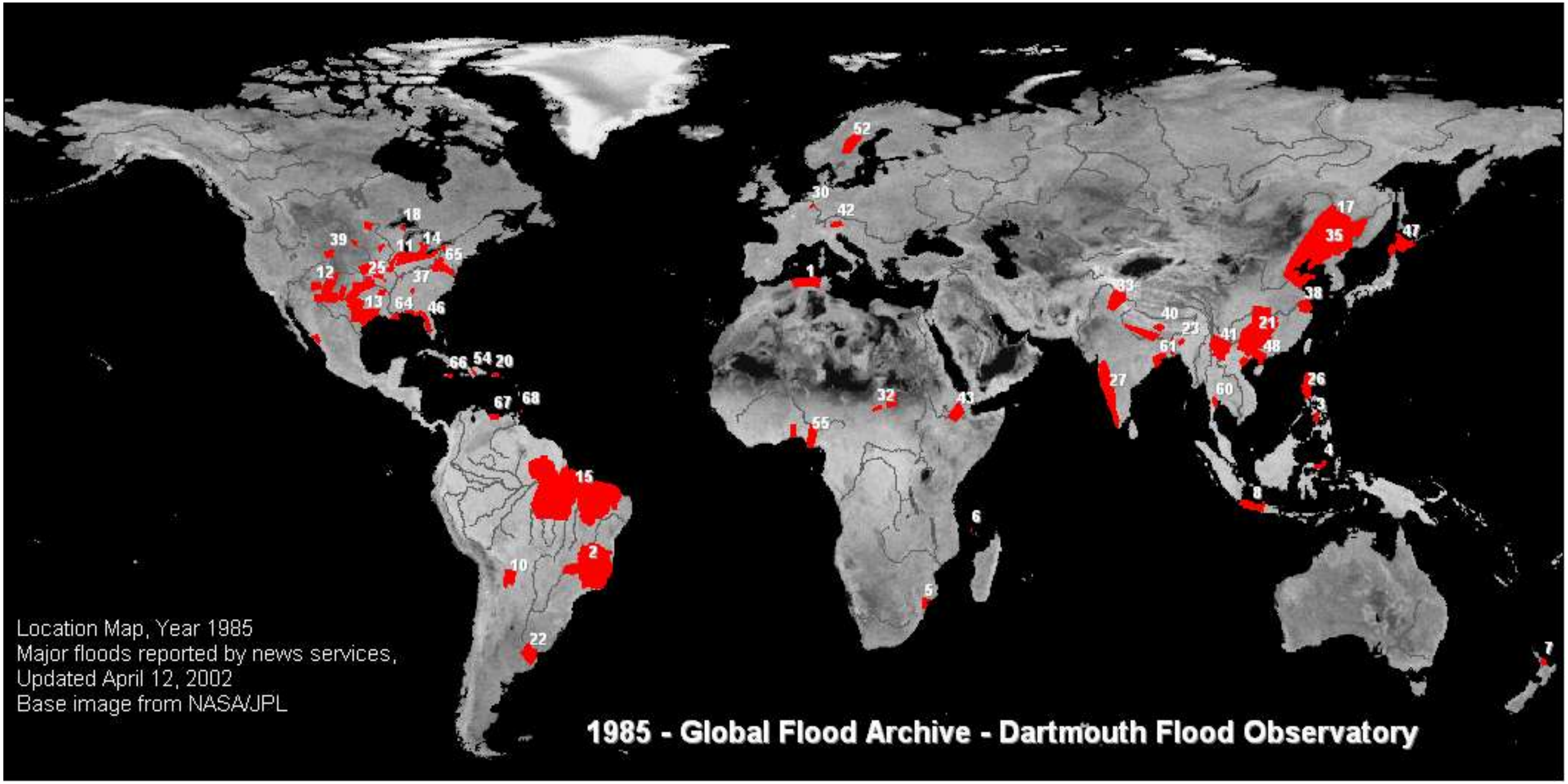
General

- Flooding essentially a natural process ⇨ we need to live with rivers, climate change and increasing storm events
- Flooding not only be caused by high rainfall ⇨ also poor drainage, groundwater saturation, debris flows etc.
- Flooding usually also leads to water pollution ⇨ large loss of life in many countries due to epidemiological outbreaks
- Flooding damage extent often exacerbated by:
  - Inadequate data, poor warning systems and planning
  - Inadequate defences and insufficient upstream storage
  - Use of crude modelling tools and inexperienced operators

• Floods are on the Rise



- Floods Cause Loss of Life

- Floods Bring Misery and Stress

- Floods Bring Contamination

- Cumbria Floods 2016 – Short Steep River Basin

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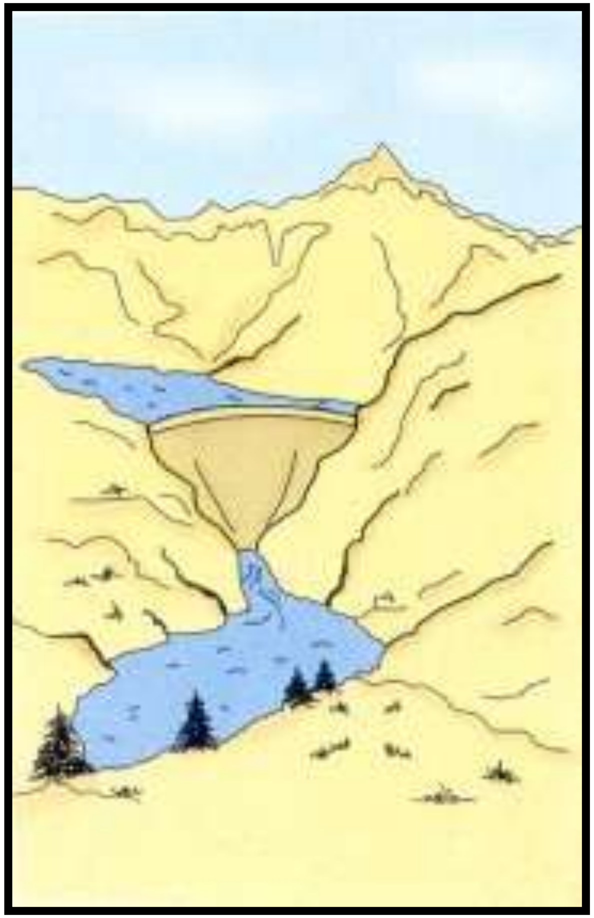
- Somerset Levels 2014 – Mild Slope River Basin

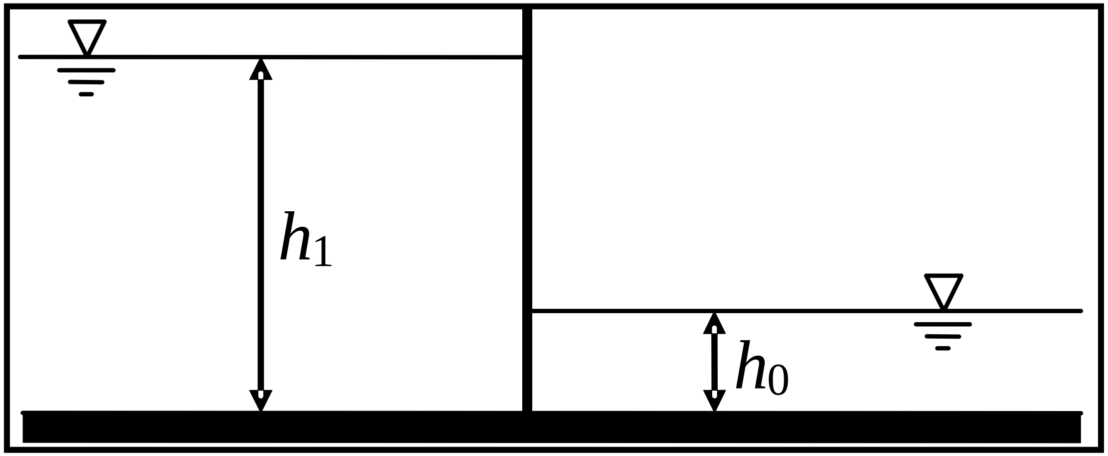
Overview of Research for Steep Catchments

- Increasing concern of flooding along steep river basins and levee breeches – particularly in Wales
- Traditional 2-D and 1-D models not ideal for such flows and need refining for trans- and supercritical flows
- Full shallow water equations solved using a finite volume scheme on a collocated grid
- Model also refined to include surface and sub-surface flow interactions and extended to include floodplain flows in urban regions

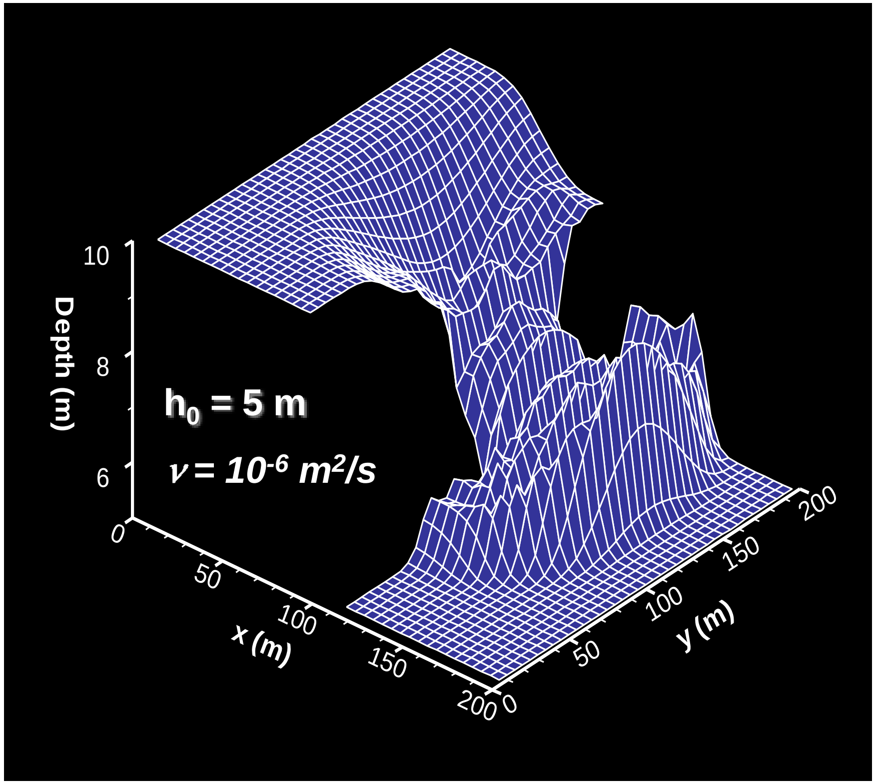
- DIVAST-ADI vs. DIVAST-TVD

Dam-Break Problem

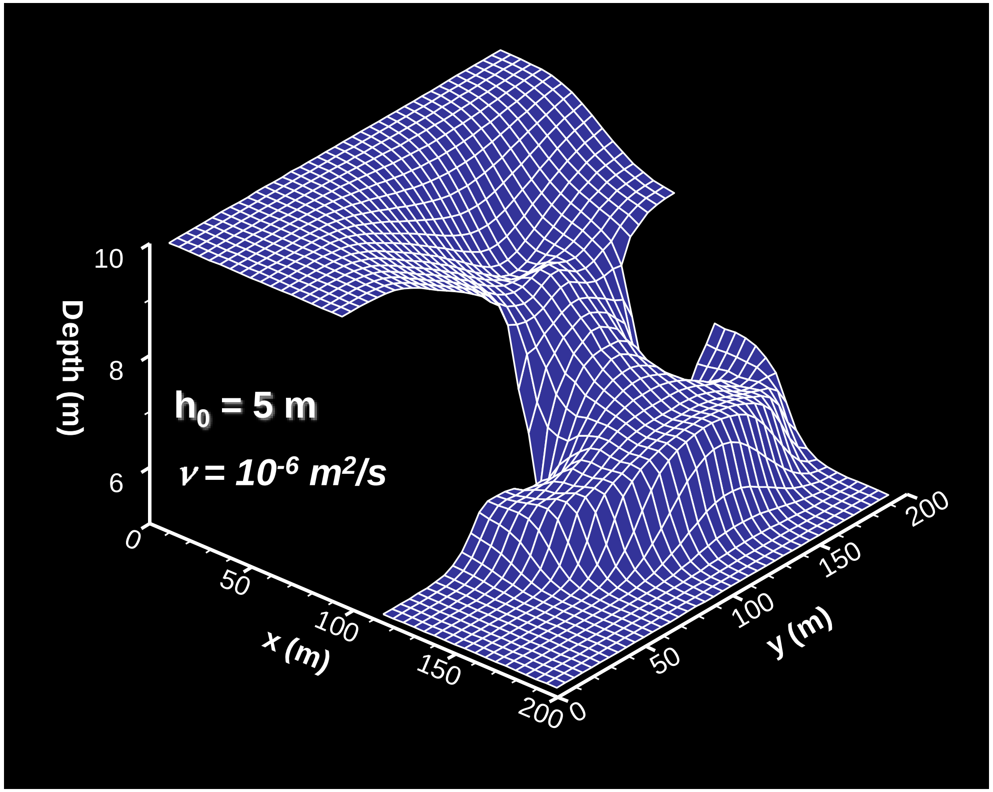




- DIVAST-ADI vs. DIVAST-TVD

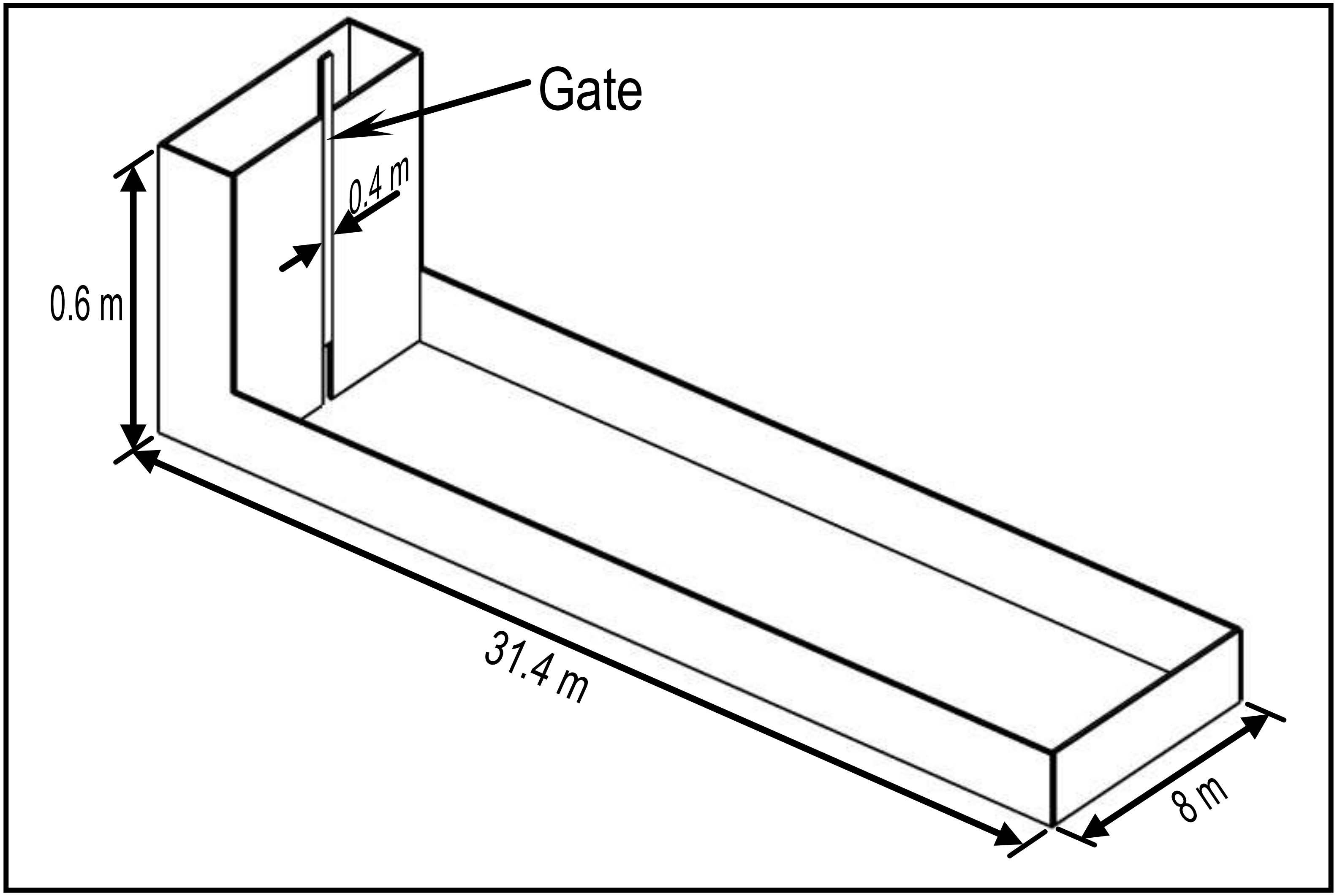


DIVAST-ADI

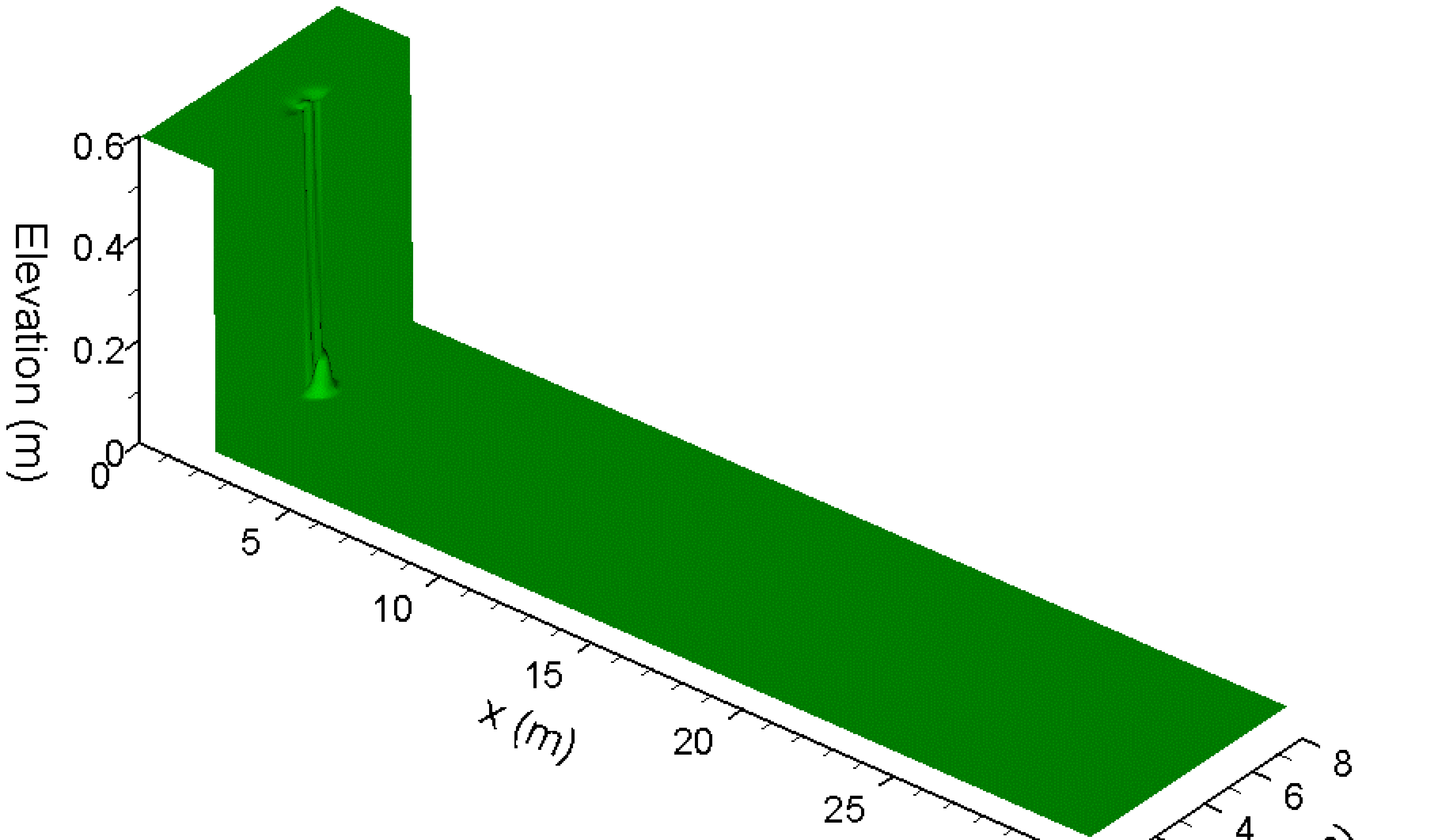


DIVAST-TVD

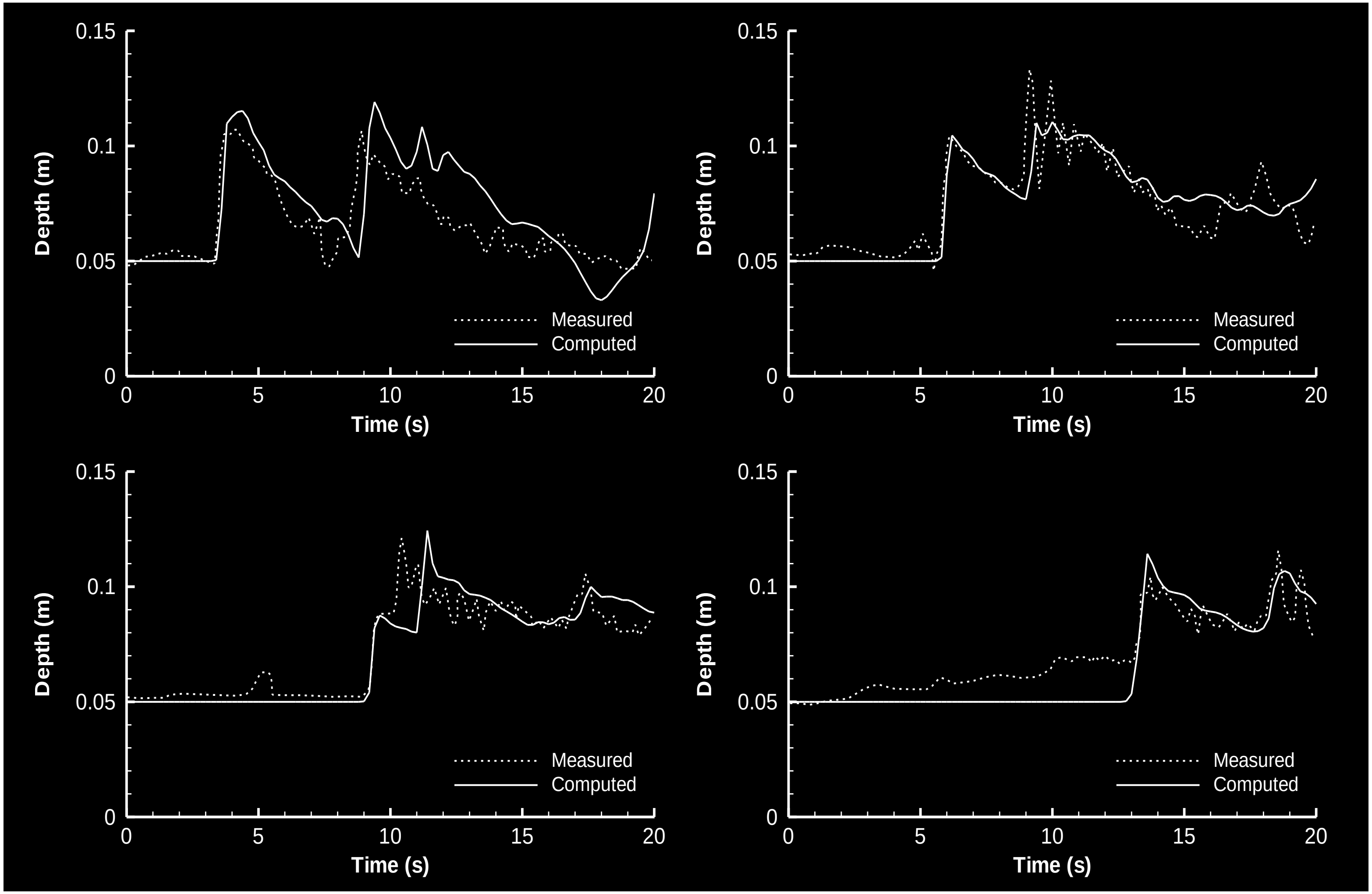
- Dyke Break Experiment (TU Delft)



- Dyke Break Experiment

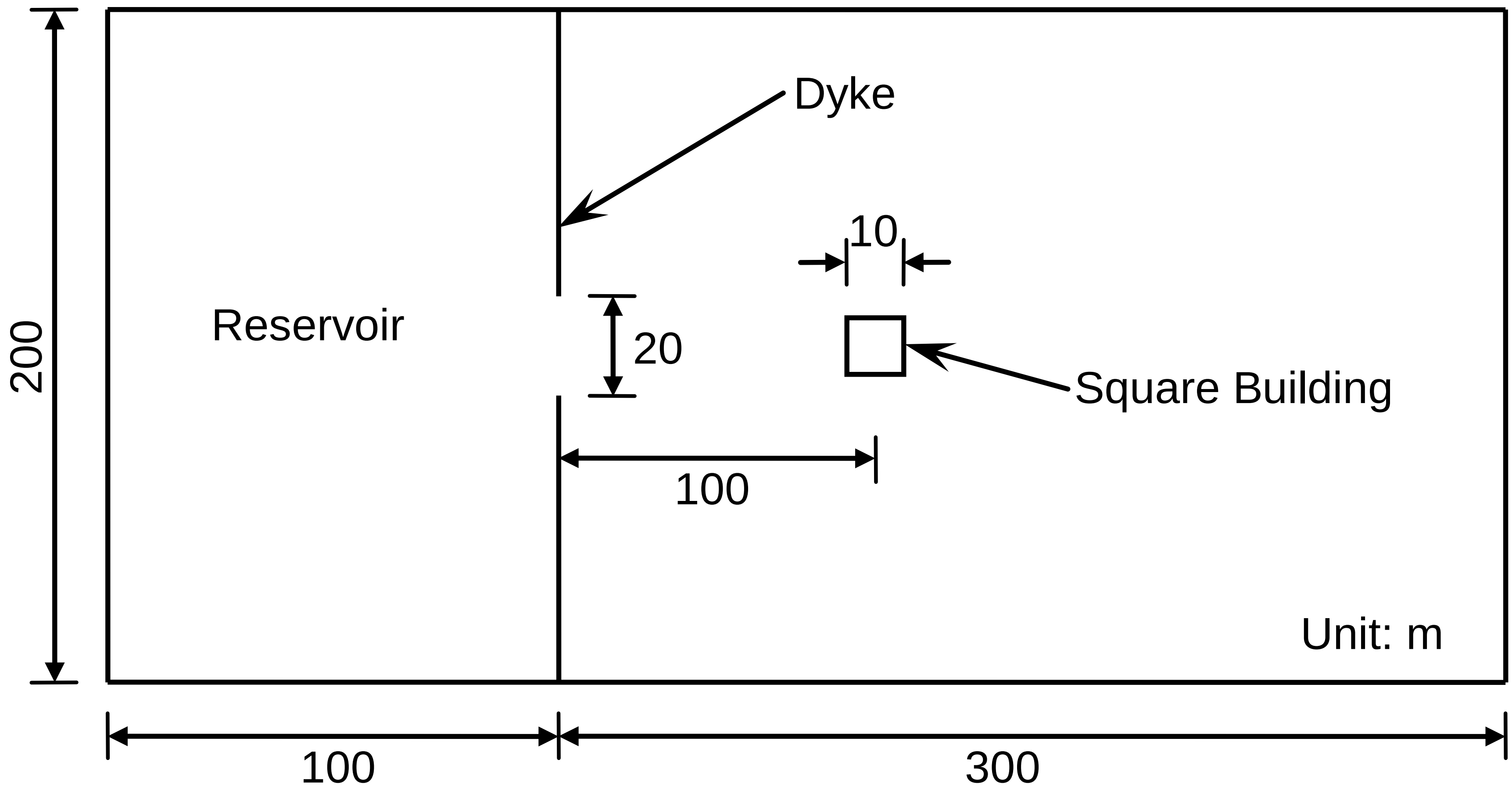


• Dyke Break Experiment



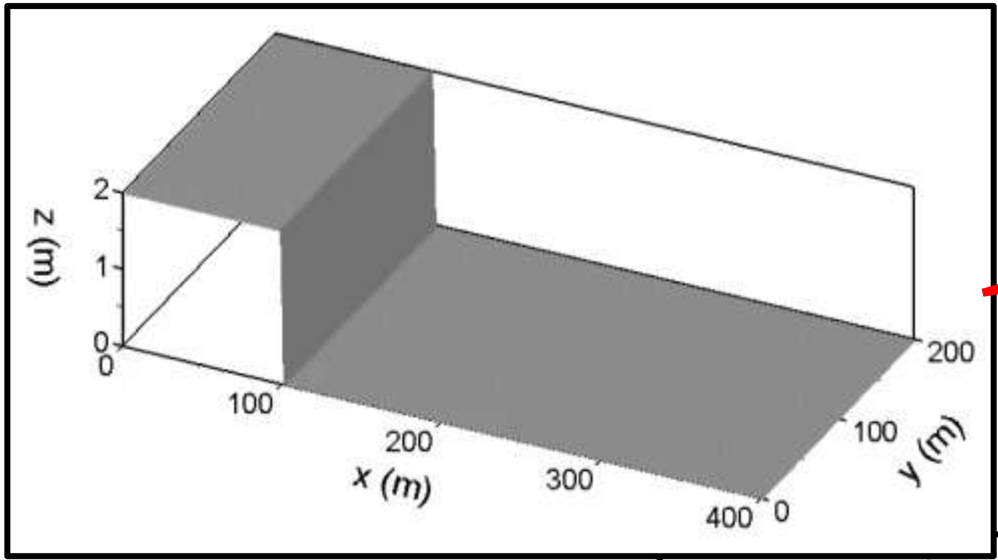
- # Refined Treatment of Buildings
  - Three modelling approaches considered:
    - Modelling buildings as solid blocks making buildings impervious
    - Remove buildings and increase local roughness ⇨ not ideal for water quality predictions
    - Remove buildings and treat as porous media ⇨ better for predicting water quality in buildings

• Flood Building Interaction

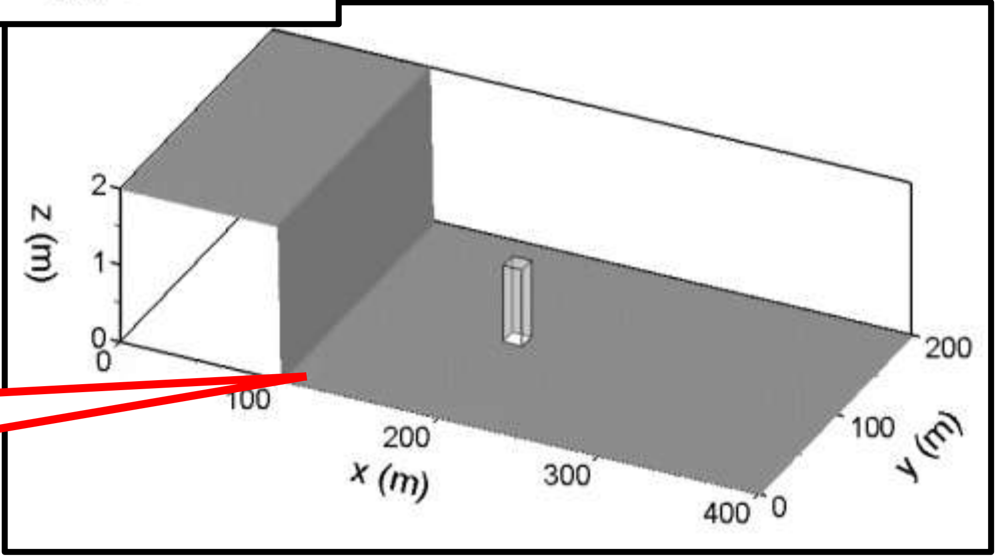


Manning's $n = 0.015$

• Flood Building Interaction 1 – Solid Building

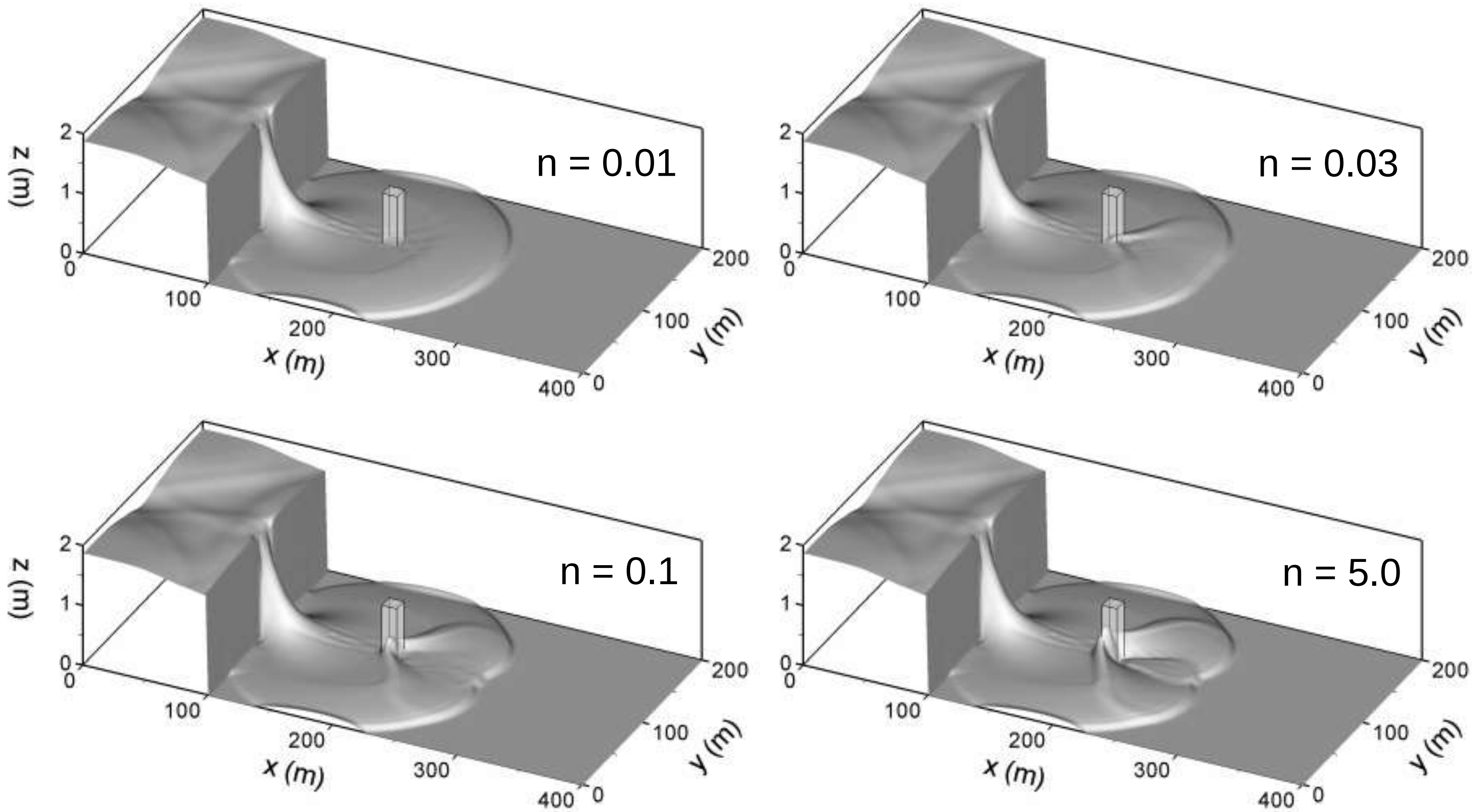


Without Building

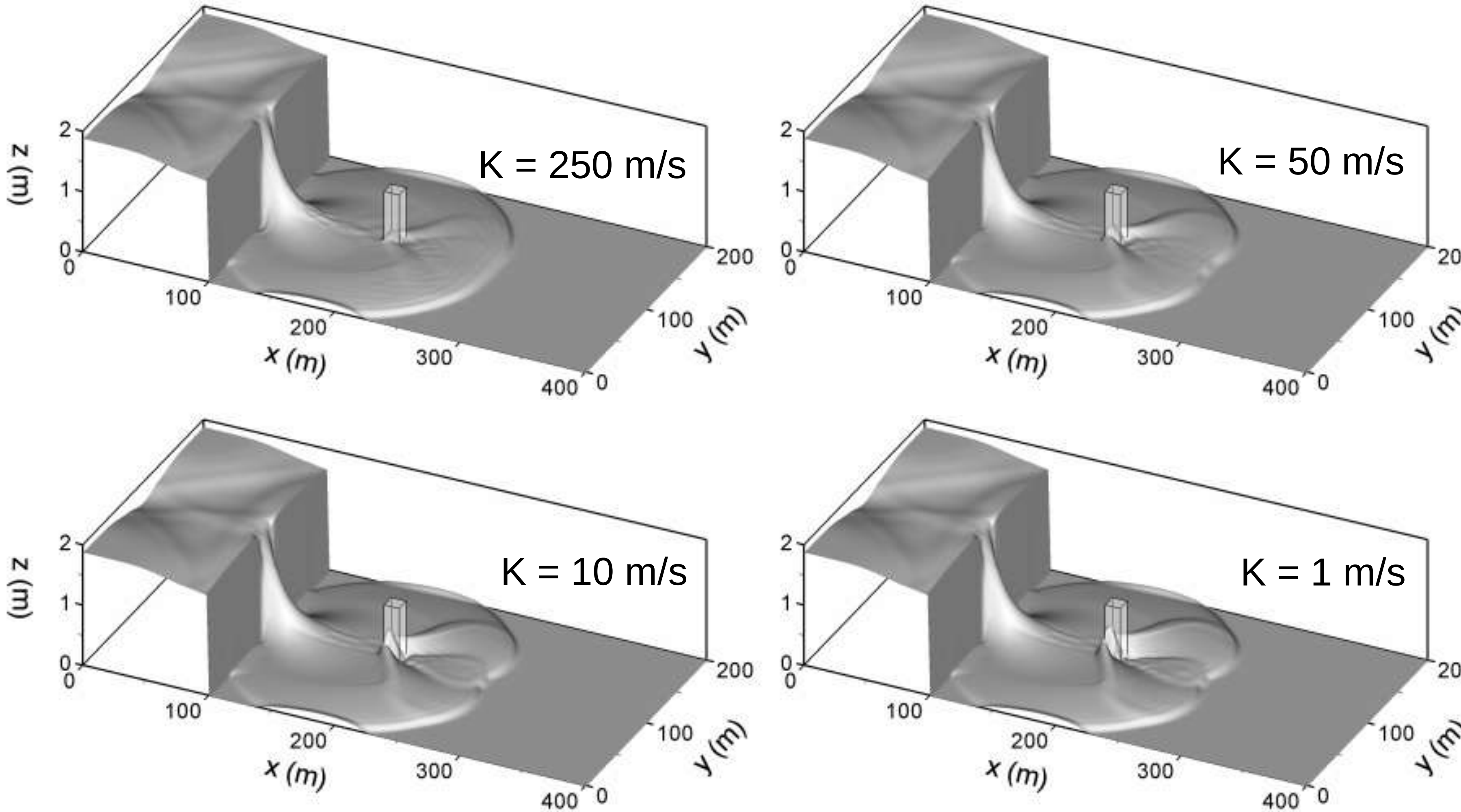


Model Building as solid block

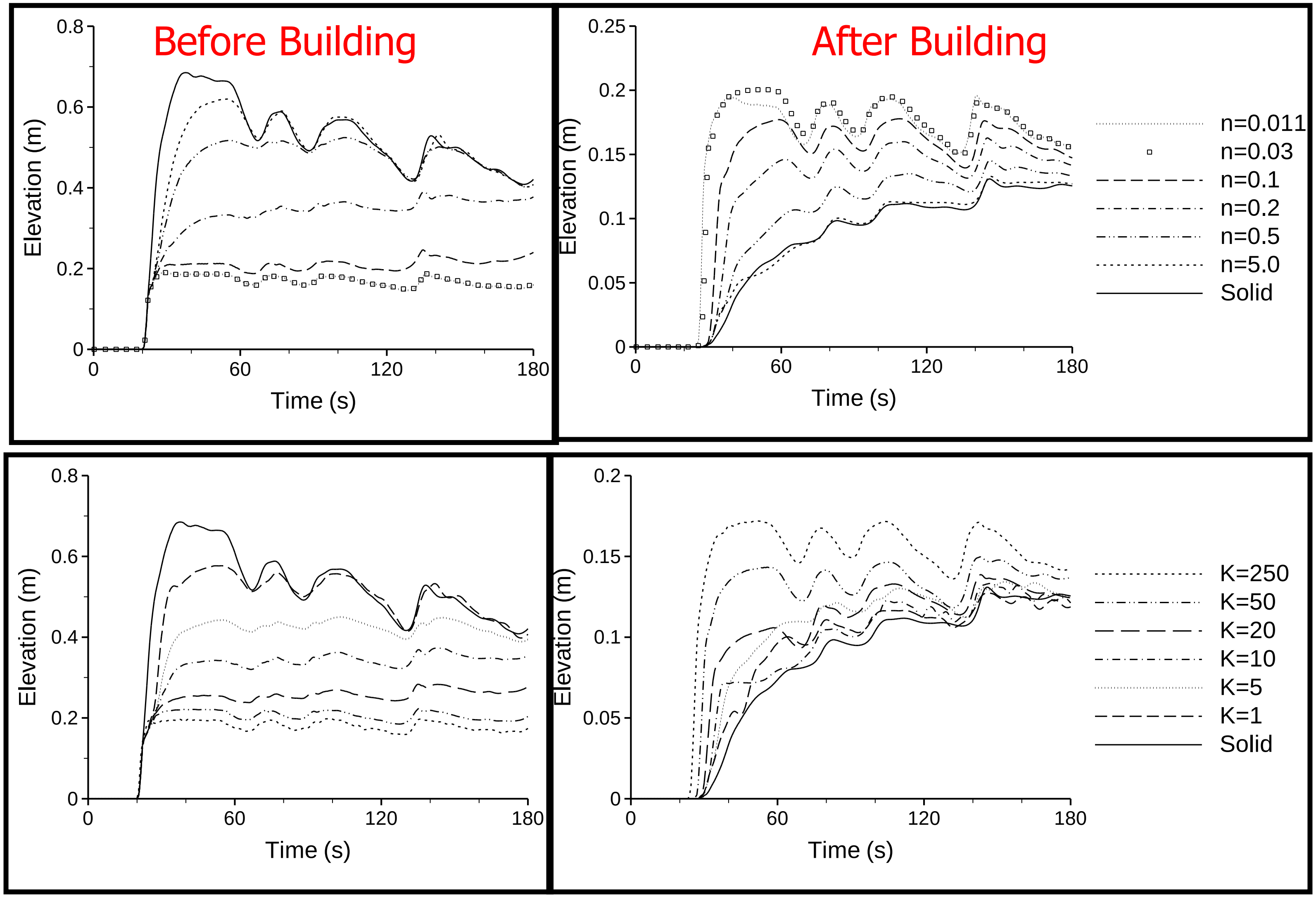
• Flood Building Interaction 2 – High Roughness



• Flood Building Interaction 3 – Porous Media



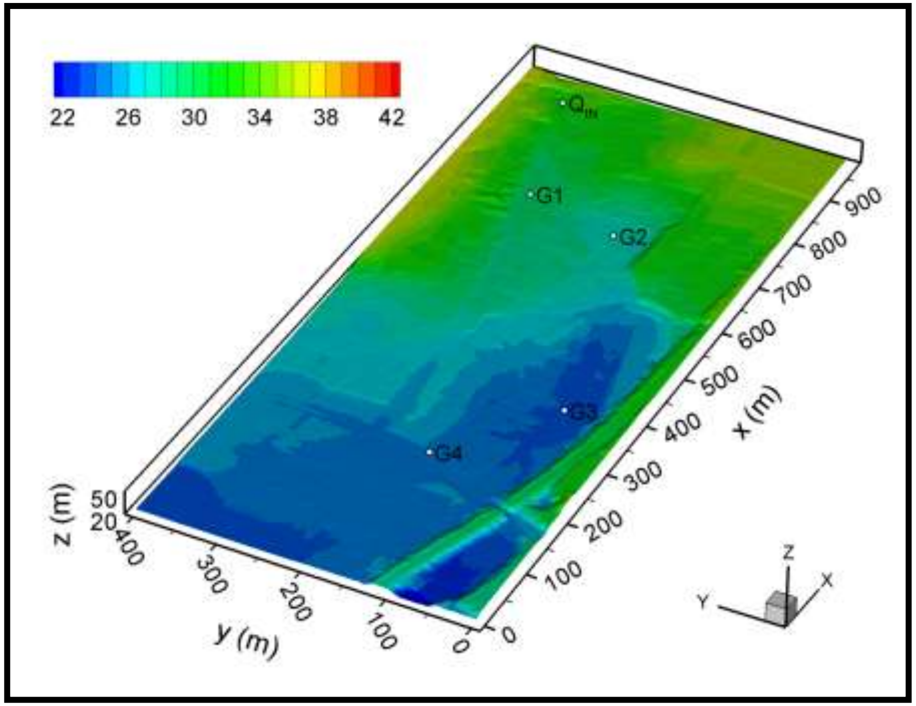
• Flood Building Interaction – Water Levels



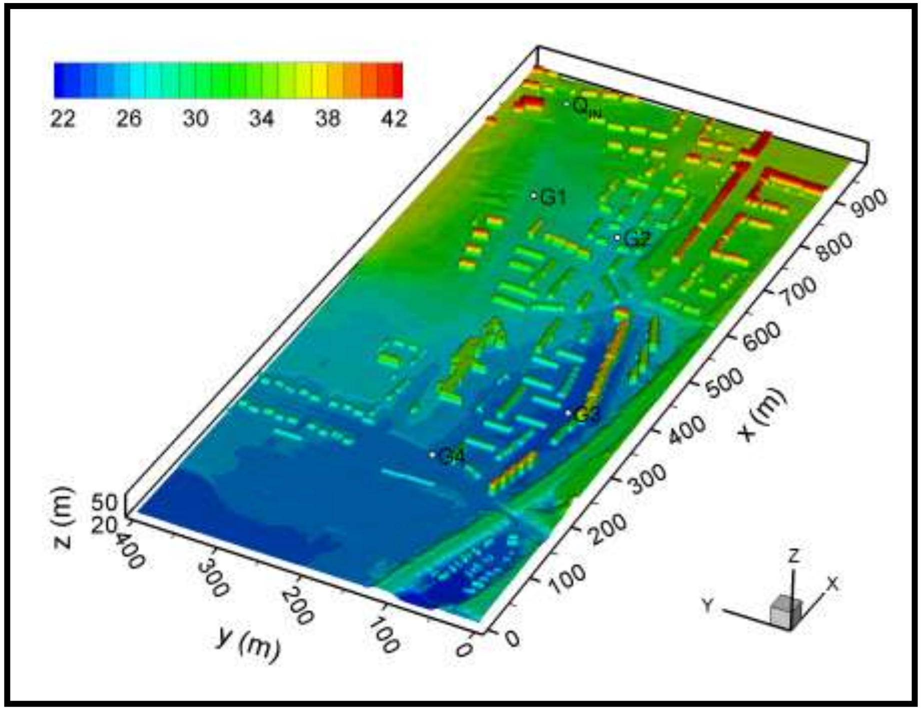
Flood risk management research consortium

- Flood Inundation of Glasgow

City in Scotland prone to urban flooding



Without buildings

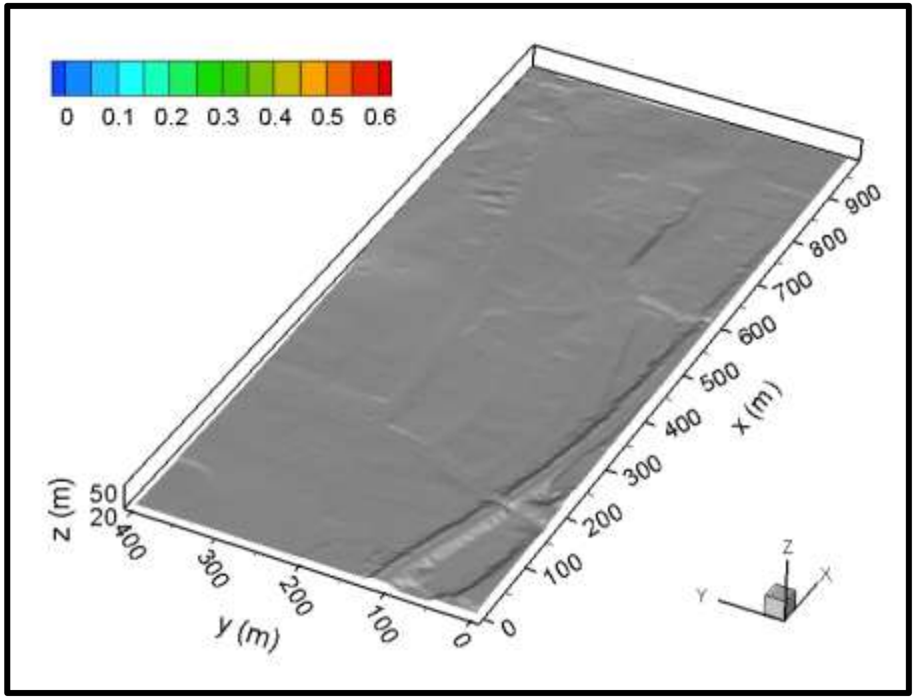


With buildings

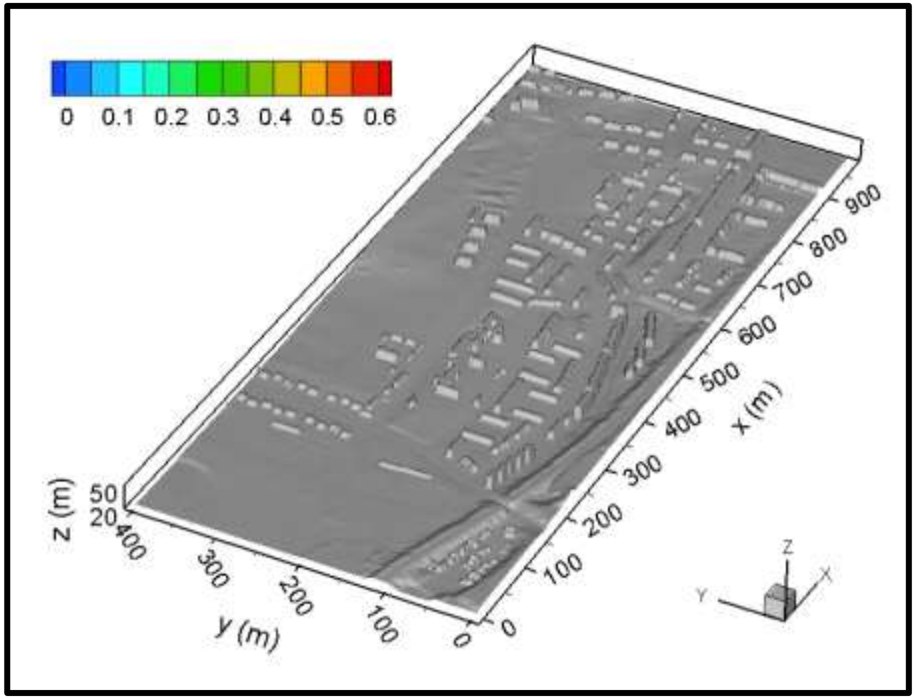
FRMRC flood risk management research consortium

- Flood Inundation of Glasgow

Porous media and solid block methods



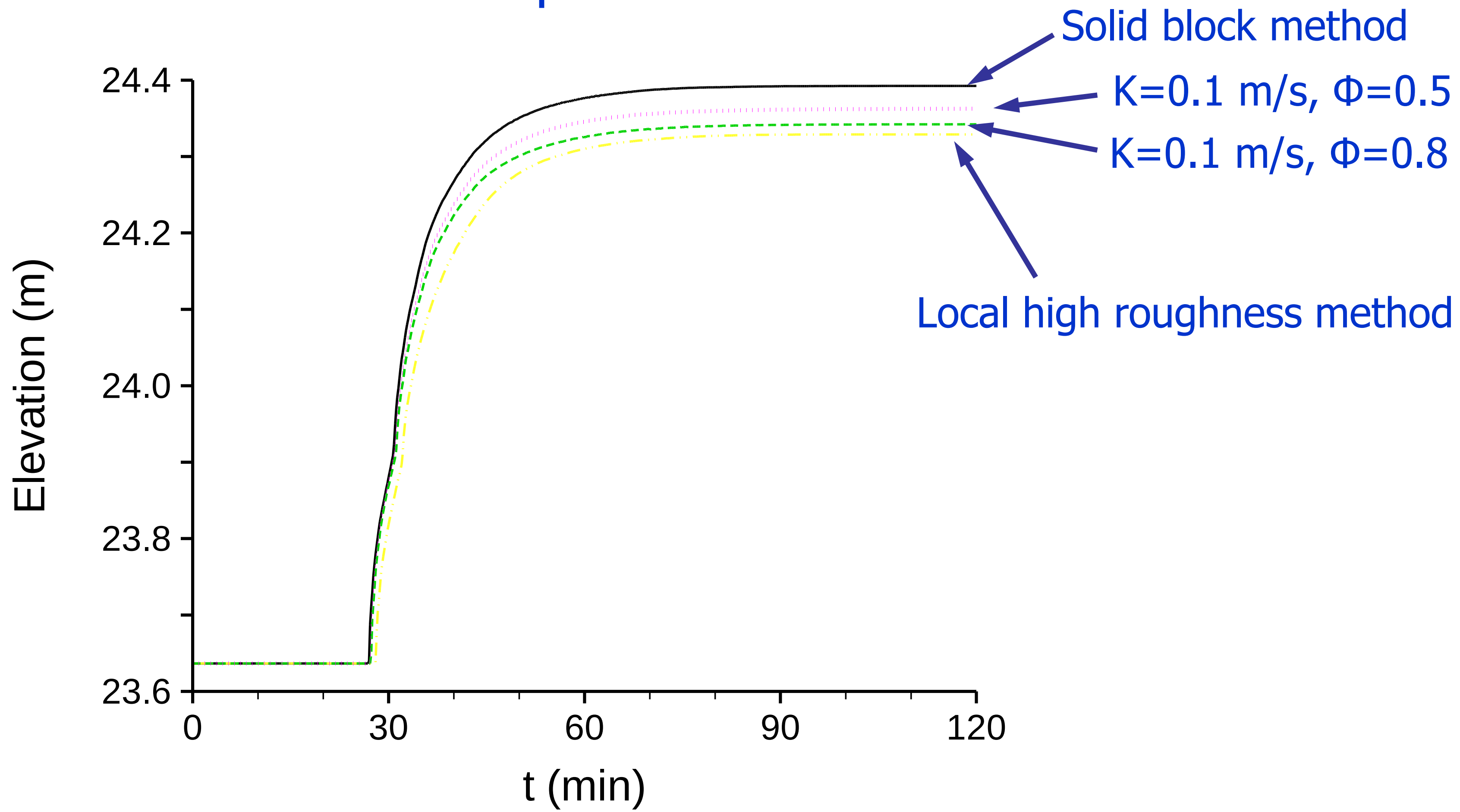
Without buildings



With buildings

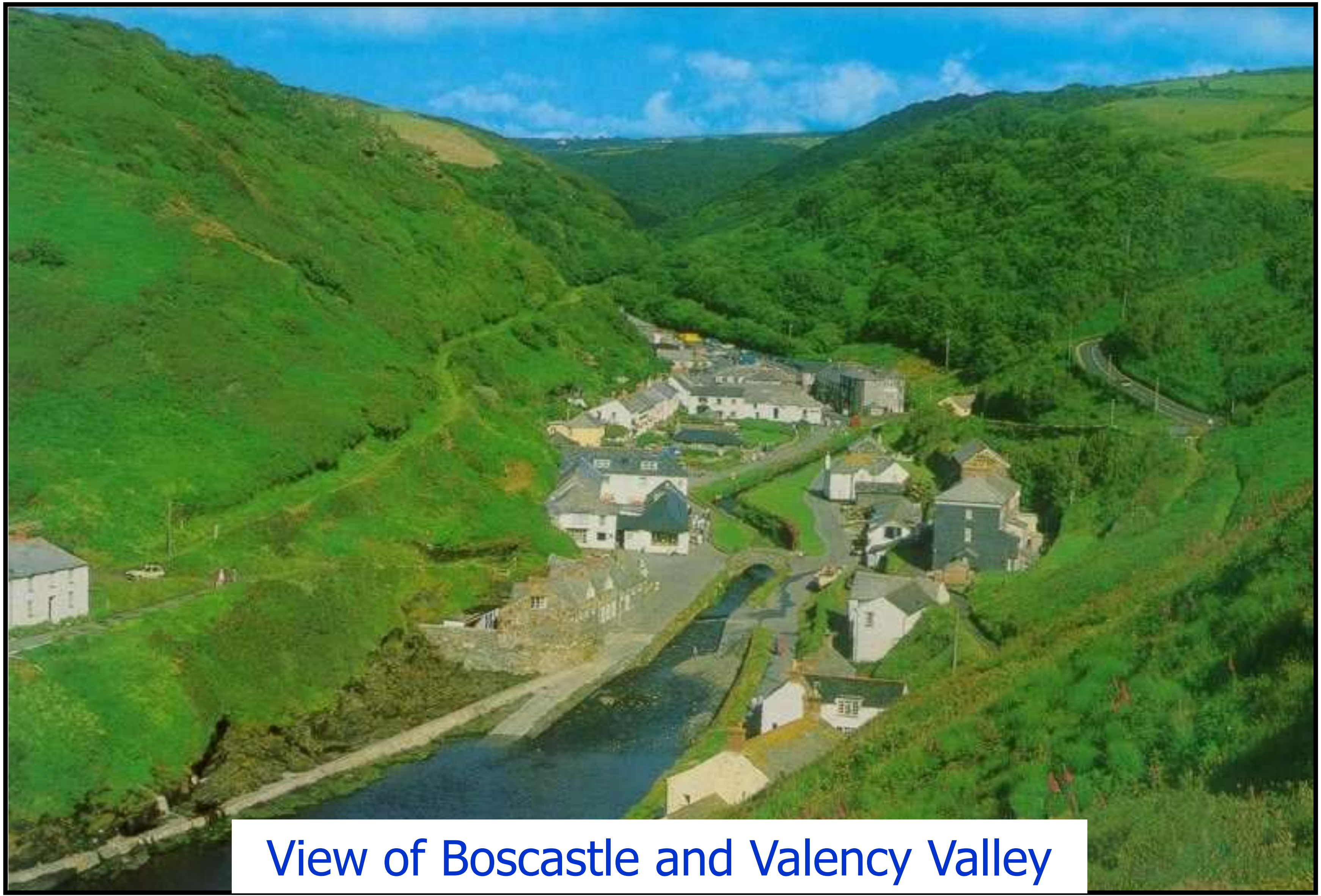
• Interaction Between Flood and Buildings

Water depth variance at G3:



- # Boscastle Flood 2004

  - Small picturesque town in South West of UK
  - Short river basin with steep valley terrain ⇨ similar to many river basins in Wales and Northern England
  - Up to 200 mm rainfall fell in 5 hr and predicted to have 1 in 400 yr return period event
  - Extensive damage to properties, bridges, highways and other infrastructure
  - One of best recorded extreme flood events in UK with trans- and super-critical flows



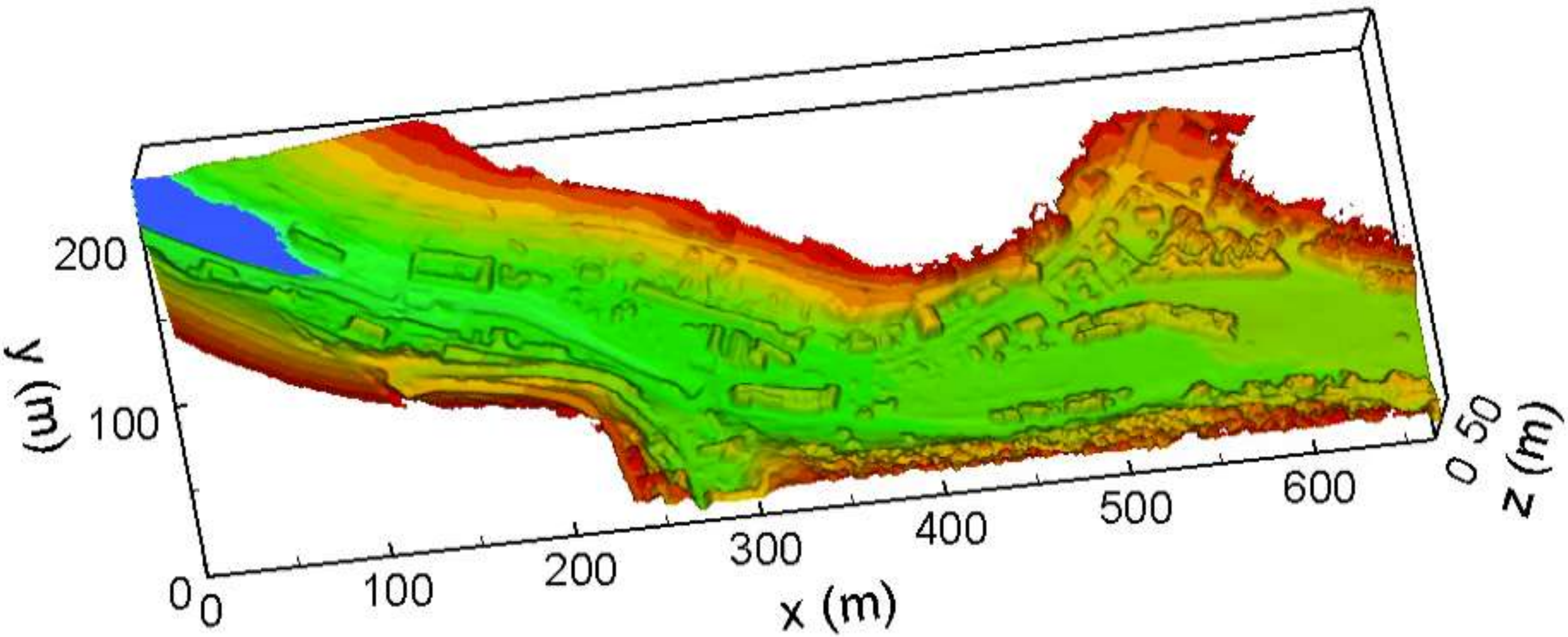
View of Boscastle and Valency Valley

Model Study Objectives

- Determine type of model scheme most appropriate for predicting key parameters for extreme flood events
- Three different schemes compared:
  - Simplified DIVAST (i.e. NI – No Inertia)
  - Standard DIVAST (i.e. ADI – Alternating Direction Implicit)
  - DIVAST – TVD (i.e. Total Variation Diminishing)
- Case studied: 2004 Boscastle flash flood
- Predicted main flood parameters (i.e. water elevations and flood inundation extent) compared with observed data

- Boscastle Study Domain

- Predicted Flood Simulation (TVD Scheme)



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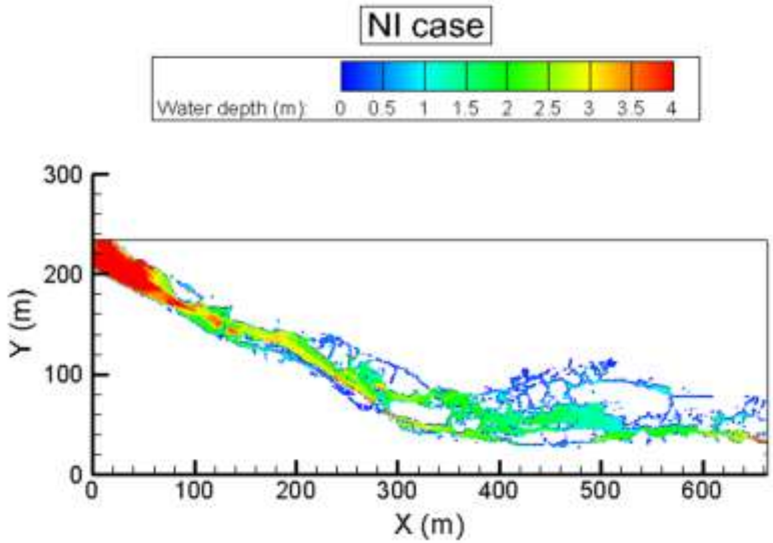
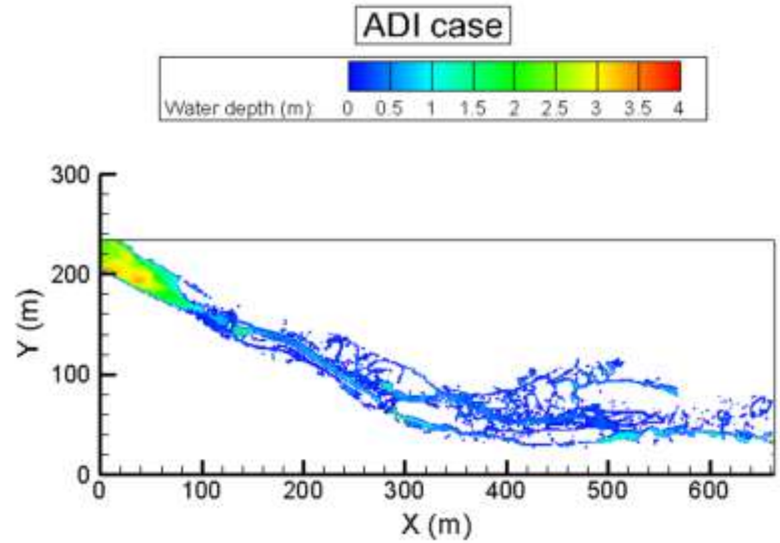
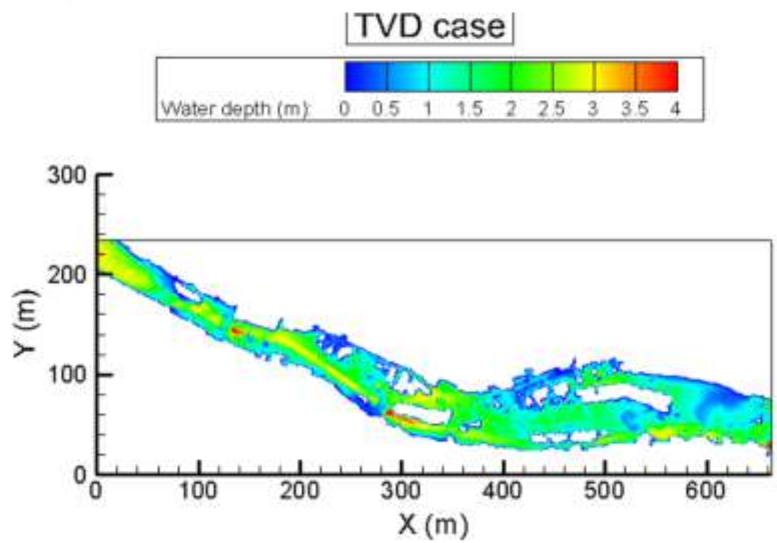
• Flood Inundation Extent Predictions







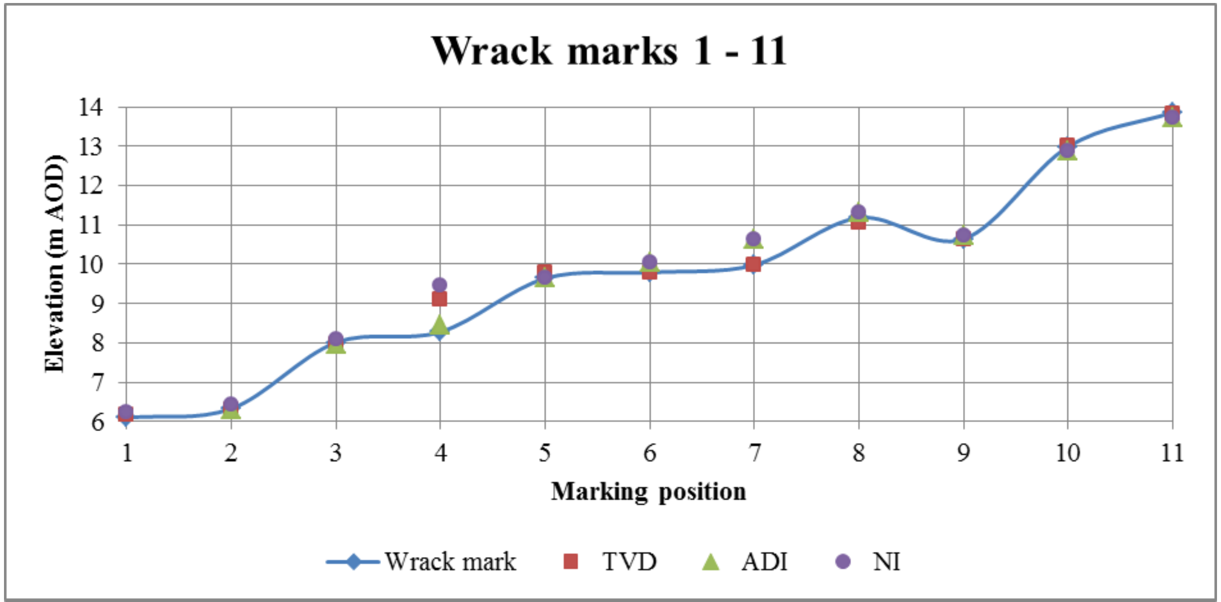
Cases

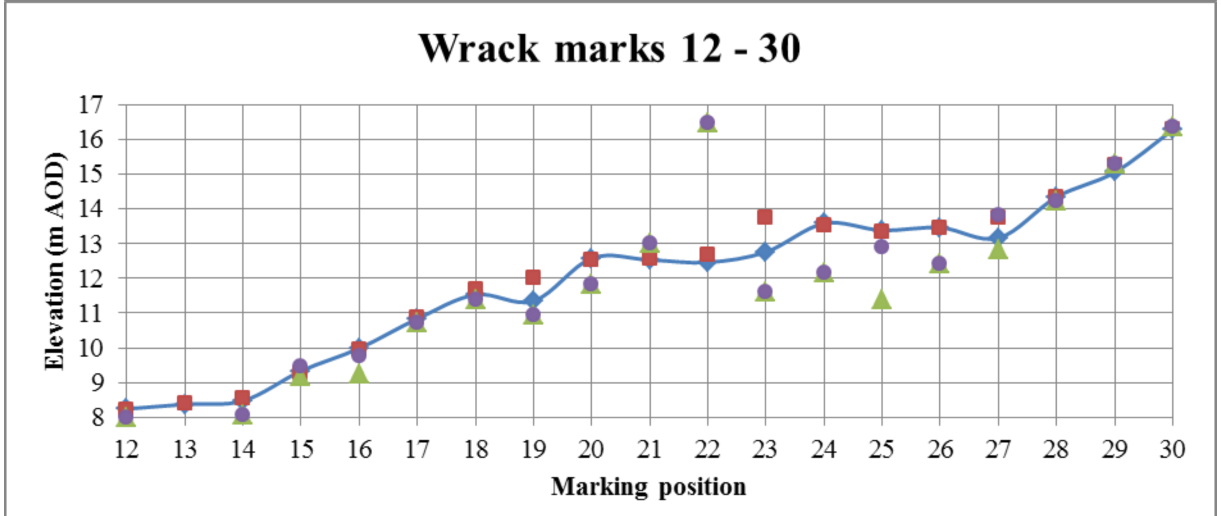
NI – No Inertia

ADI – Alternating Direction Implicit

TVD – Shock Capturing

Predicted and Measured Water Levels





- Summary
  - Models can be extended to include treatment of buildings on floodplains using surface/subsurface models ⇨ offering attractive options for flood modelling (e.g. health impact)
  - For rivers with trans- or supercritical flows, or levee breeches, then need to use more complex models and replicate hydrodynamic processes more accurately
  - Computational models with shock capturing algorithms provide more accurate predictions of flood elevations
  - Debris and vehicles can increase flood risk by blocking bridges and culverts to reduce local discharges

Wrong exit

Debris flow problem


For more clips go to
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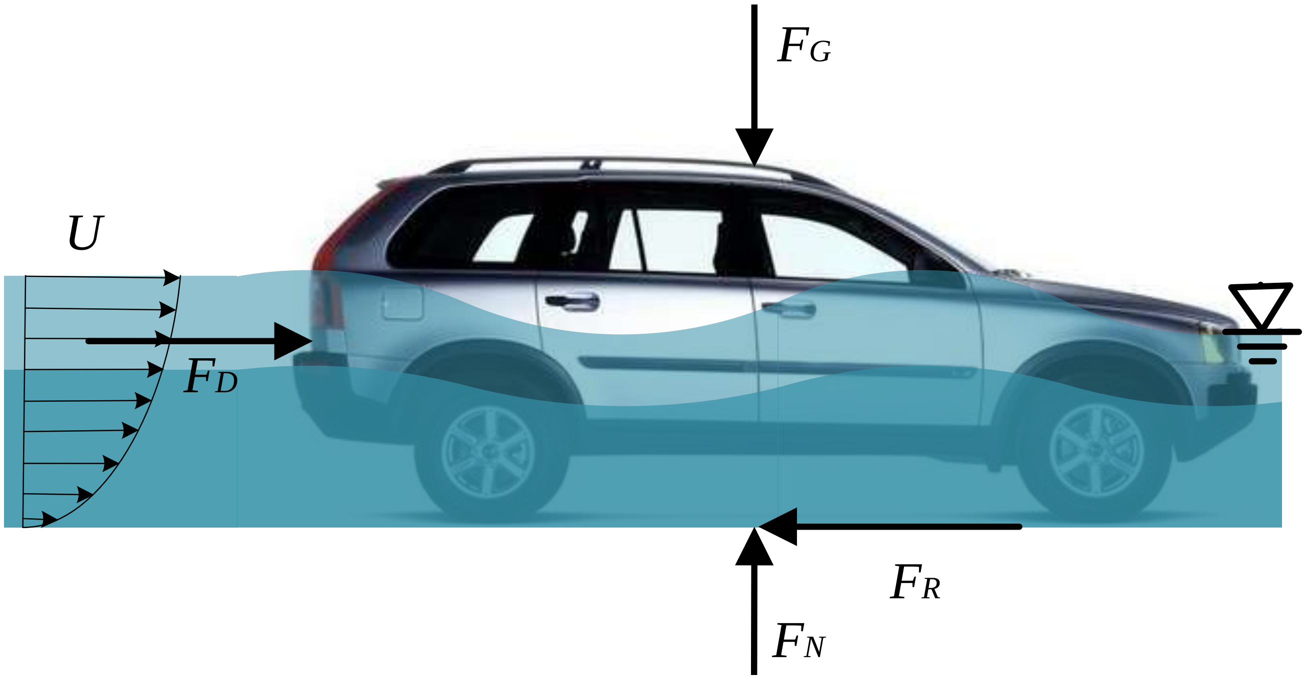
- # Incipient Velocity for Vehicles in Floodwaters

  - Study first undertaken to determine incipient velocity for fully submerged vehicles

  - Subsequent studies undertaken for partially submerged vehicles based on:
    - Based on physics derived formulae
    - Flume experiments based on similarity laws
    - Parameter determination and formulae validation
    - Based on incipient velocity for prototype vehicles

- # Formula Derivation

Different forces acting on a partially submerged vehicle



F_G : Effective weight

F_D: Drag force

F_N : Normal force

F_R: Frictional force

$$F_D = F_R$$

$$C_d[a_d(h_f b_c)]\gamma_f \frac{u_b^2}{2g} = \mu[a_c l_c b_c(h_c\gamma_c - R_f h_f \gamma_f)]$$

$$u = (1+\beta)\left(\frac{y}{h_f}\right)^{\beta} U$$

$$u_b = \sqrt{\frac{\mu a_c}{a_d C_d}}\sqrt{2gl_c\left(\frac{h_c\rho_c}{h_f\rho_f} - R_f\right)}$$

$$\alpha = \frac{1}{1+\beta\ a_b^{\beta}}\sqrt{\frac{\mu}{C_d}\frac{a_c}{a_d}}$$

$$\boxed{U_c = \alpha\left(\frac{h_f}{h_c}\right)^{\beta}\sqrt{2gl_c\left(\frac{\rho_c}{\rho_f}\frac{h_c}{h_f} - R_f\right)}}$$

α, β = Parameters, to be calibrated using flume experiments;

U_c = Incipient velocity for a partially submerged vehicle.

• Flume Experiments for Vehicle Instability

- Experiments conducted in HRC flume Cardiff University. Flume: 15 m long, 1.20 m wide and 1.00 m deep, plastic bed and glass sides
- To estimate critical conditions for prototype vehicles - scaled model vehicles used, with 3 similarity laws used to design flume experiments

Experimental test flume

Partially submerged vehicle test

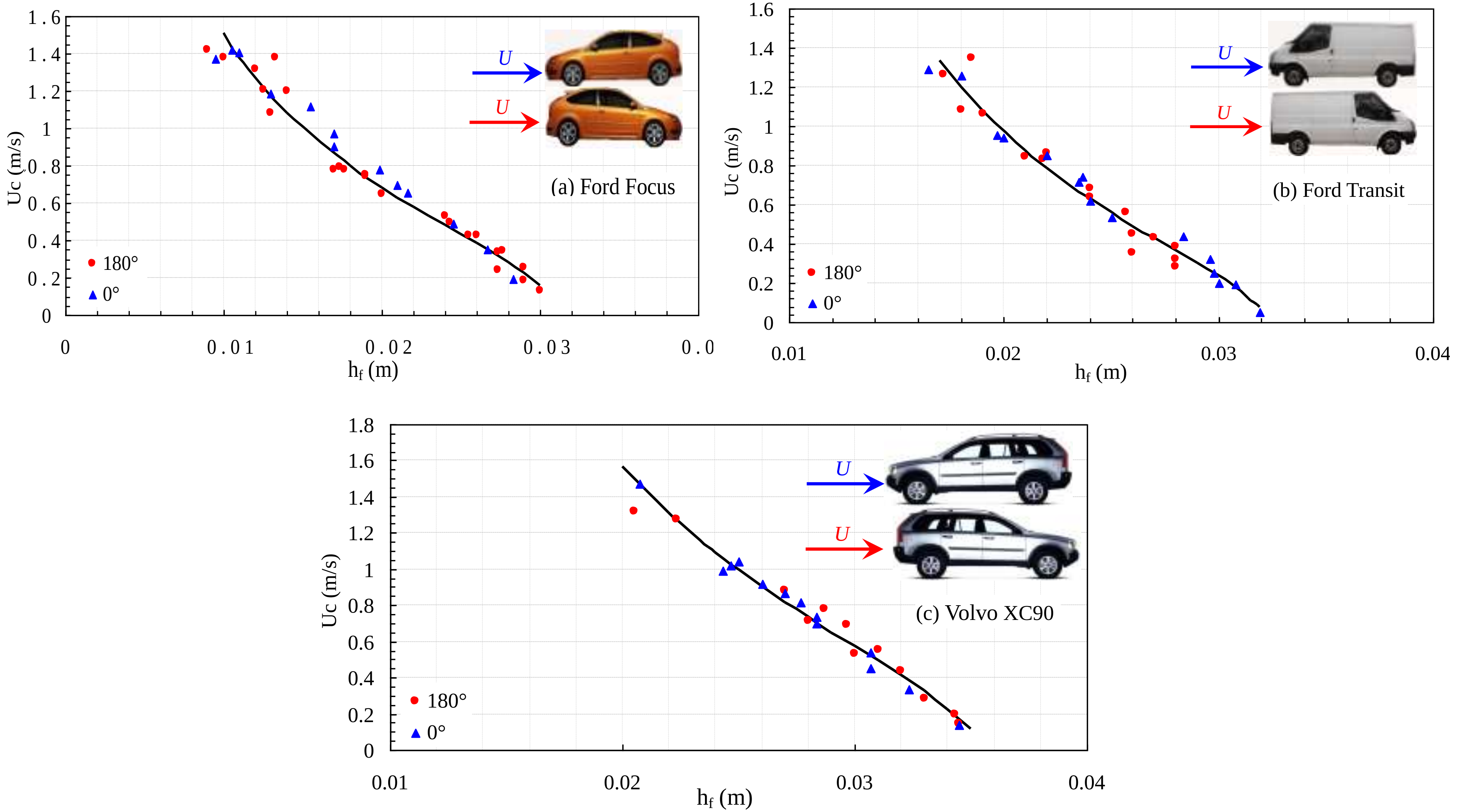
Design of Flume Experiments

Prototype can be analysed from experiments if similarity occurs with: form (geometric), motion (kinematic) and force (dynamic) .

Scale ratios of model experiments

Similarity Scale		Symbol	Design scale
Geometric similarity	Horizontal or vertical scale	$\lambda_L = \lambda_H$	18
Kinematic similarity	Velocity scale	$\lambda_U = \sqrt{\lambda_L}$	$\sqrt{18}$
Dynamic similarity	Force scale	$\lambda_{F_g} = \lambda_{F_b} = \lambda_{F_N} = \lambda_{F_R} = \lambda_{F_D} = \lambda_F$	18^3

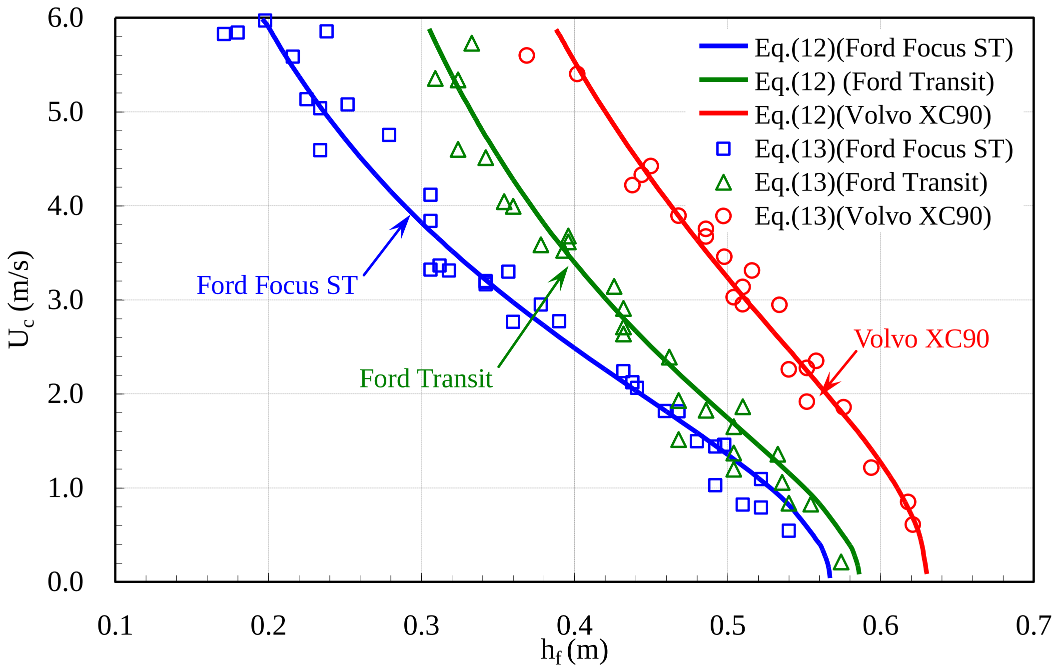
Flow and dimensions used typical for Taff



Depth-incipient velocity relationships for partially submerged vehicles

• Incipient Velocity for Prototype Vehicles

Incipient velocities for partially submerged vehicles in floodwaters estimated using two methods: (i) using model scale ratios, (ii) computations based on derived formulae



Comparison between estimated incipient velocities using two different approaches

• Assessment of People Safety

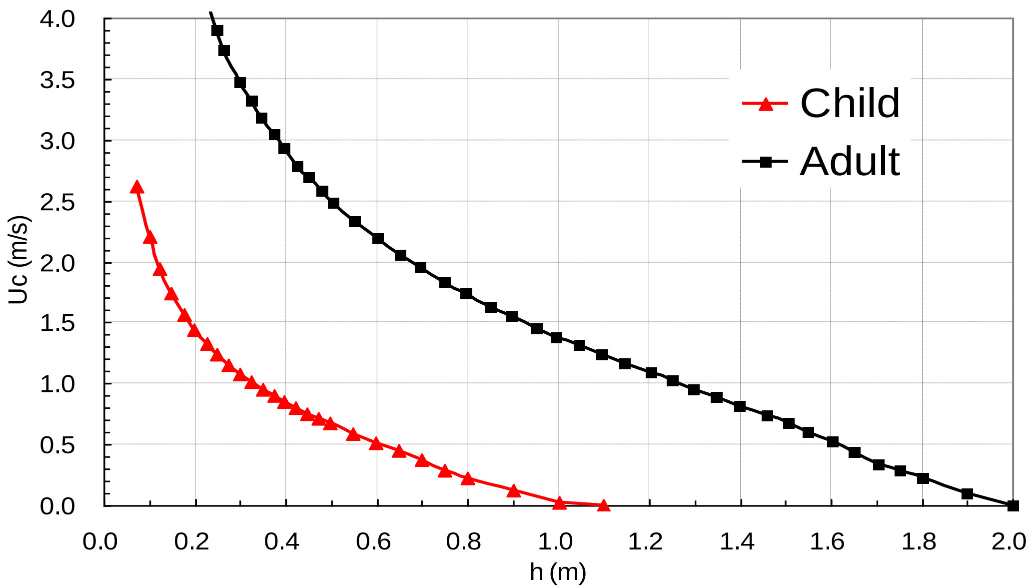
Previous studies carried out using two approaches:

- Empirical or semi-quantitative criteria
- Stability analysis validated by experimental data

Keller and Mitsch (1992) established balanced forces acting on a flooded person:- buoyancy, weight, frictional resistance and drag due to flow:-

$$\boxed{U_c = 2\left(\frac{F_r}{\rho_f C_d A}\right)^{0.5}}$$

F_r = restoring force due to friction;
A = submerged area normal to flow;
C_d = drag coefficient .



Instability curves for child and adult in floodwaters

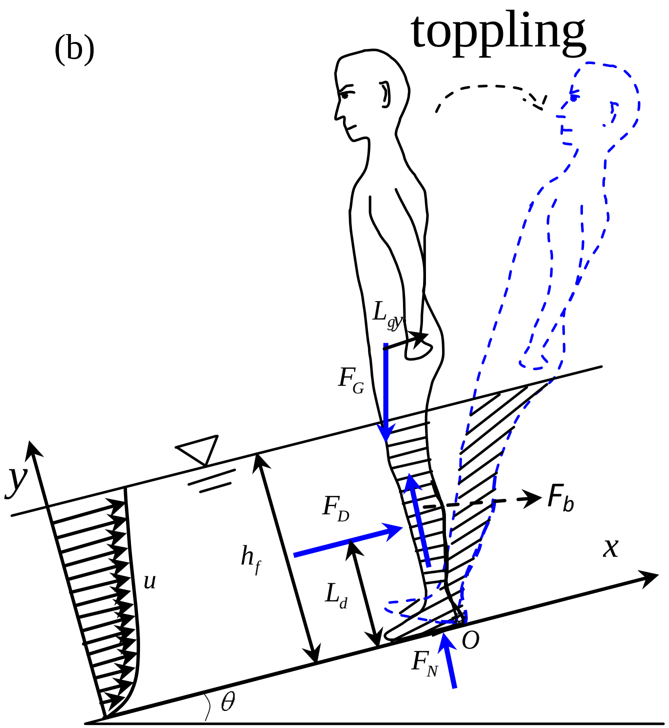
Incipient Velocity for People in Floodwaters

- Similar approach adopted to previous study on incipient velocity for vehicles

- Current study for partially submerged people
  - Formula derivation
  - Flume experiments following similarity laws
  - Parameter determination and formula validation
  - Estimation of incipient velocity for prototype people

Formula Derivation

- 186 tests undertaken in China using 1:5.54 scale models
- Different forces acting on partially submerged person



F_G : Effective weight

F_D: Drag force

F_b: Buoyancy force

F_N : Normal force

F_R: Frictional force

Critical condition for toppling instability, given by moment around pivot point O :

$$F_{Gy}L_{gy} + F_{Gx}L_{gx} - F_D L_d = 0$$

Giving for velocity v. depth:-:

$$U = \alpha\left(\frac{h_f}{h_p}\right)^{\beta}\sqrt{\frac{m_p}{h_f^2\rho_f}\left(\cos\theta + \gamma\sin\theta\right) - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p}\right)\left(a_2 m_p + b_2\right)}$$

where: α, γ = coefficients (see paper), m_p = body mass,
h_p = body height, h_f = flow depth,
a_1, a_2, b_1, b_2 = body shape coefficients

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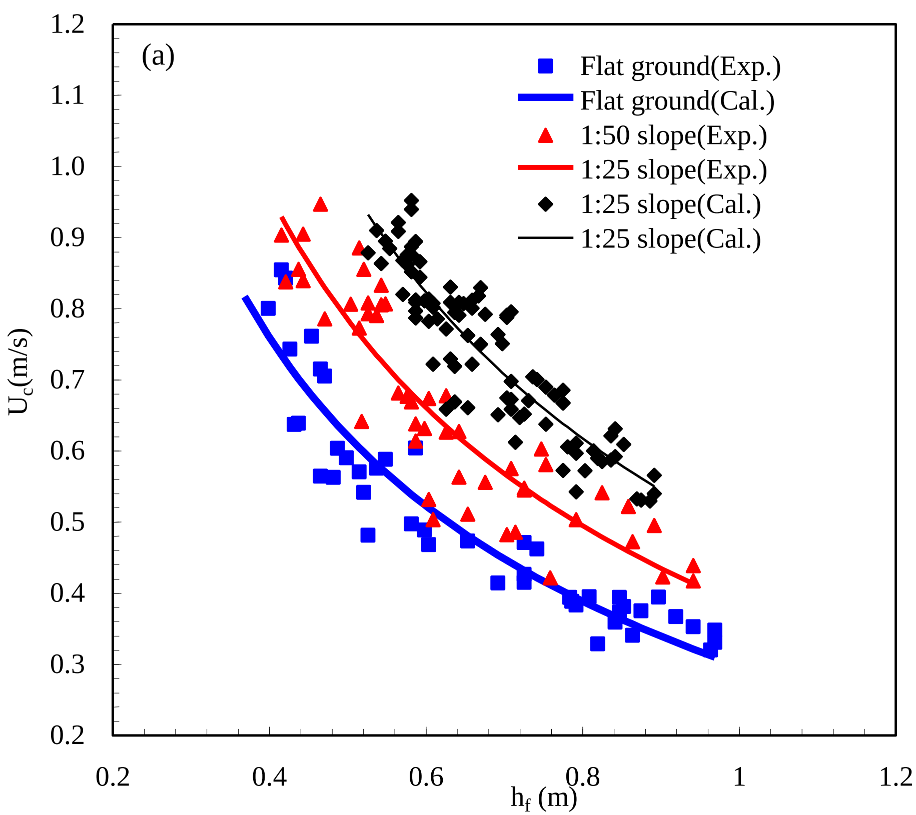
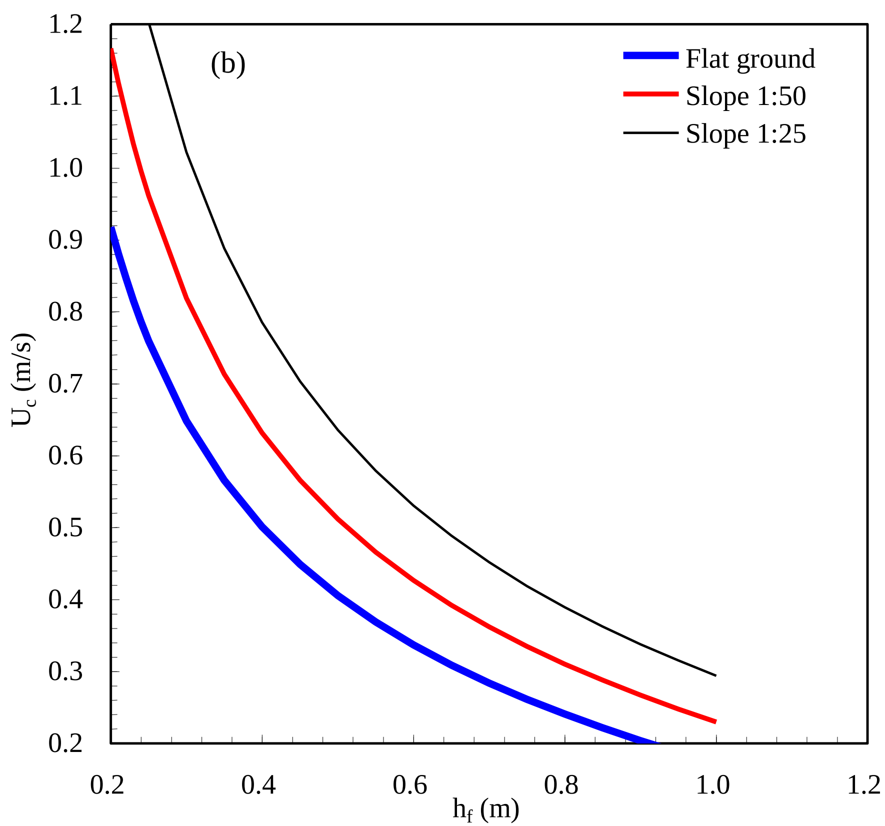
- # Scaled Incipient Velocity vs. Depth



Adult



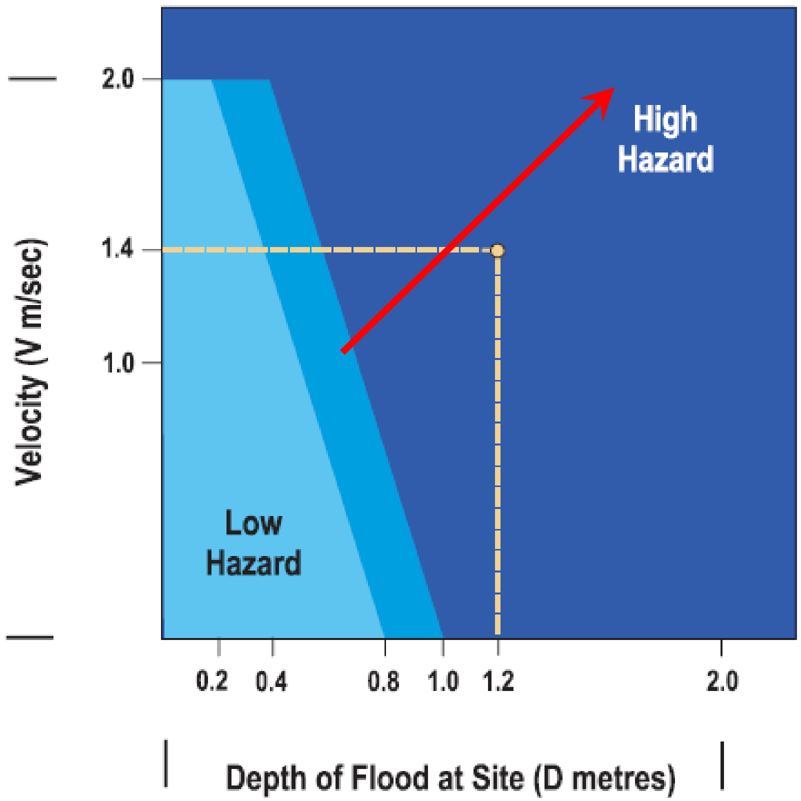
Child

• Empirical or Semi-quantitative Criteria

Defra (2003) in UK use simple method to assess flood hazard based on velocity, depth and debris:

$$\boxed{HR = h \times (U + 1.5) + DF}$$

HR = flood hazard rating;
H = depth of flooding (m);
U = velocity of floodwaters (m/s);
DF = debris factor (= 0, 1, 2 varies with probability that debris will lead to greater hazard)



• Determination of Hazard Degree

Incipient velocity formula from our studies used to assess vehicle and people safety

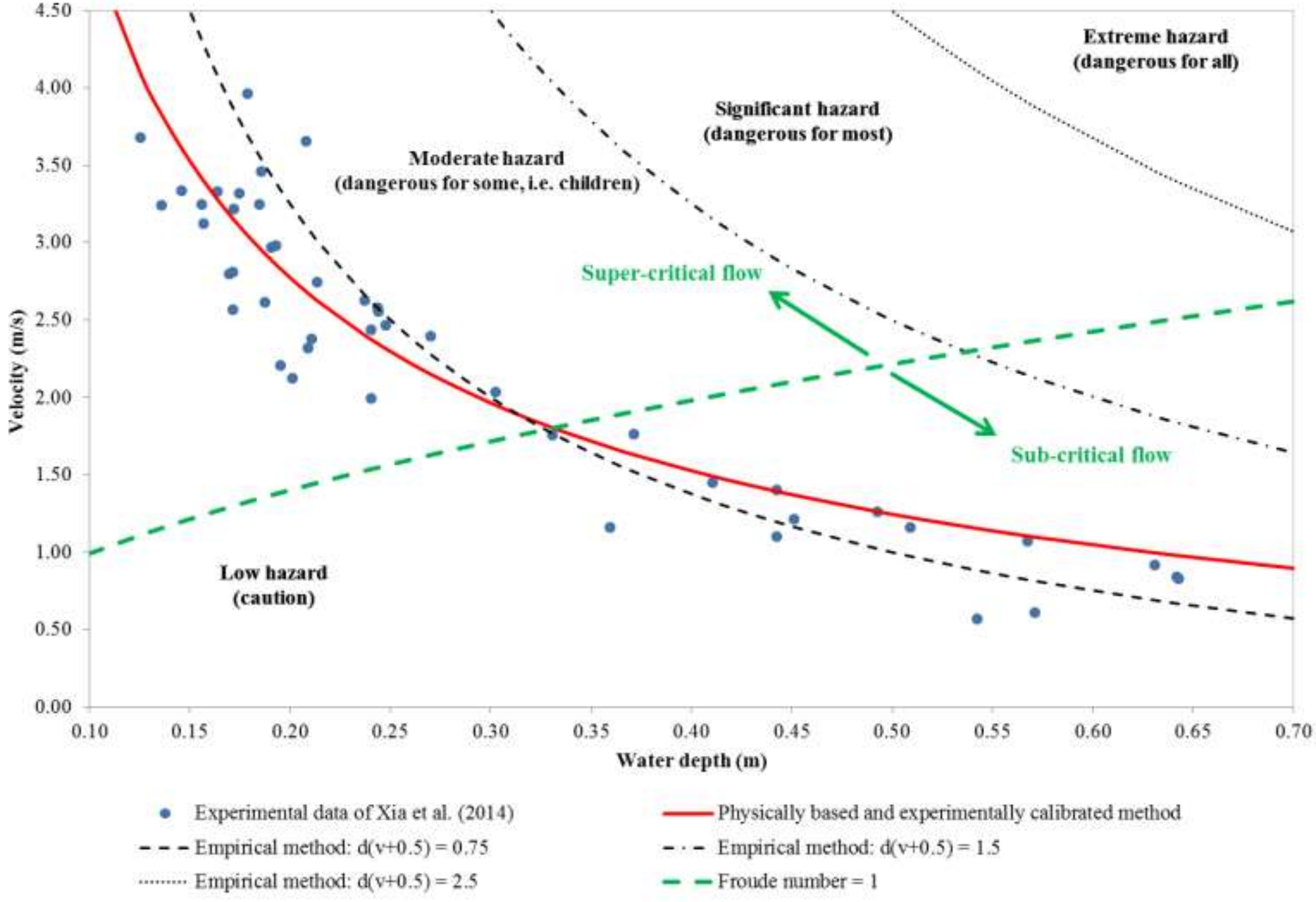
Expression used to determine degree of hazard:-

$$\boxed{HD=Min(1.0, U/Uc)}$$

U = depth-averaged velocity in a cell (m/s);
h = flow depth in a cell (m);
Uc = critical velocity for depth (h) ⇨ for vehicle or people(m/s);
HD = Hazard degree for vehicle or people in floodwaters

Safe if HD=0, Dangerous if HD =1.0

- # Comparison of Hazard Formulae

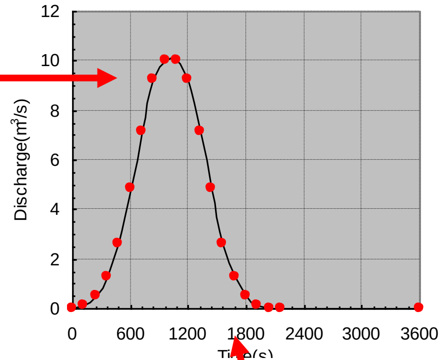


- Model Application

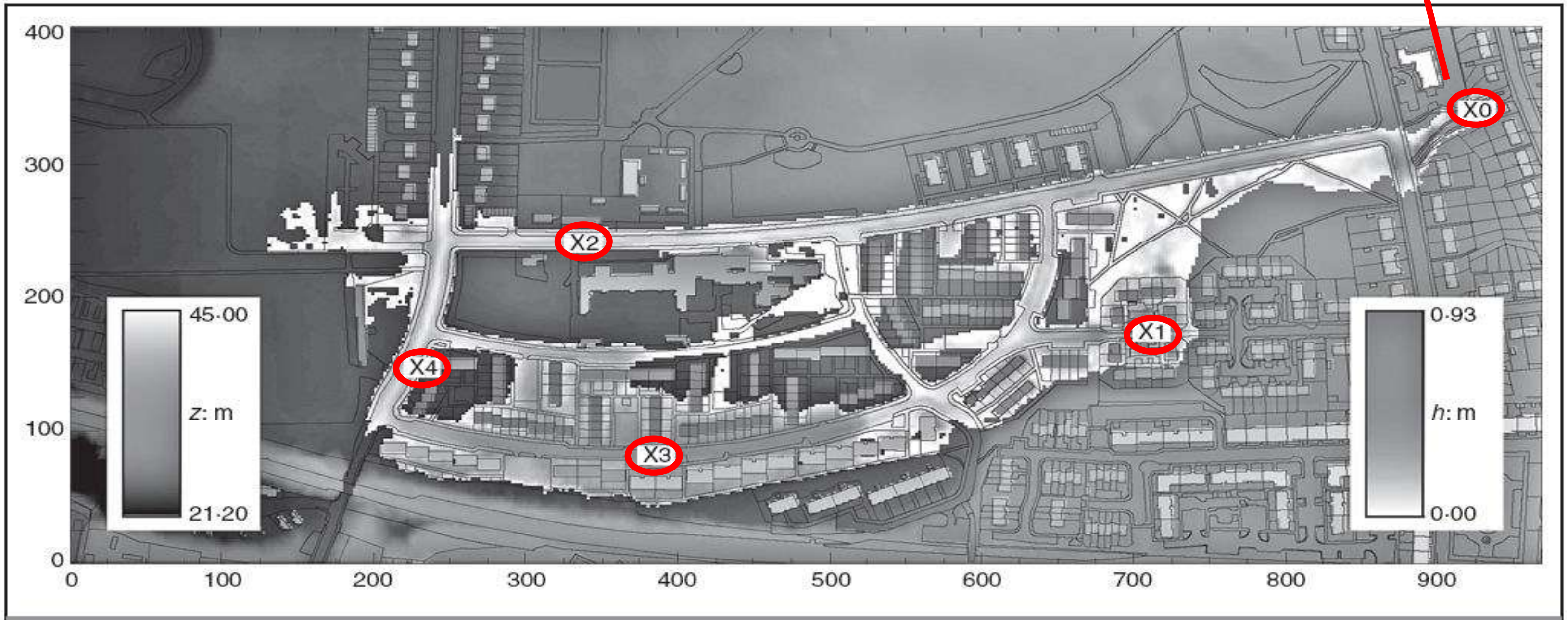
1. Glasgow flood in the UK
2. Boscastle flood in the UK

- Glasgow

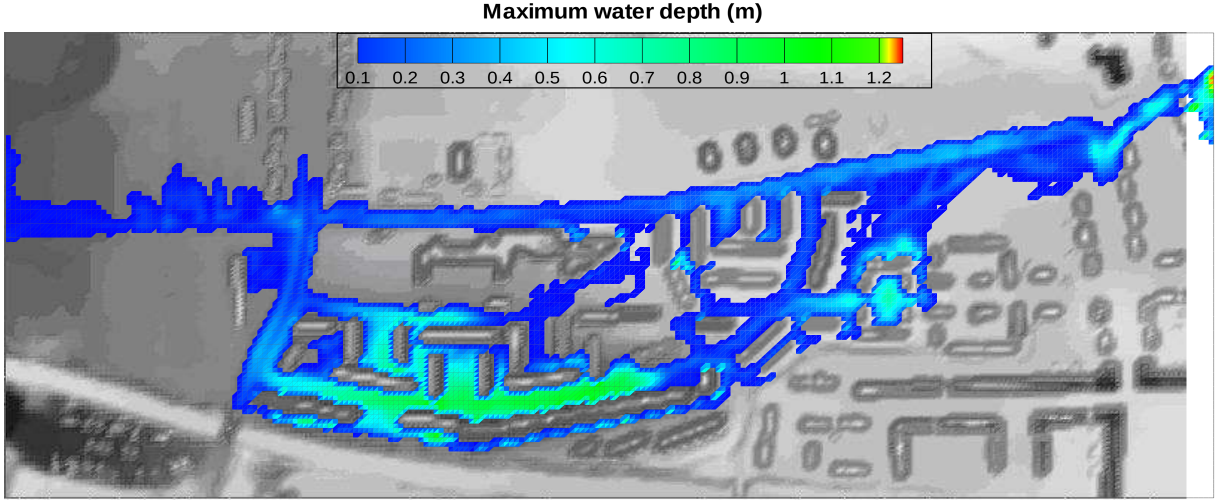
Qmax=10 m³/s



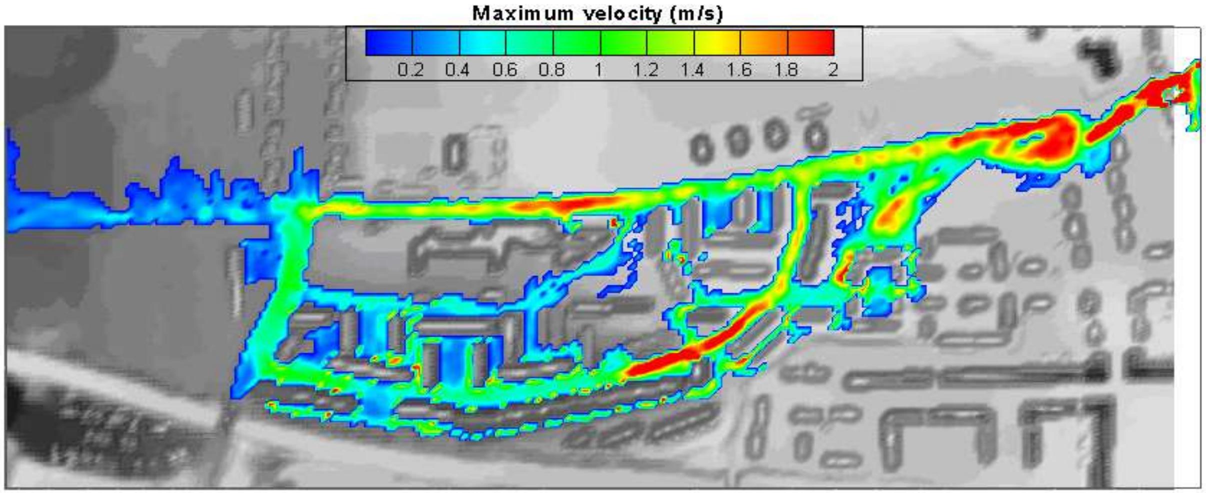
Point X0 = Inflowing location
Points X1-X4= Comparison sites



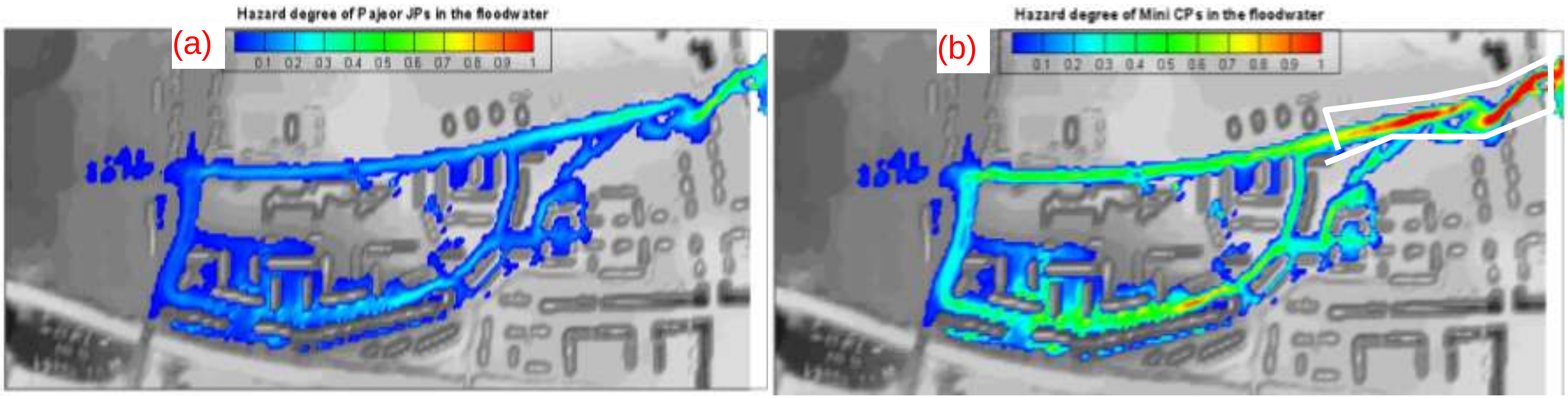
Map of a small urban area in Glasgow



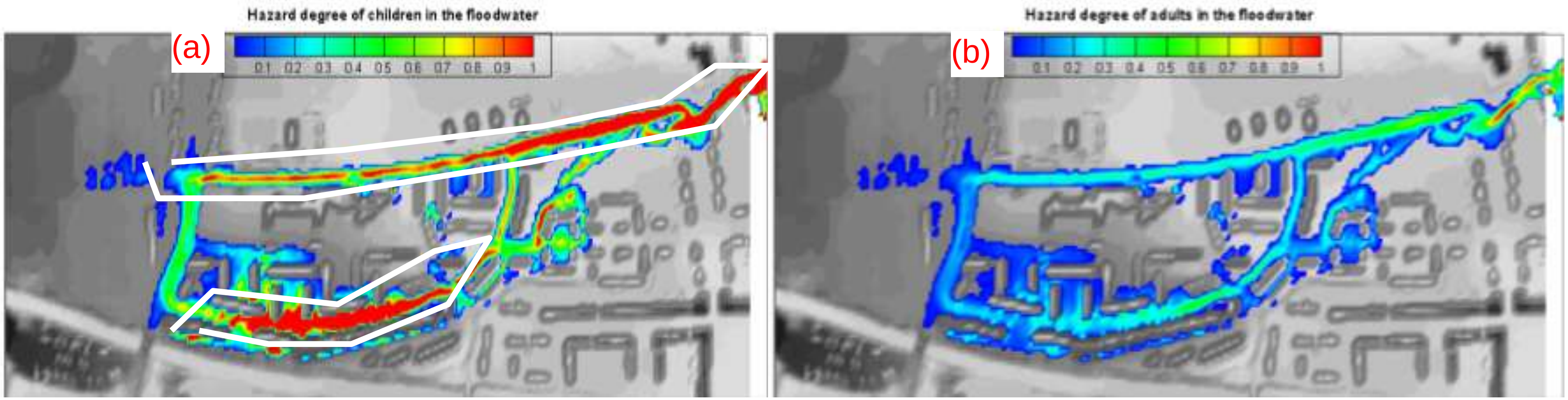
Predicted maximum water depth distribution



Predicted maximum velocity distribution



Distributions of hazard degree for vehicles: (a) Pajero; (b) MiniCooper

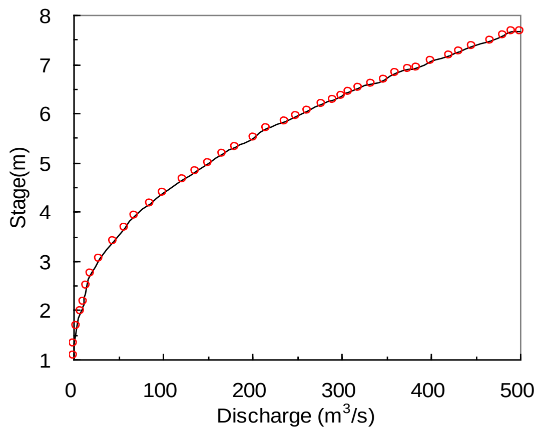


Distributions of hazard degree for people: (a) Children; (b) Adults

Boscastle Flood

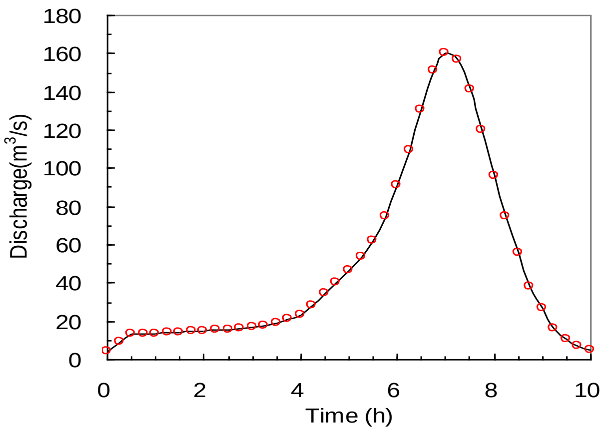
- Water depths on streets over 2 m, with high velocities transporting debris and cars
- Over 100 vehicles washed away, but no fatalities

Rating curve



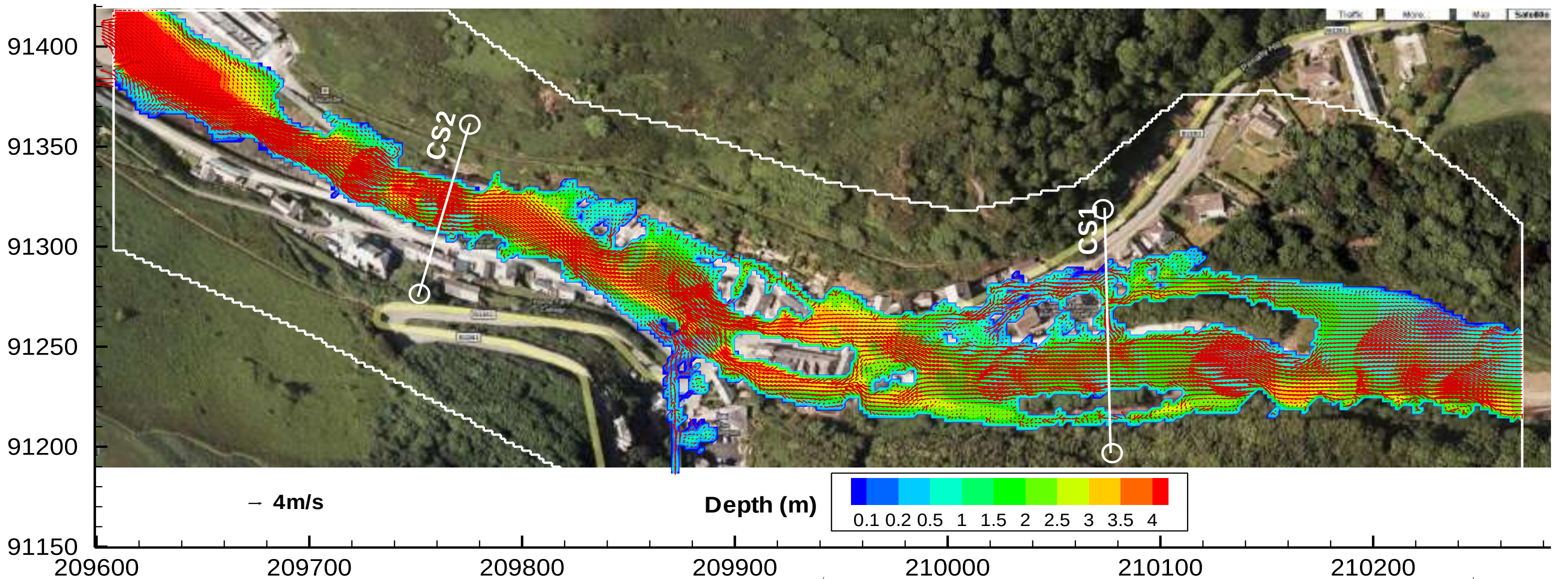
Flood Frequency
0.25%=400 Years

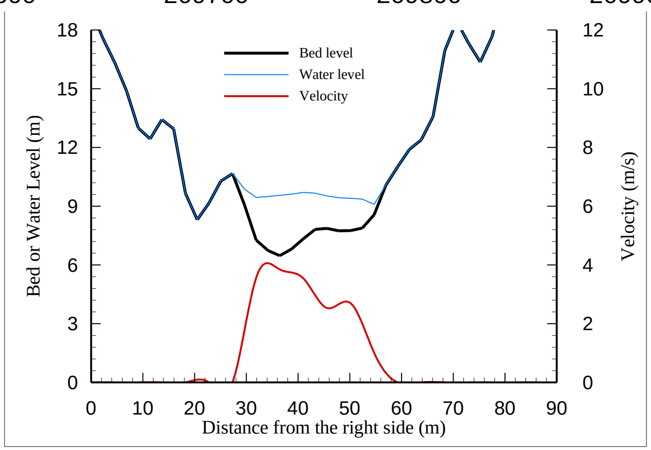
Discharge hydrograph



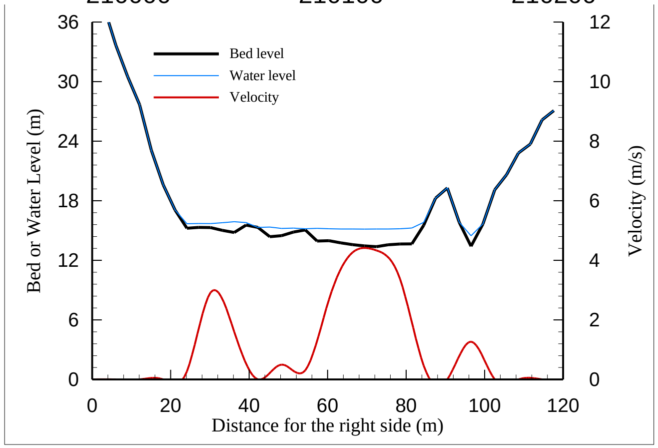
Domain showing upstream and downstream boundaries

Distribution of water depth and velocity at Q_{pk}

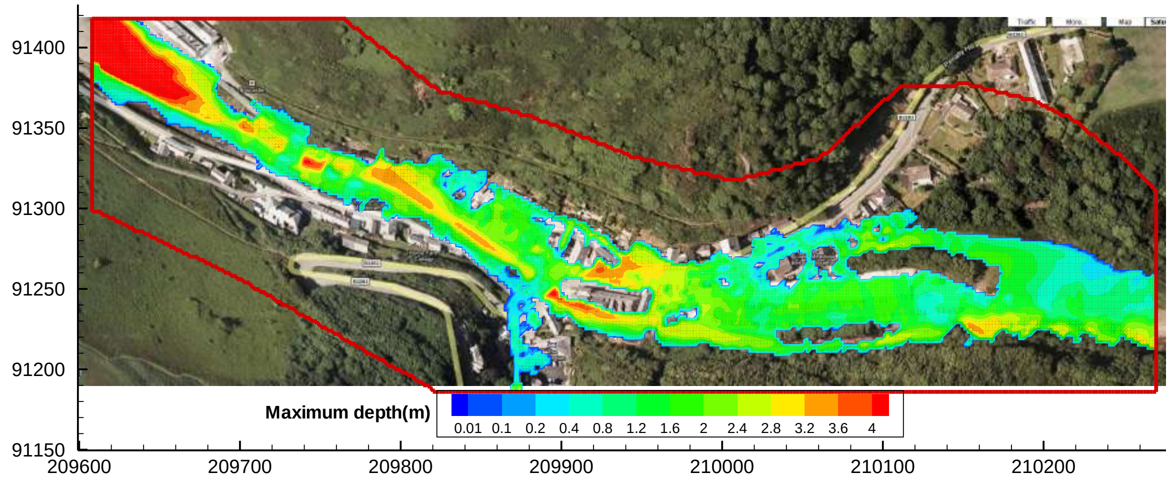




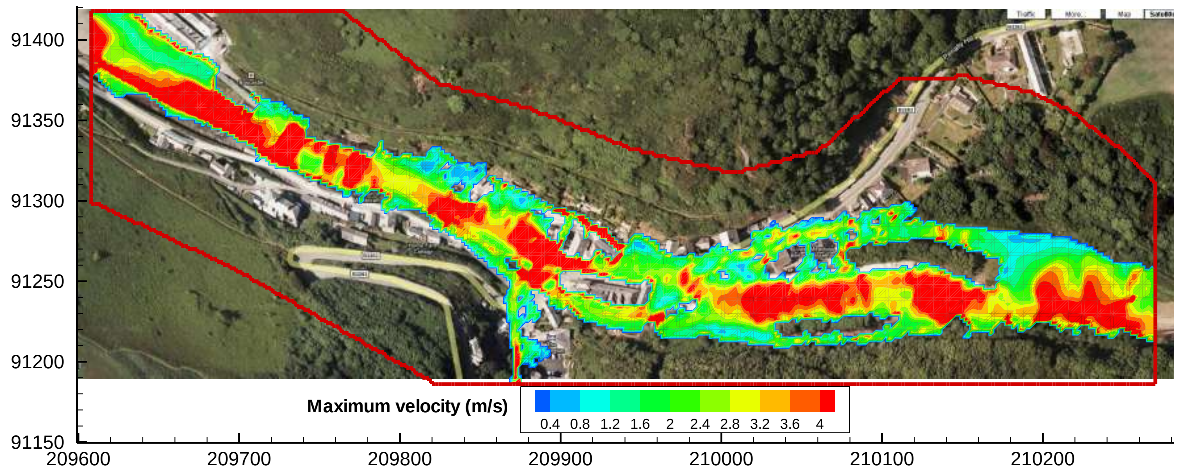
CS2



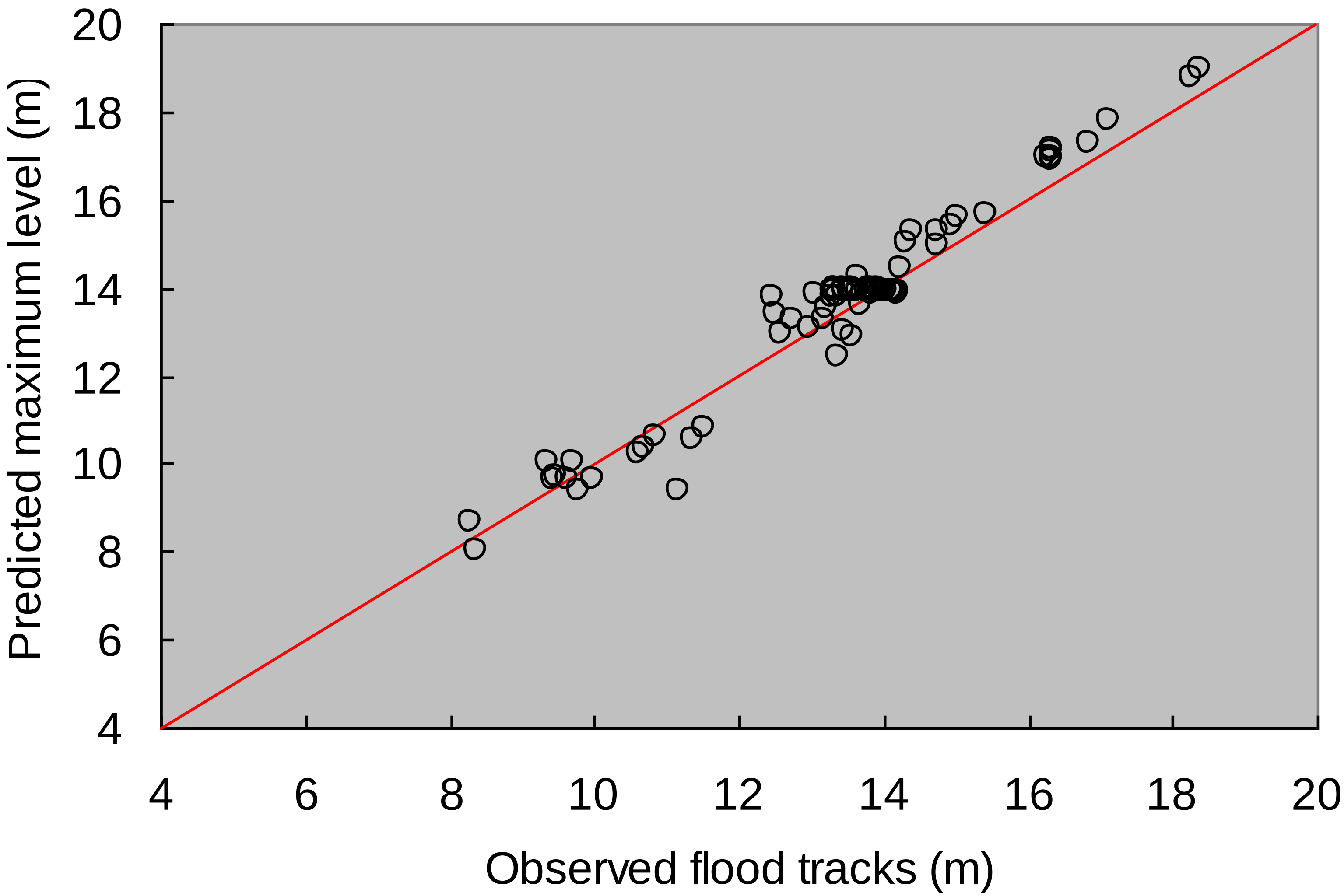
CS1



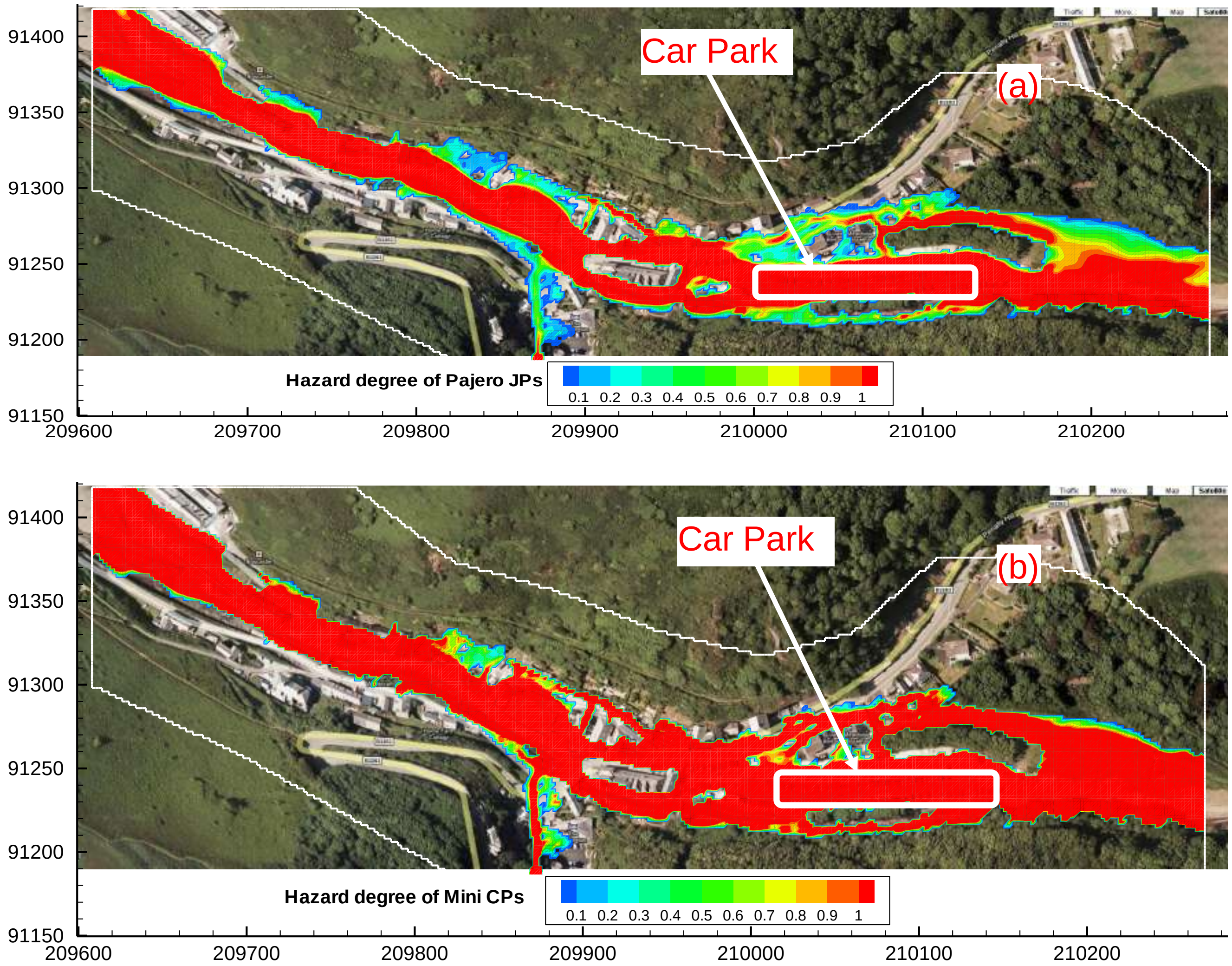
Maximum water depth



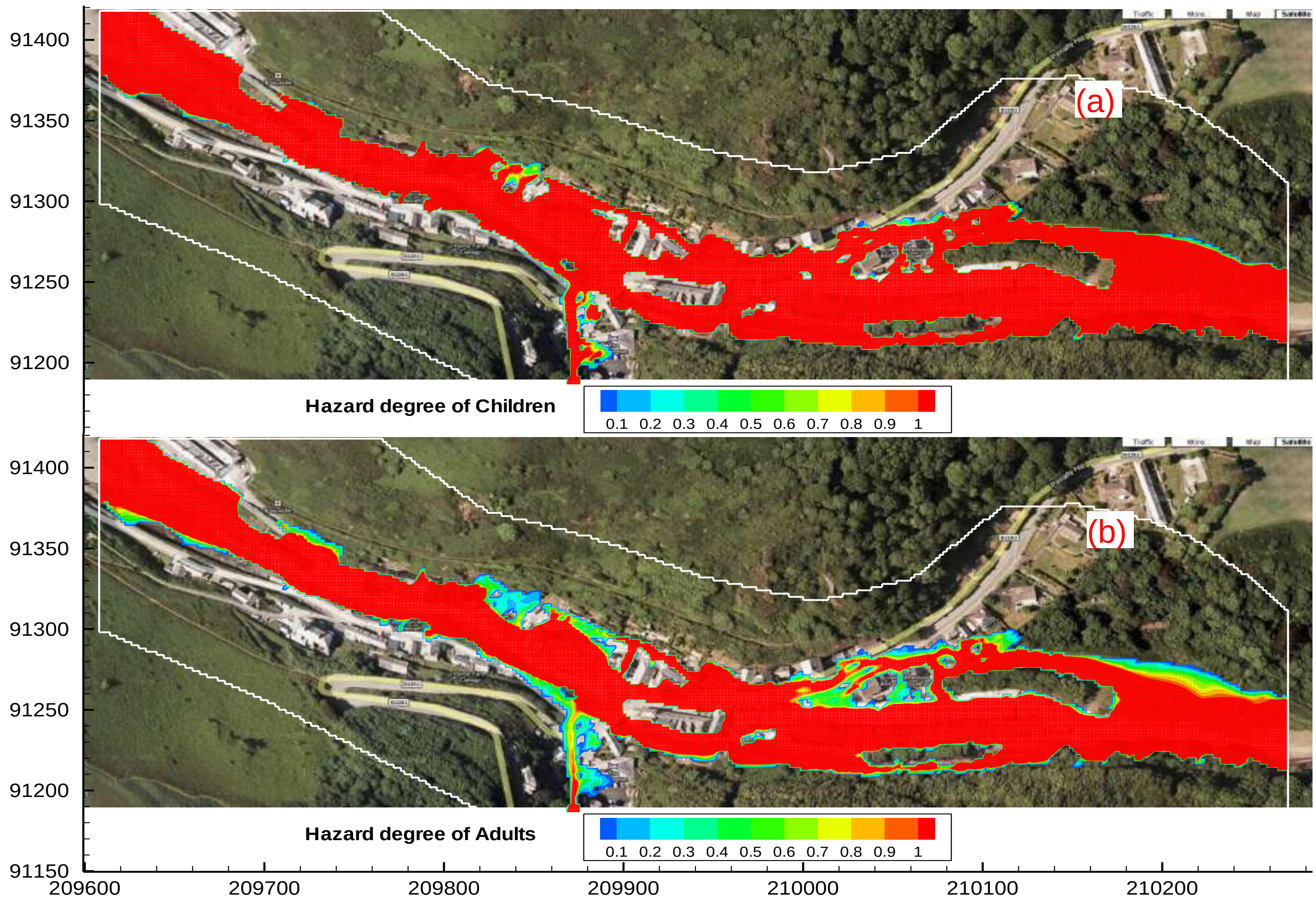
Maximum velocity



Comparison between predicted peak levels and flood tracks



Hazard degree for vehicles: (a) Pajero; (b) MiniCooper



Hazard degree for people: (a) Children; (b) Adults

• Conclusions

- Accurate modelling of flooding in steep catchments and levee breaches requires shock capturing models and DIVAST-TVD provides engine for Flood Modeller Pro
- Novel treatment of buildings using high roughness or low porosity and Darcy flow attractive for modelling floods
- New formulae developed for critical velocity of vehicles and people under flood conditions
- New formulae developed for flood hazard risk ⇨ based on fundamental physics vis-à-vis empirical formulae
- Models tested successfully for two sites predicting hazard levels for people and vehicles ⇨ new algorithms provided

Thank You

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