Modelling Extreme Flood Events and Associated Processes

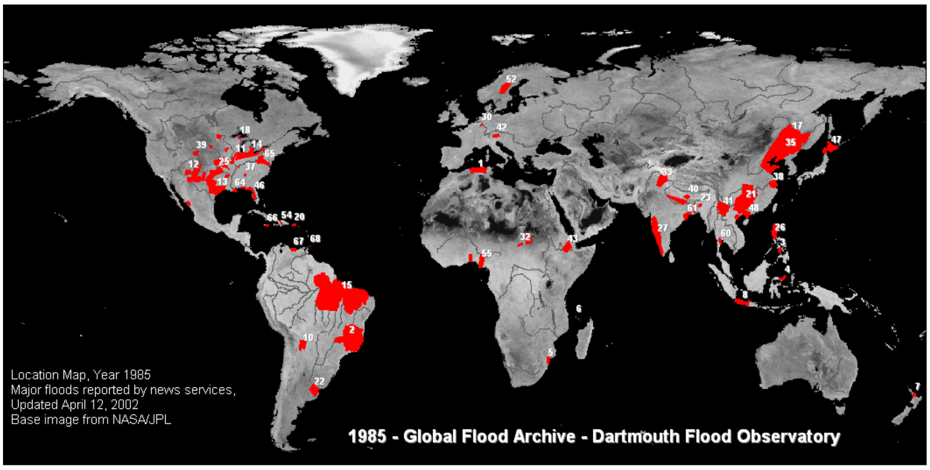
Roger A. Falconer
Professor of Water Management
Past President of IAHR (2011-15)

Hydro-environmental Research Centre (HRC)
School of Engineering, Cardiff University

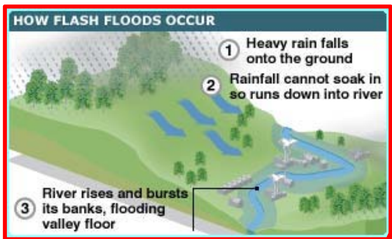
General

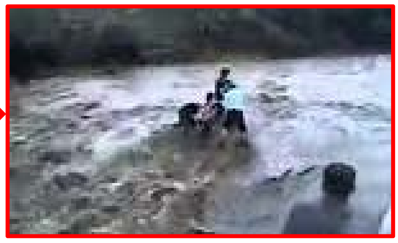
- Flooding essentially a natural process ⇨ need to adapt to climate change and build flood resilience
- Flooding caused by high rainfall ⇨ exacerbated by poor drainage, groundwater saturation, debris etc.
- Flooding leads to water pollution ⇨ often causing significant loss of life due to water-borne diseases
- Flood impact often inadequately predicted due to:
  - Inadequate data and warning systems ⇨ poor planning
  - Inadequate defences and/or insufficient upland storage
  - Inappropriate modelling tools ⇨ non-specialist users

Floods on the Rise



Flash Floods ⇨ Hazard and Contamination





Safety of People

Water Contamination

Stability of Vehicles

Cumbria Floods 2016 ⇨ Short Steep Rivers

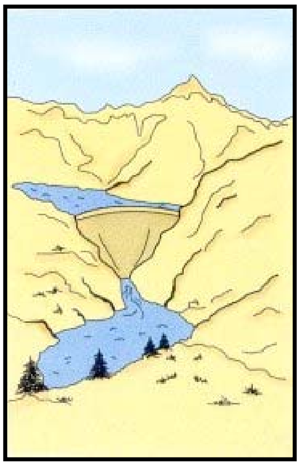
Somerset Levels 2014 ⇨ Mild Slope Rivers

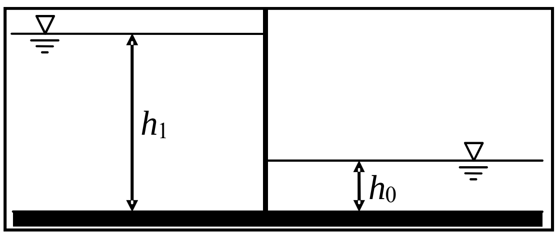
Drivers of Research Needs for Steep Rivers

- Concern about non-specialist hydraulic modellers with limited expertise using complex CFD tools
- Increasing concern about flood model accuracy for steep river basins & levee breaches ⇨ e.g. Wales
- Traditional 2-D/1-D models not ideal for such flows ⇨ need refining for trans- and supercritical flows
- Models refined to include:- (i) surface/sub-surface flow interactions, (ii) treatment of buildings in urban sites, (iii) hazard risk to people & vehicles in floods

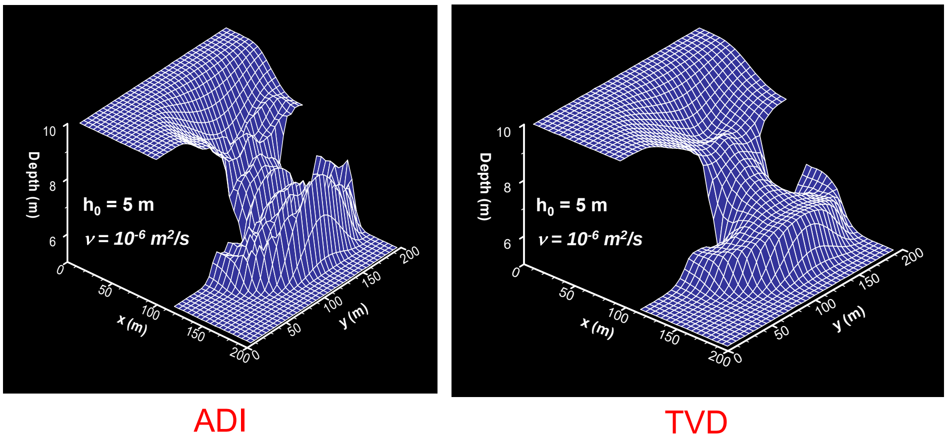
2-D Models ⇨ ADI v. TVD (Shock Capture)

- Dam-Break Problem



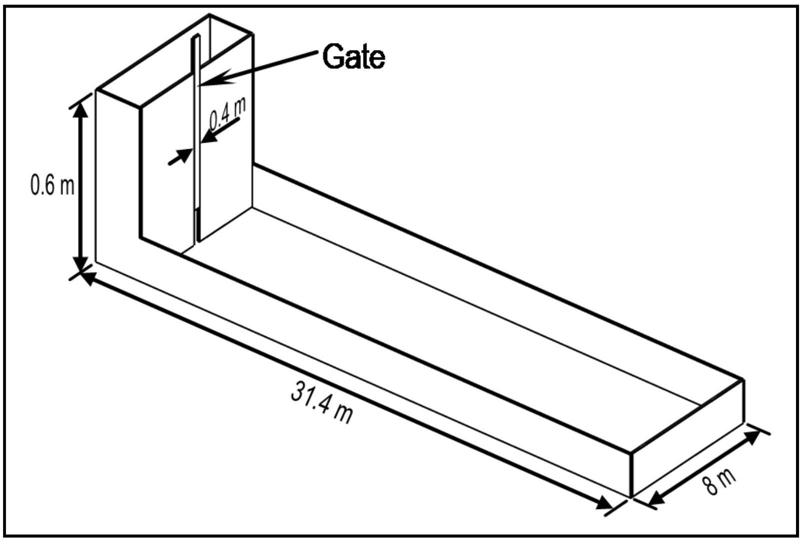


2-D Models: ADI v TVD (Shock Capturing)

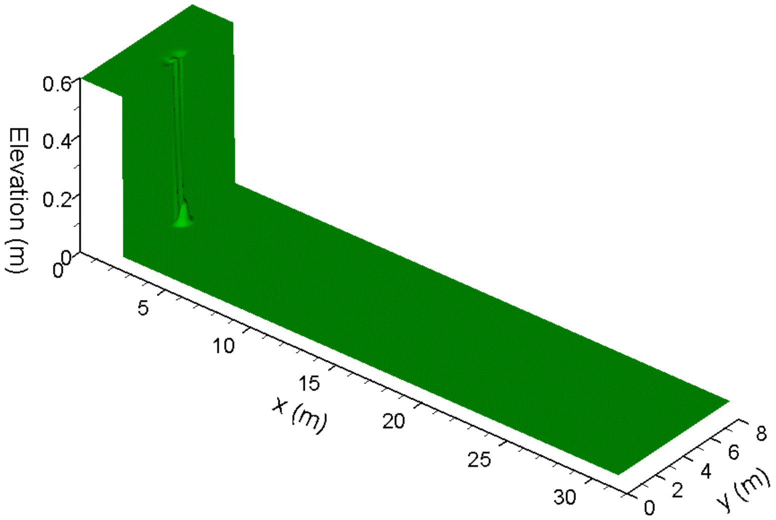


Need increased dissipation to remove oscillations for ADI Scheme and high Froude number flows

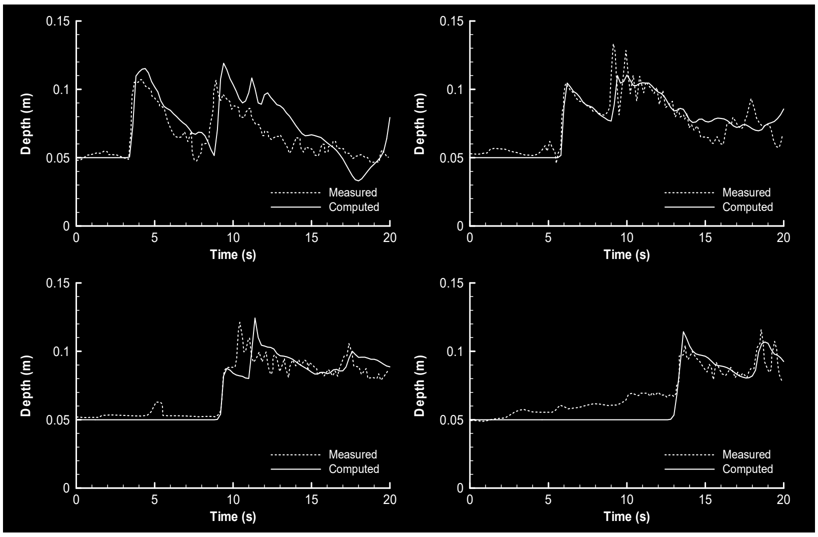
Dyke Break Experiment (TU Delft)



Dyke Break Experiment



Dyke Break Experiment ⇨ TVD Results



Boscastle Flood 2004 ⇨ Short Steep River

- Small picturesque town in South West of UK
- Short river basin with steep valley terrain ⇨ similar to many river basins across UK and world-wide
- Up to 200 mm rainfall fell in 5 hr and predicted to be 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

View of River Valency ⇨ Normal Flow

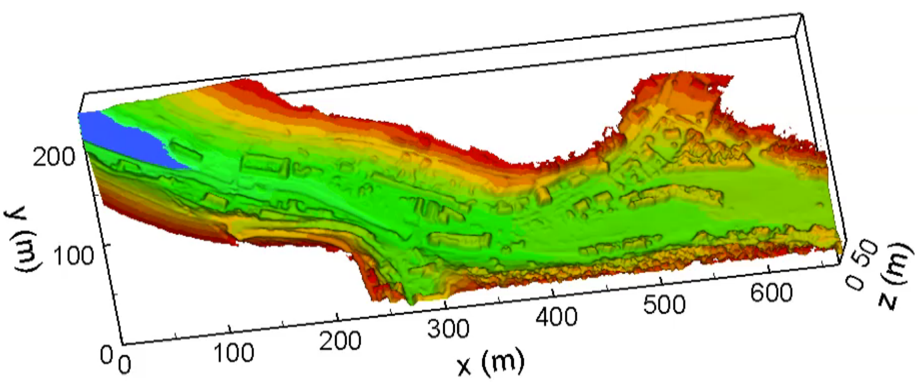
Boscastle During 2004 Flood

Model Study Objectives

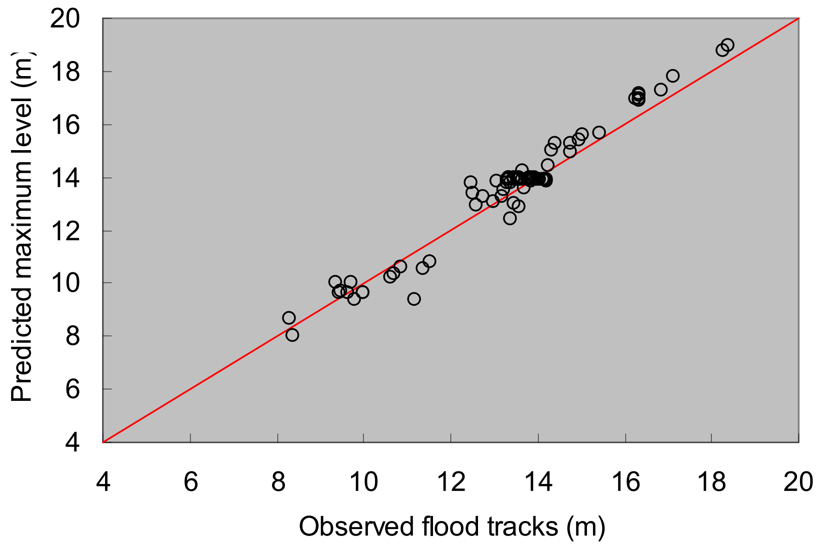
- Determine model type most accurate for predicting key hydraulic parameters for extreme flood events
- Three different schemes compared:
  - TVD MacCormack (i.e. with shock capturing)
  - MacCormack (i.e. without shock capturing)
  - Simple Inertia (i.e. without inertia – kinematic wave)
- Case studied: 2004 Boscastle flash flood
- Predicted main flood parameters (elevations and inundation extent) compared with wrack marks

Boscastle Study Domain

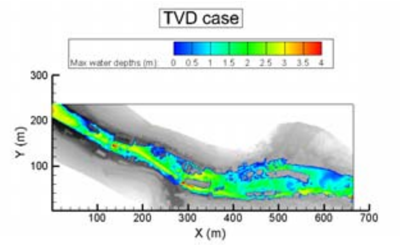
Predicted Flood Simulation (TVD Scheme)

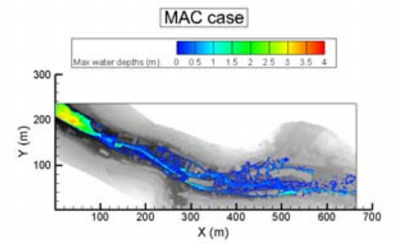


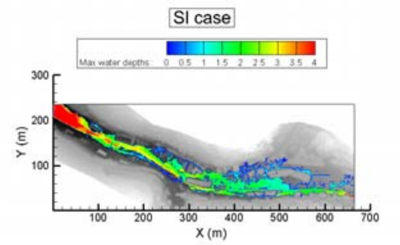
Comparison of TVD Levels & Wrack Marks



Flood Elevation Predictions







Model configuration	Nash – Sutcliff model efficiency
TVD case	0.9863
MAC case	0.8530
SI case	0.8684

Comparisons with wrack mark data

Very different peak elevations and inundation extents

Borth Flood Wales (2012)

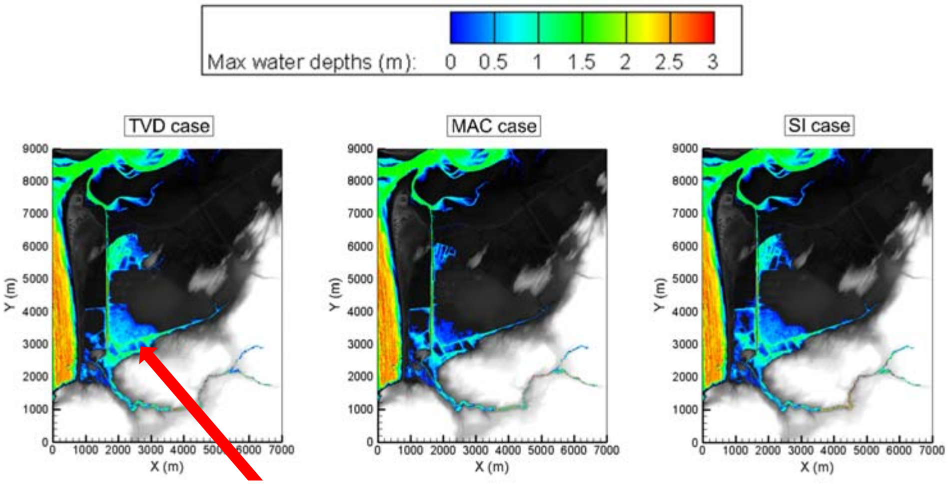
River Leri Flash Flood (2012)

Borth Study Domain and Depth Monitoring

Depth Monitoring Points at:-

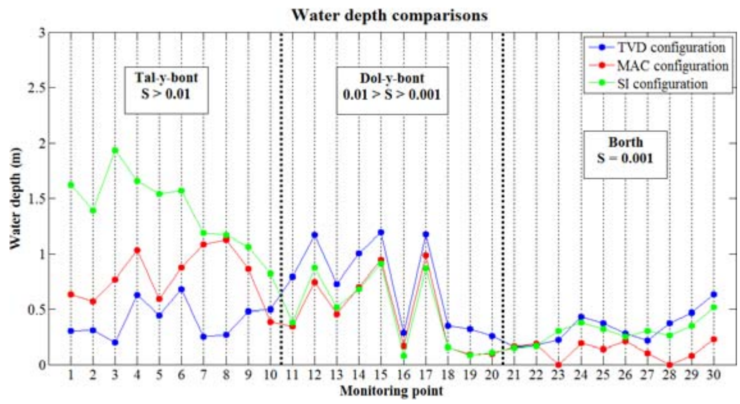
- Talybont (10)
- Borth (10)
- Dalybont (10)

Flood Inundation Extent Predictions



More extensive flooding
in location of caravan site

Depth Comparisons at Monitoring Points

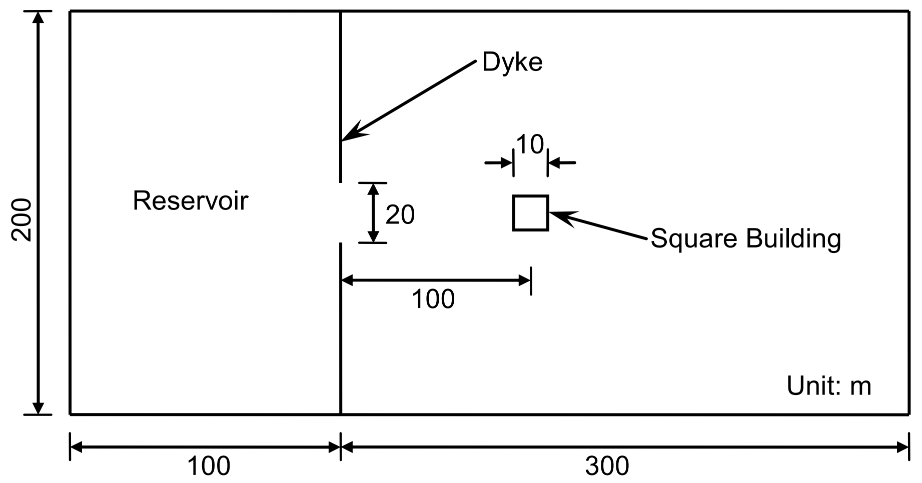


	Average difference in water depth prediction	
Bed slope	MAC vs TVD	SI vs TVD
S > 0.01	40.9 cm	99.0 cm
0.01 > S > 0.001	25.9 cm	26.2 cm
S ≈ 0.001	20.8 cm	6.6 cm

Refined Treatment of Buildings

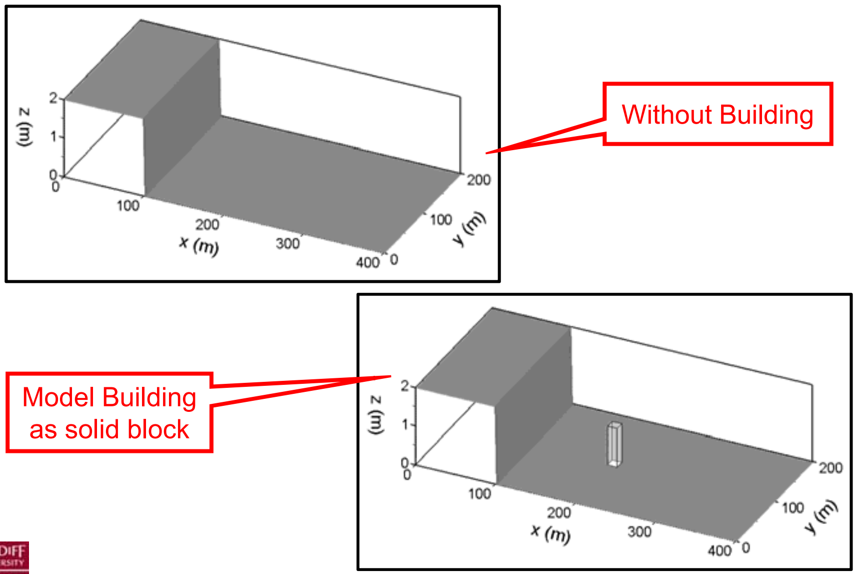
- Buildings in urban environments ⇨ difficult to treat in models to predict accurately key flood features, such as elevations and inundation extent
- Three modelling approaches considered:
  - Modelling buildings as solid blocks ⇨ making buildings impervious
  - Remove buildings and increase local roughness ⇨ not ideal for predicting water quality levels in buildings
  - Remove buildings and treat as porous media ⇨ better for predicting contaminant fluxes into buildings

Flood Interaction with Buildings

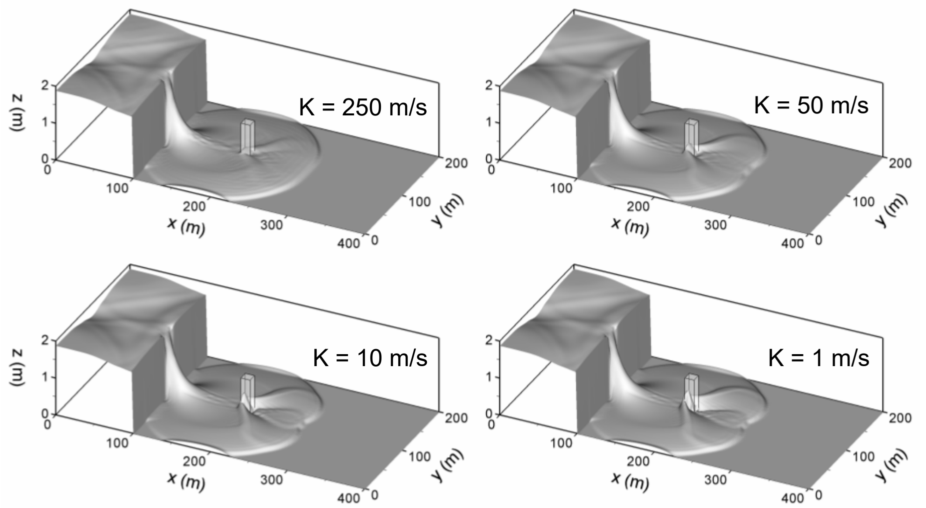


Manning's n = 0.015

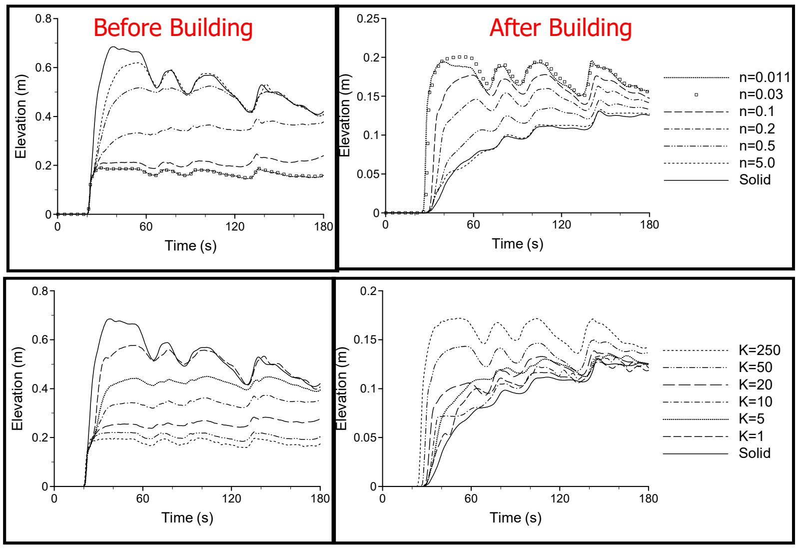
Flood Building Interaction 1 ⇨ Solid Building



Flood Building Interaction 3 ⇨ Porous Media

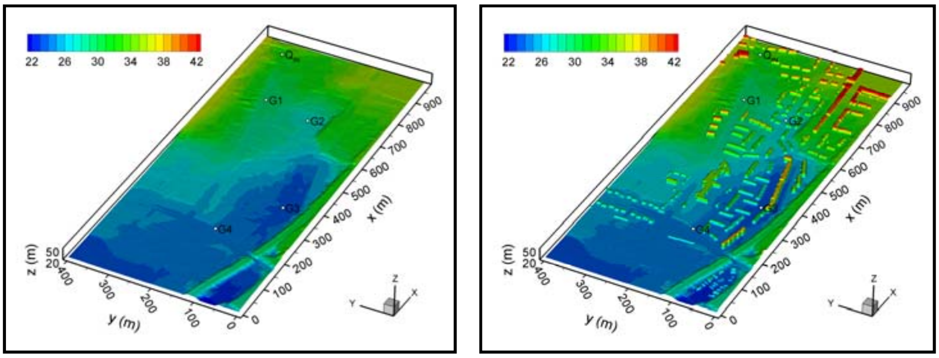


Flood Building Interaction ⇨ Water Levels



Flood Inundation of Glasgow

City in Scotland prone to urban flooding

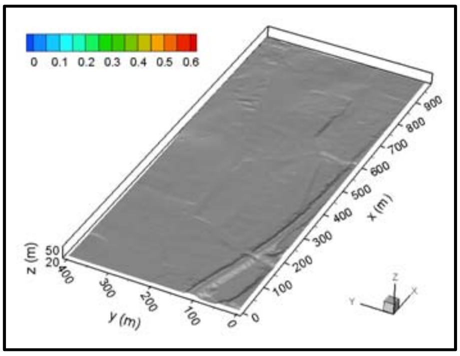


Without buildings

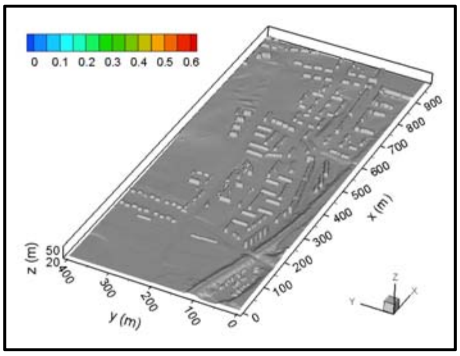
With buildings

Flood Inundation of Glasgow

Porous media and solid block methods

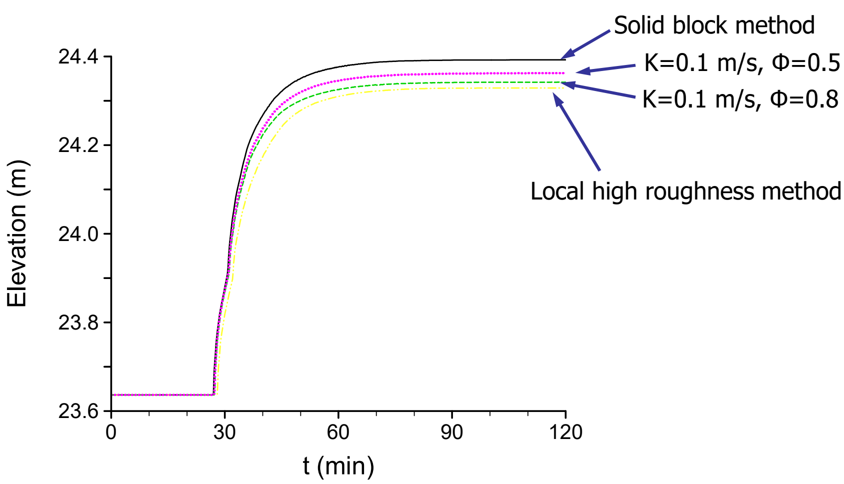


Without buildings



With buildings

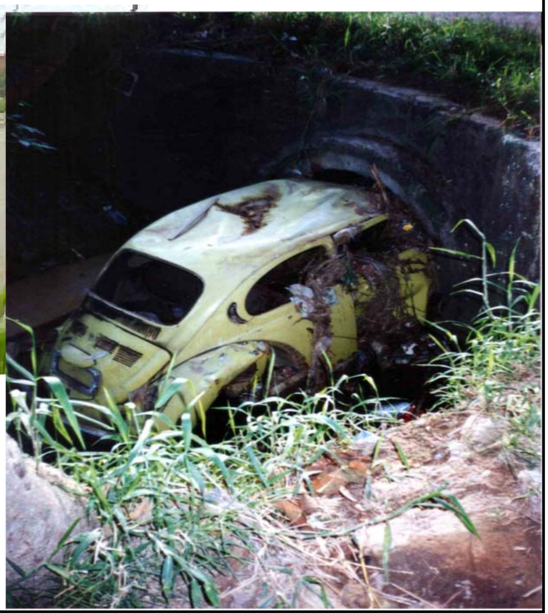
Interaction Between Flood and Buildings



Moving Vehicles ⇨ Can Exacerbate Floods

Wrong exit

Debris flow problem



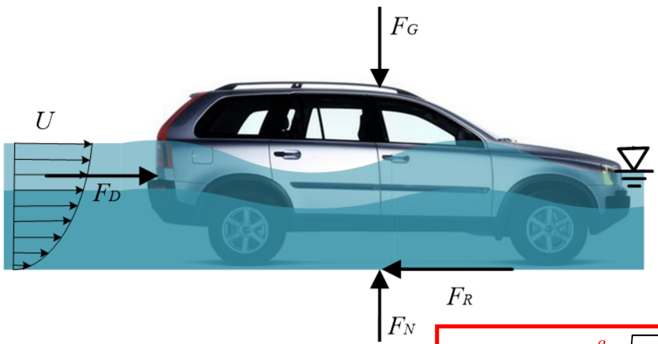
Emergency Services ⇨Affected by Floods

Incipient Velocity ⇨ Vehicles in Floodwaters

- Study first undertaken to determine incipient velocity for fully submerged vehicles
- Subsequent studies undertaken for partially submerged vehicles based on:
  - Formulae derived from fundamental hydrodynamics
  - Scaled flume experiments based on similarity laws
  - Parameter determination and formulae validation
  - Upscaling of incipient velocity for prototype vehicles

Physics Derived Formulation

- Different forces acting on a partially submerged vehicle



F_G : Effective weight
F_D: Drag force
F_N : Normal force
F_R: Frictional force

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

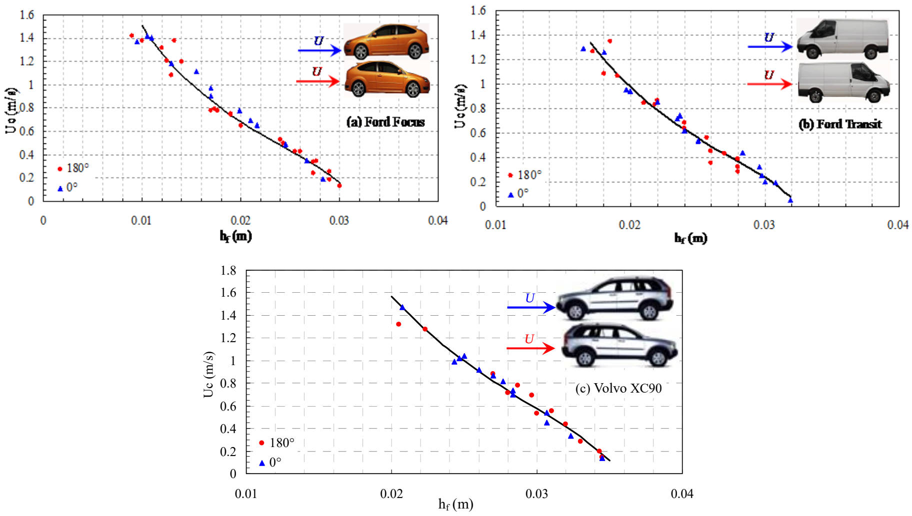
Flume Experiments for Vehicle Instability

- Experiments conducted in HRC flume: 15 m long, 1.2 m wide, 1.0 m deep, plastic bed, glass sides
- Critical conditions estimated for prototype vehicles ⇨ models scaled at 1:18 and 3 similarity laws

Experimental test flume

Partially submerged vehicle test

Depth-Incipient Velocity Relationships



Depth-incipient velocity relationships for partially submerged vehicles

Incipient Velocity ⇨ People in Floodwaters

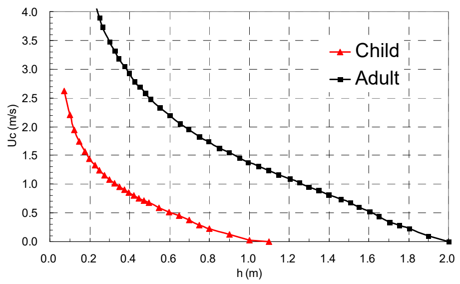
- Similar approach adopted to previous study on incipient velocity for vehicles
- Recent studies for partially submerged human bodies based on:
  - Formulae derived from fundamental hydrodynamics
  - Flume experiments based on similarity scaling laws
  - Parameter determination and formulae validation
  - Estimation of incipient velocity for prototype bodies

Incipient Velocity of People in Floodwaters

- Keller & Mitsch (1992) balanced forces acting on a flooded body:- buoyancy, weight, frictional resistance and drag:-

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

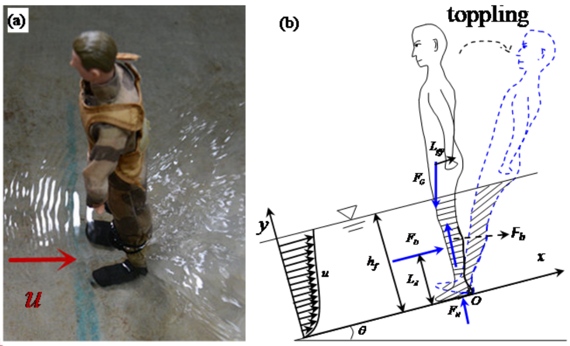
F_r = restoring friction force
A = submerged flow area
C_d = drag coefficient



Instability curves for child and adult in floodwaters

Collaborative Experimental Model Studies

- 186 tests on 1:5.5 scale models undertaken at Wuhan University, China
- Forces analysed on partially submerged body



F_G : Effective weight

F_D: Drag force

F_b: Buoyancy force

F_N : Normal force

F_R: Frictional force

Hydrodynamics Based Formulations

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

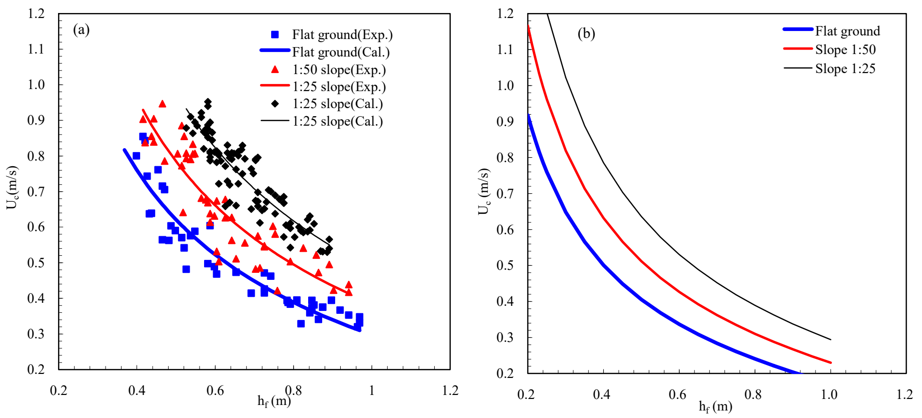
$$F_{Gy}L_{gy} + F_{Gx}L_{gx} - F_D L_d = 0$$

Giving for velocity v. depth:-:

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

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

Scaled Incipient Velocity vs. Depth



Adult

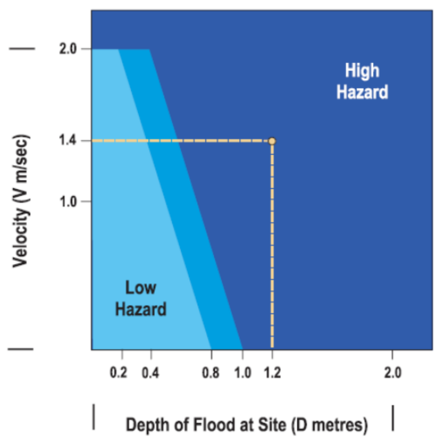
Child

Empirical or Semi-Quantitative Criteria

UK ⇨ widely used hazard risk assessment method based on velocity, depth and debris factor:

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

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



Determination of Hazard Risk

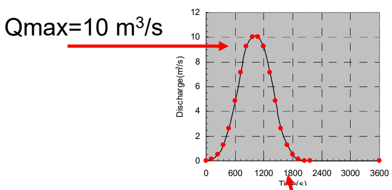
- Incipient velocity formula from current studies used to assess vehicle and people safety
- Expression used to determine degree of hazard:-

$$HR = \mathrm{Min}(1.0,\ U/U_c)$$

U = depth-averaged velocity in a cell (m/s);
h = flow depth in a cell (m);
U_c = critical velocity for vehicles or people (m/s);
HR = Hazard risk for vehicles and/or people in floods

Safe: if HR = 0, Dangerous: if HR = 1.0

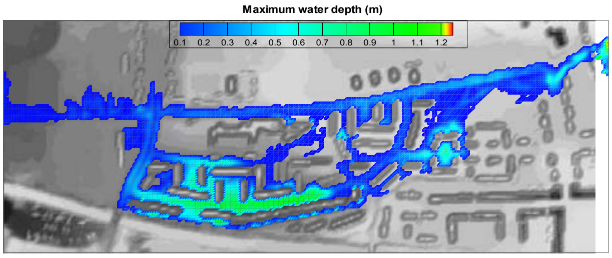
Application ⇨ Urban Flooding in Glasgow



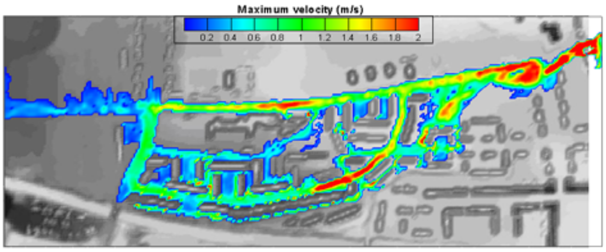
Point X0 = Inflowing location
Points X1-X4= Comparison sites

Map of a small urban area in Glasgow

Predicted Peak Water Depths & Velocities

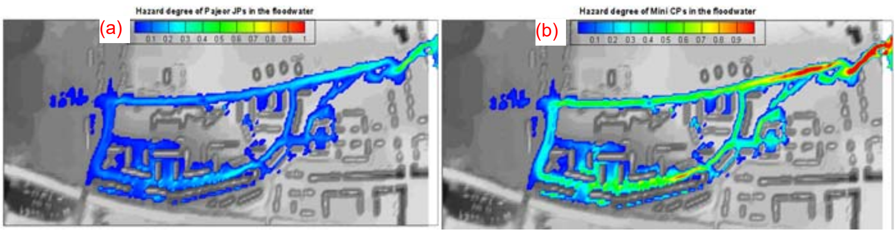


Predicted maximum water depth distribution

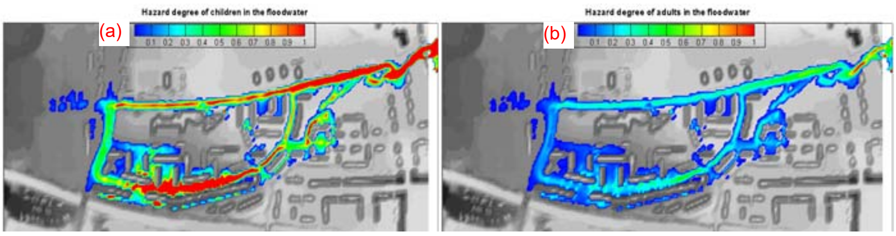


Predicted maximum velocity distribution

Predicted Hazard Risk ⇨ Vehicles & People



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



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

Conclusions

- Accurate modelling of flooding in steep river basins requires shock capturing (or similar) algorithms
- Treatment of buildings using Darcy's equation with low porosity ⇨ predict pollutant levels in buildings
- New formulae developed to predict critical velocity & depth for people & vehicle safety in floodwaters
- New formulae developed for flood hazard risk ⇨ based on hydrodynamics & experimental data
- Scope for IAHR to engage more with practitioners ⇨ providing CPD for flood risk modelling etc.

Thank You

Professor Roger. A. Falconer
E: FalconerRA@cardiff.ac.uk
www.rogerfalconer.com