Multi-scale hydrodynamic modelling of flood risk: a non-calibrated approach applied to cities and river basins

Chris Kilsby

Vassilis Glenis, Robert Bertsch, Fergus McClean, Steve Birkinshaw and many others...

School of Engineering
Newcastle University

Overview

- Background and motivation
  - Calibration, validation
  - Model de-composition – do we need to?
  - How far can we get with hydrodynamics ?
- The CityCAT approach
  - Hydrodynamics: pipes : buildings : soils : etc.
  - Validation - not calibration
- Applications to cities
- Applications to large catchments
- Conclusions, further work and all that stuff

Calibration is evil!

A **physical basis** should always be used …

- atmospheric scientists (generally) do not calibrate – why should hydrologists?!

If **parametrisation** is needed: it should be **universal** not **individual**

- *hydrology*: catchment-by-catchment approach adjusts for (different) data errors
- *hydraulics*: calibrating *Mannings n* creates inadequate models and more (different) errors

Validation – should not be selective and partial

Use one big model?

Breaking the space domain down is dangerous: many hydrosystems have inter-dependencies and cannot be broken into sub-models, e.g.

- Large basins/continents: 100-year event requires space-time event set;
- Floods may have **fluvial** and **pluvial** components interacting at the receptor (city)
- Effect of flood storage/floodplains cascades downstream

NB – domain decomposition using different grid resolution usually (always?) violates CFL conditions

Breaking the time domain down can be useful:

- **Continuous simulation** used to **update storage** conditions
- Detailed modelling only needed during **flood events**

Some motivations and philosophy

1. Floods are important to study

Large scale risk management : river basins….

(Re)insurance : river basins + cities together

Urban design : cities - rainfall and rivers

Infrastructure : rivers, cities, defences, assets, transport…

And: increasingly useful to consider all these in combination

Some motivations and philosophy

Newcastle University
UK | Malaysia | Singapore

2. Saturated hydraulic processes dominate floods

- Simpler than unsaturated processes ("hydrology")!
- Relatively well understood and well modelled

Some motivations and philosophy

3. Modern computational power allows

- High resolution terrain and channels
- Accurate solutions of real world flows
- Large domains (and/or long time scales)

The proposal

- Physically-based flood modelling (zero or low-cal!)
- Building on hydrodynamic paradigms (for now!)
- Sufficient space-time resolution to represent physical processes without parameterisation

Accepting the high expense until :

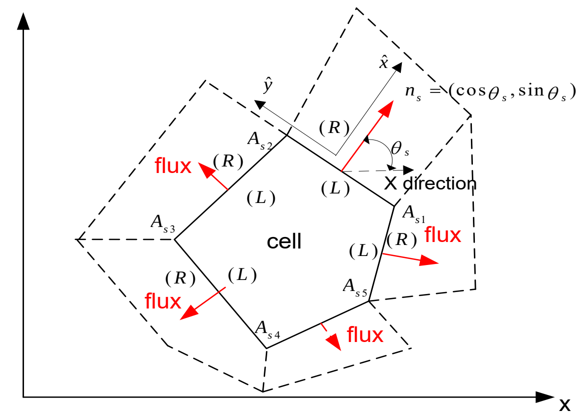
(a) computers get faster

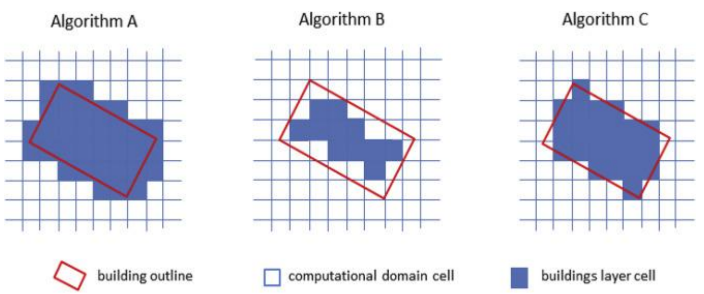
(b) we learn which approximations are good

The CityCAT model

City and Catchment Analysis Tool

- 2D hydrodynamic shock-capturing finite volume scheme (Osher-Solomon Riemann solver)
- Grid : 1m cities, 30m for basin
- Buildings and infrastructure explicitly represented
- Soil : Green-Ampt, vertical
- Fully coupled pipe network : pressurised/free surface/mixed phase





Glenis V, Kutija V, Kilsby CG. **A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions**. *Environmental Modelling & Software* 2018, **109**, 272-292.

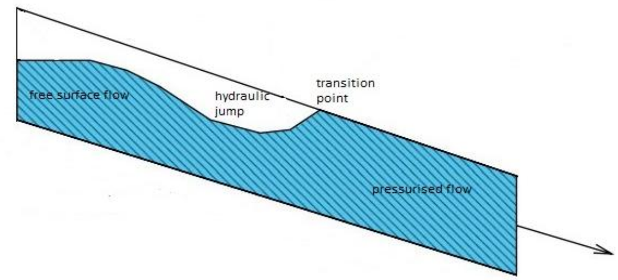
Unique CityCAT features

- All methods published
- Validated against lab, field and analytical test cases
- Small numerical dispersion – no need for calibration
- Rapid and automatic set up from standard data sets
- Sewer networks – full solution – NOT Preissman slot
- Accurate building treatment – NOT stubby or friction
- Runs on desktop or Cloud

Glenis V, Kutija V, Kilsby CG. A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions. *Environmental Modelling & Software* 2018, **109**, 272-292.

Unique CityCAT features: pipes

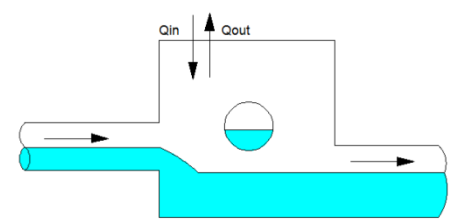
The model is based on the St Venant equations and a conservative form of the Alievi equations based on the compressible Euler equations :



$$\frac{\partial}{\partial t}\begin{bmatrix}\rho A\\ \rho Q\end{bmatrix} + \frac{\partial}{\partial x}\begin{bmatrix}\rho Q\\ \rho Q^2/A + Ap\end{bmatrix} = \begin{bmatrix}0\\ \rho g^{A}(So - Sf)\end{bmatrix}$$

Where: ρ is density, Q is discharge, A is cross sectional area, p is pressure, So is slope, Sf is the friction term

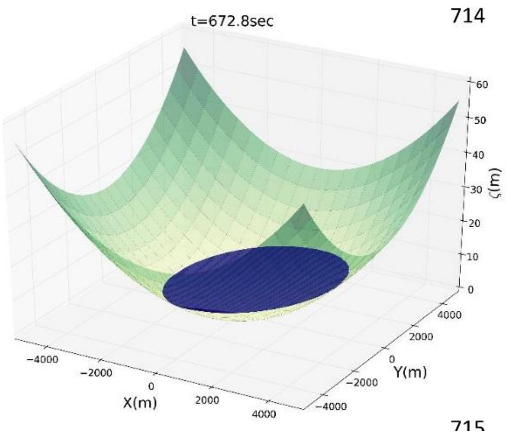
New Riemann solvers have been developed which can handle free surface, pressurised and mixed flows. Non-linear systems are solved with robust **iterative solvers**.

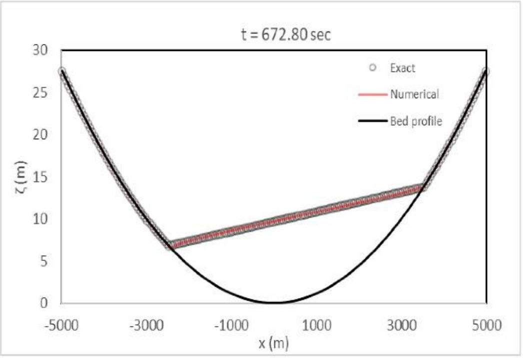


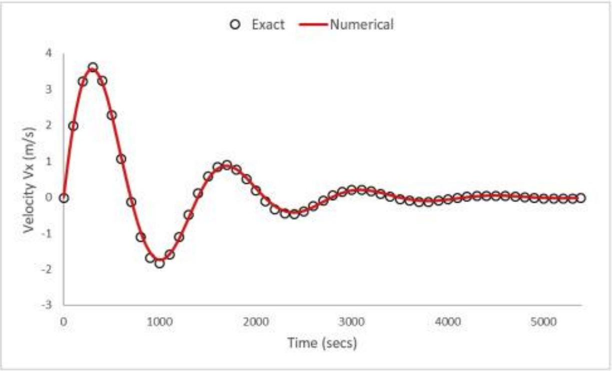
- The link between the gullies/inlets and the drainage network are included in the model which is **fully coupled** with the surface flow model.
- The model has been fully validated against lab measurements
- The solutions for pressurised flow can also be used for transient flows in pipes (water supply systems)
- There is a price to pay… 1000 x slower than surface model

CityCAT validation : 1

Analytic solution of “sloshing bowl”
– with and without friction





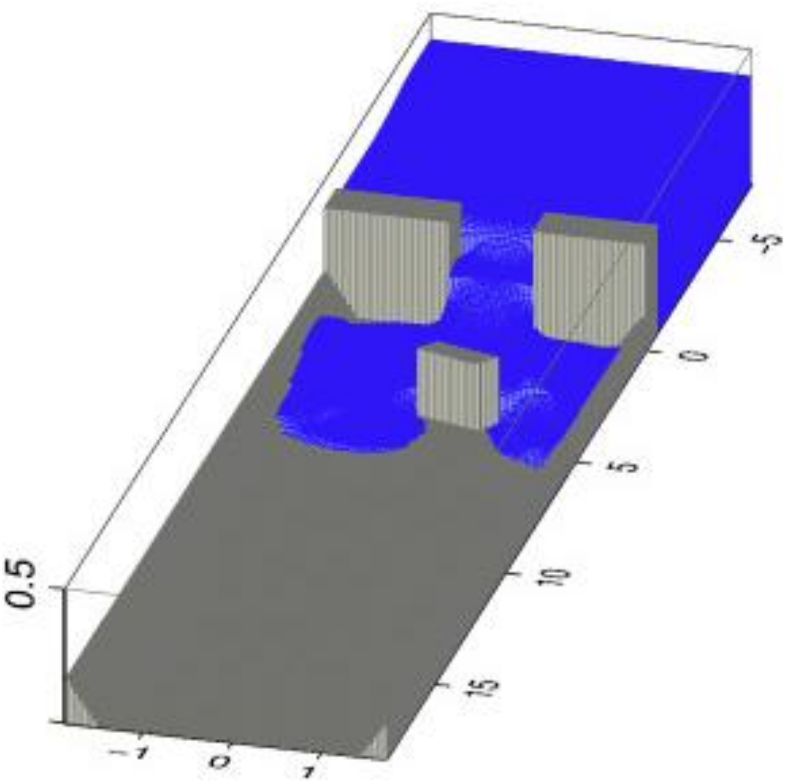


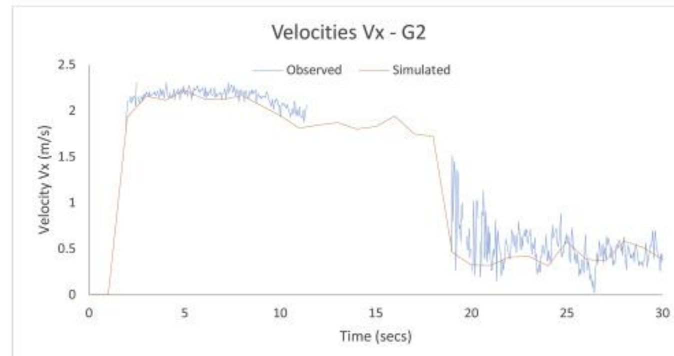
Glenis V, Kutija V, Kilsby CG. **[A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions](#)**. *Environmental Modelling & Software* 2018, **109**, 272-292.

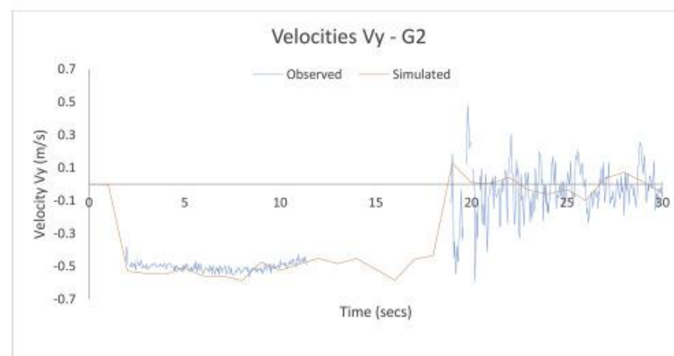
CityCAT validation : 2

Dambreak - lab study

(Test 6A Neelz and Pender benchmark study)





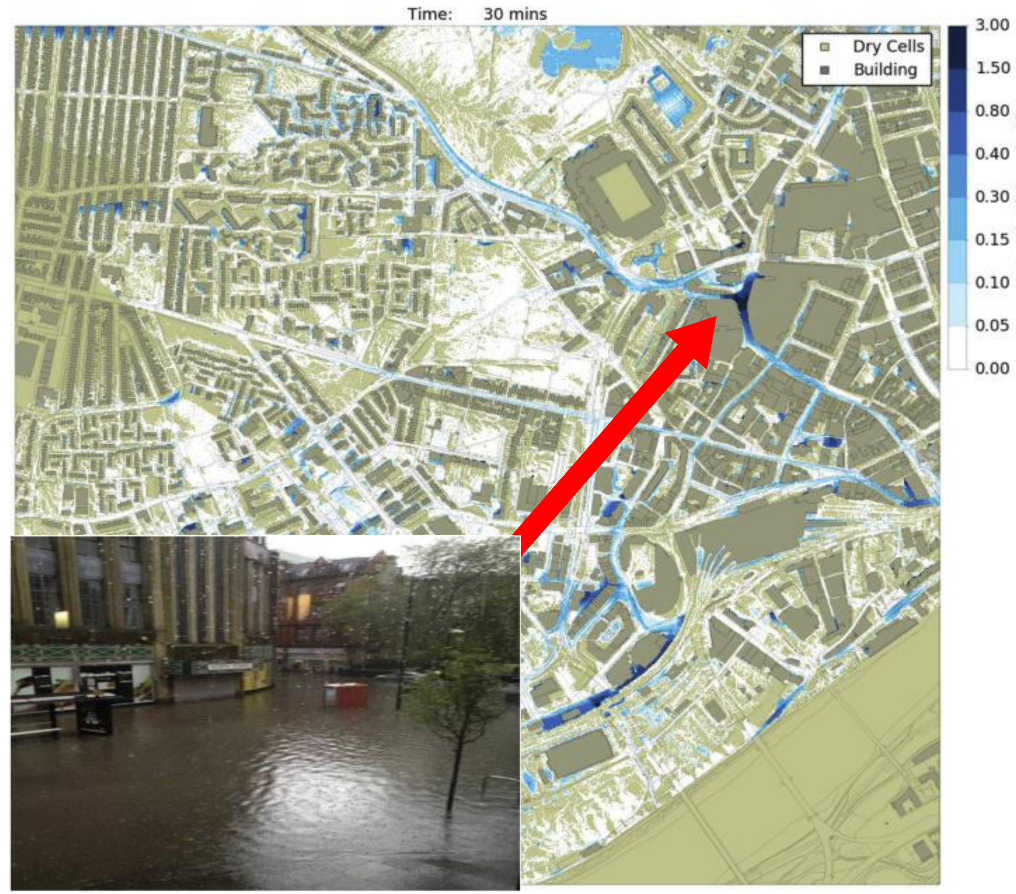


Glenis V, Kutija V, Kilsby CG. **A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions**. *Environmental Modelling & Software* 2018, **109**, 272-292.

CityCAT validation : 3

Newcastle pluvial flood:

- 2012 “Toon monsoon”
- 50 mm in 2 hours
- extensive field data of depths and timing



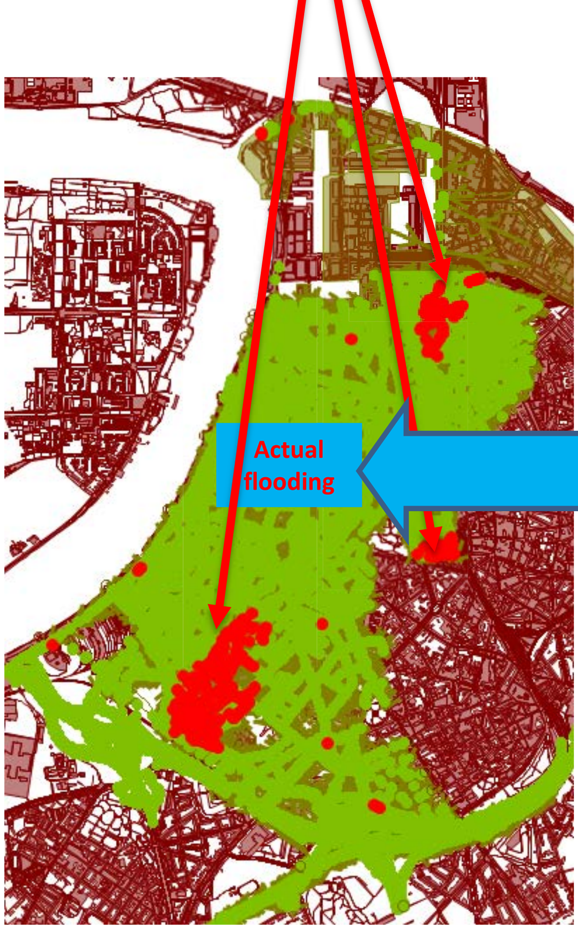
Glenis V, Kutija V, Kilsby CG. **A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions**. *Environmental Modelling & Software* 2018, **109**, 272-292.

CityCAT validation: 4

City of Antwerp : sewer network flooding

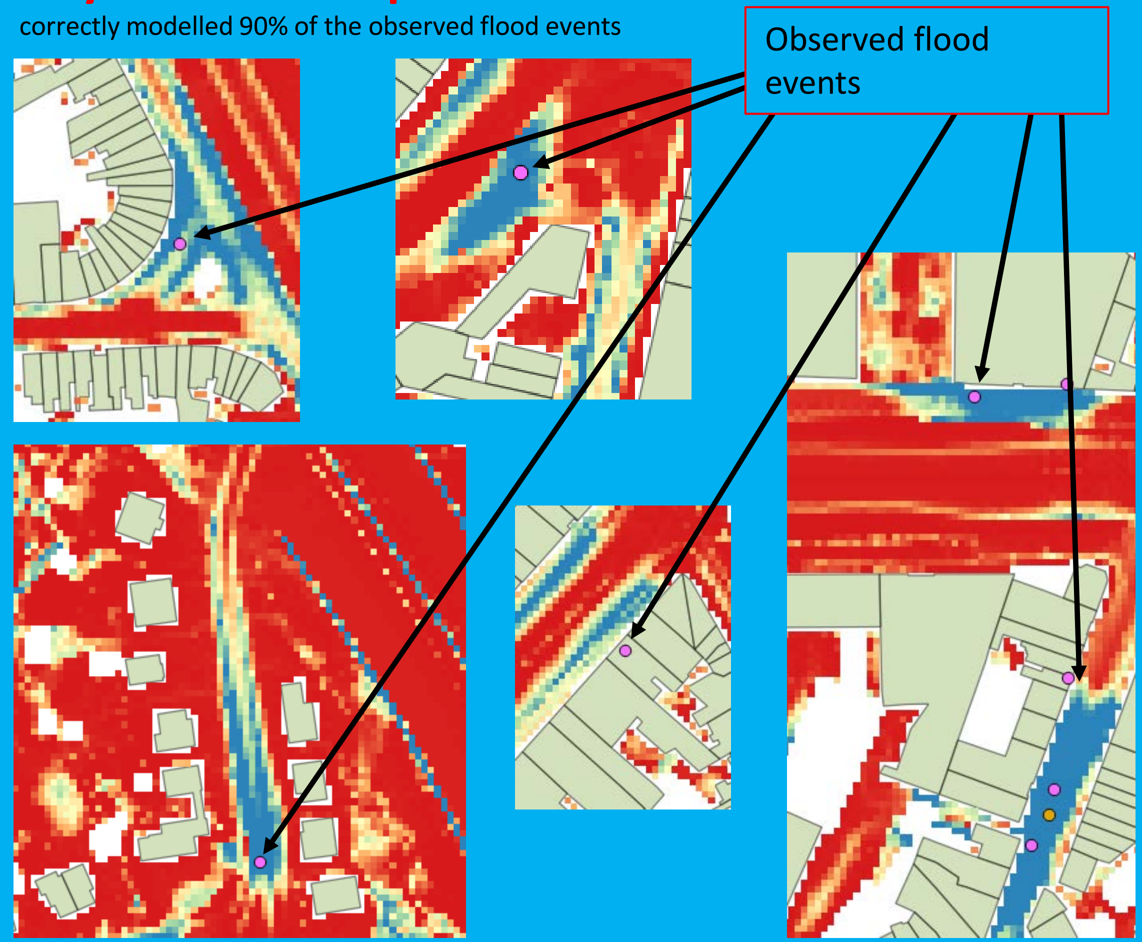
"Industry model" flood map

- 90% of model events "false alarms"



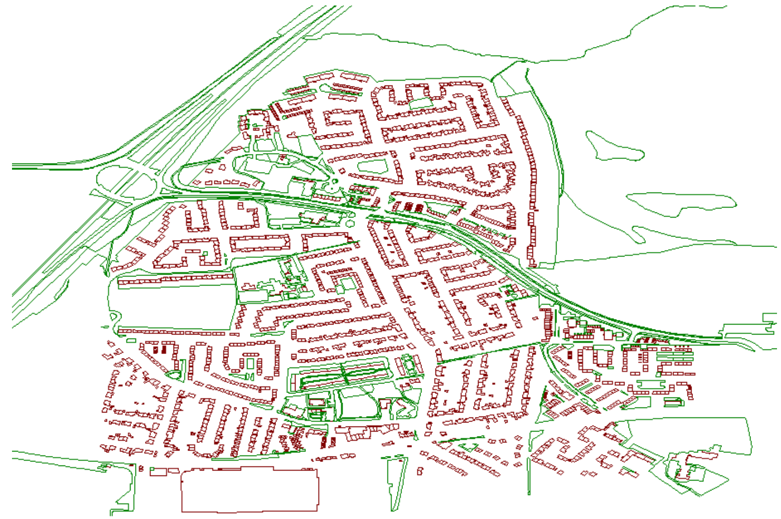
CityCat flood maps

correctly modelled 90% of the observed flood events

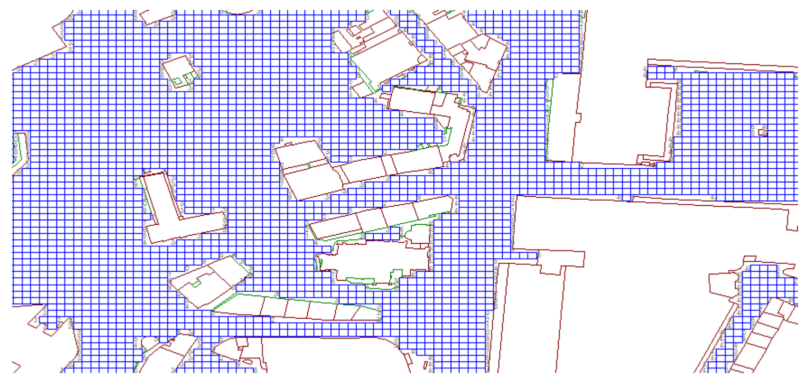


CityCAT in Cities

OS MasterMap or OpenStreetMap data are used to define **buildings**, **roads** and **permeable surfaces** and then combined with a **DTM** (ideally from lidar at 1m).



The computational grid is generated automatically : the buildings' footprint is excluded from the grid.

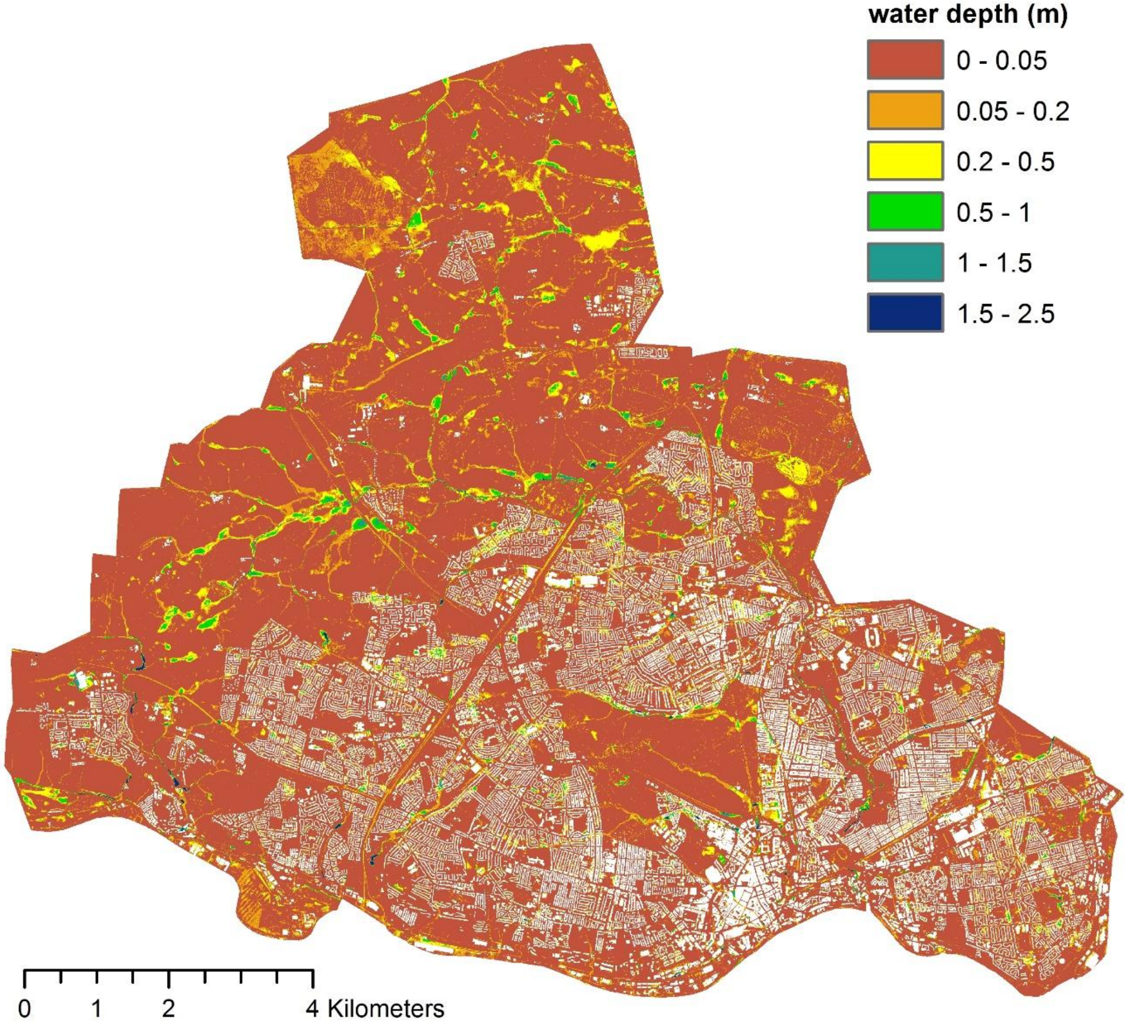


There are two unique advantages doing this:

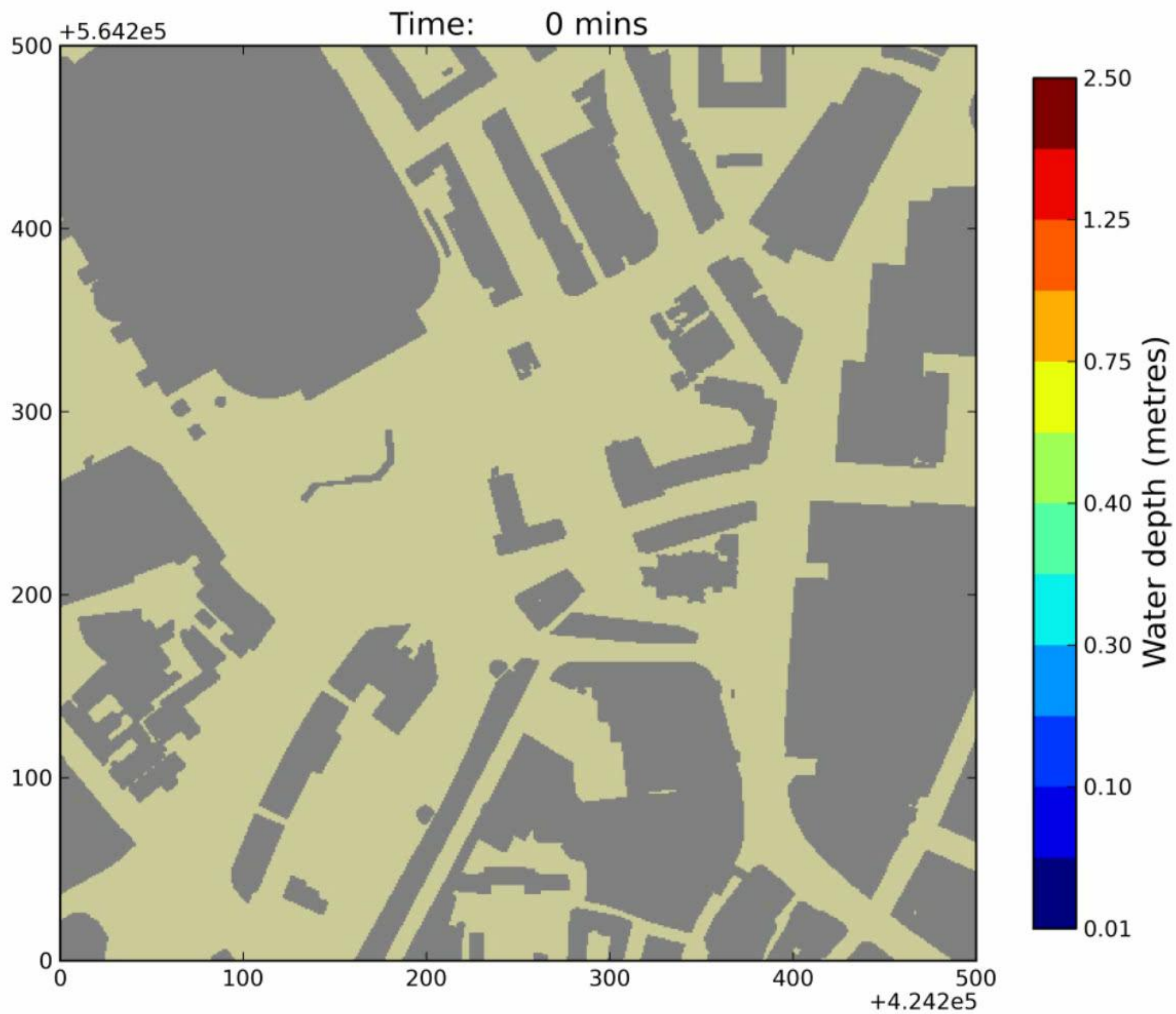
1. **The buildings are retained as objects** so roof drainage, occupants and damages can be modelled.
2. The **flow processes are more realistic and faster** to model than other software where the buildings are part of the flow grid

Pluvial flood
-Newcastle 100 year event

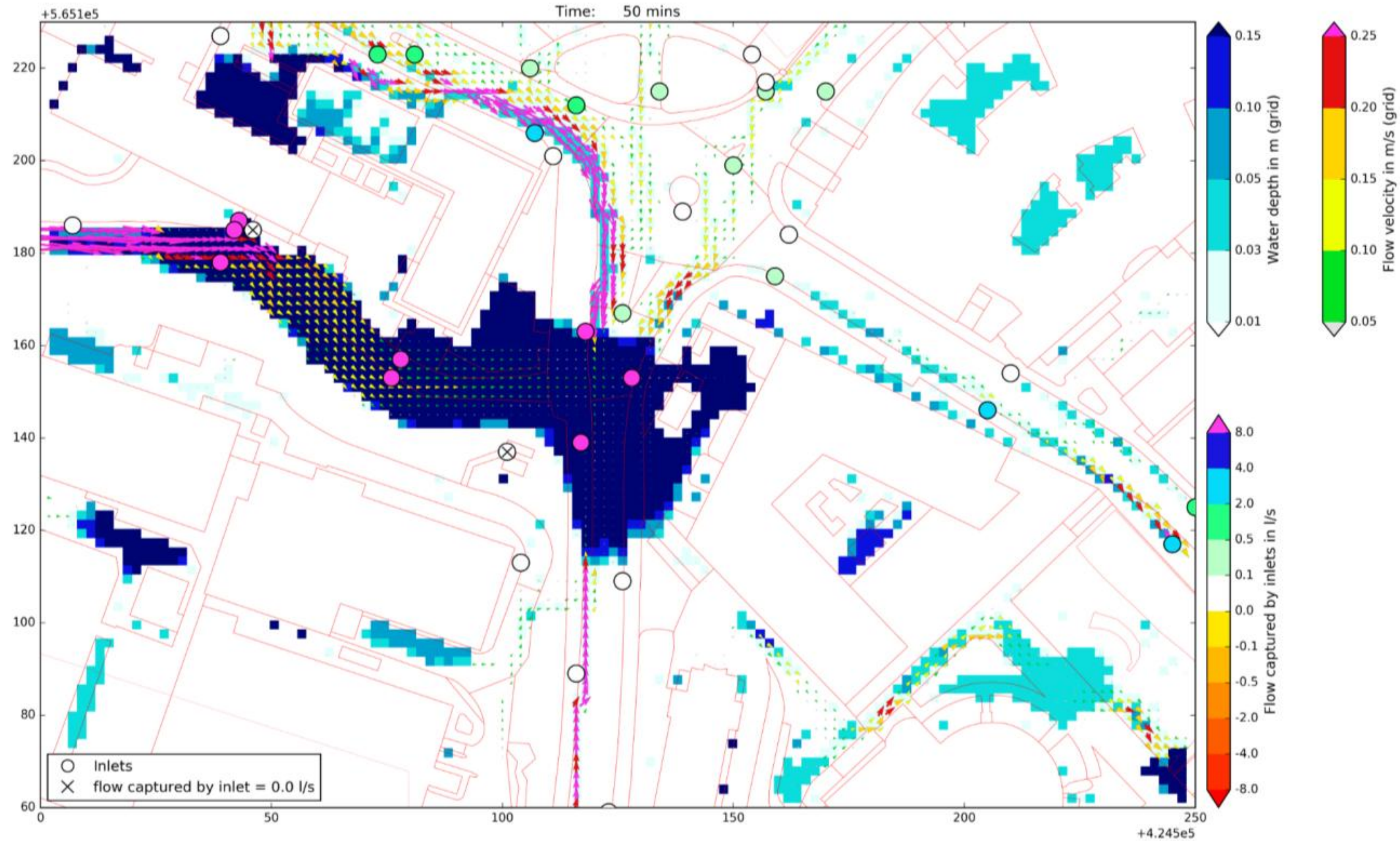
Area = 120km^2, Numerical grid cell size = 2m and 4m
1 hour design storm



Newcastle city June 28th 2012 event
Return Period ≈ 100yrs, Duration=120min

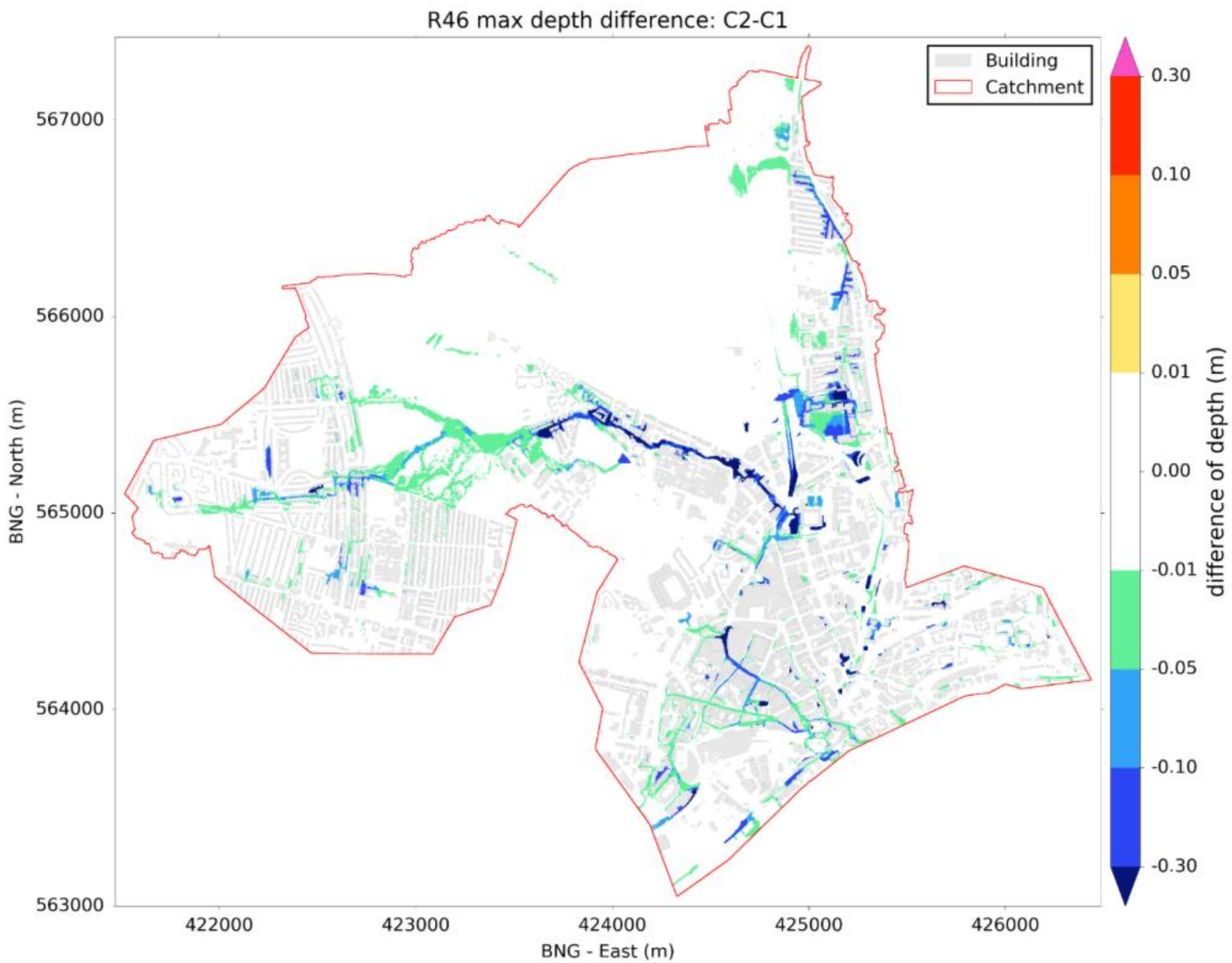


City CAT Simulation of Toon Monsoon



Including sewer network
Showing flow vectors and inlet/manhole flows

How well do the storm sewers work?

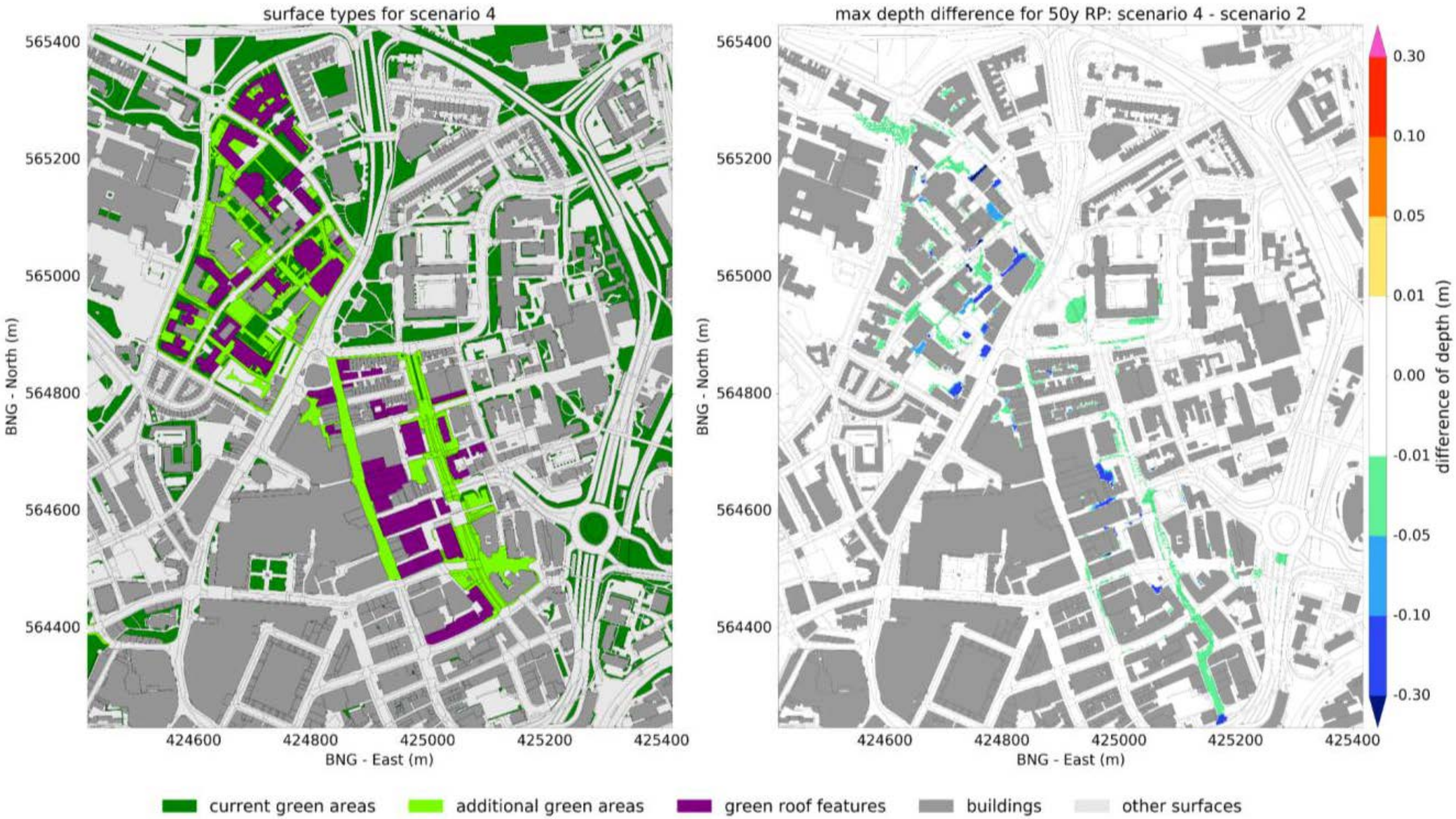


Map shows difference with and without sewer network for Toon Monsoon storm

Reduces flood depths in places by 10-30 cm

Blue Green Infrastructure : roofs and permeable pavements

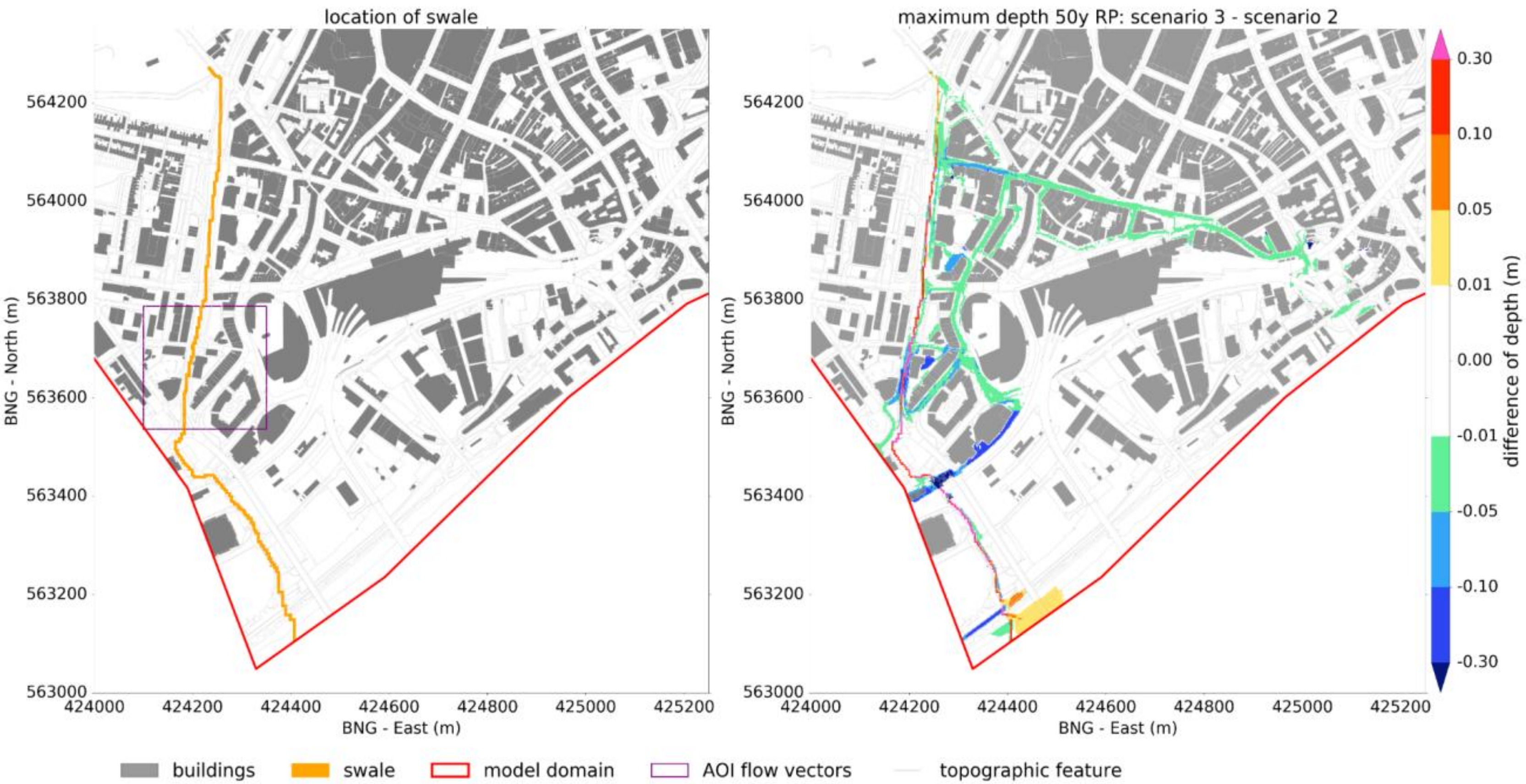
Green Roofs & Permeable Surfaces



Intervention

Effect – reduction of flood depth

How effective are swales ?



Intervention

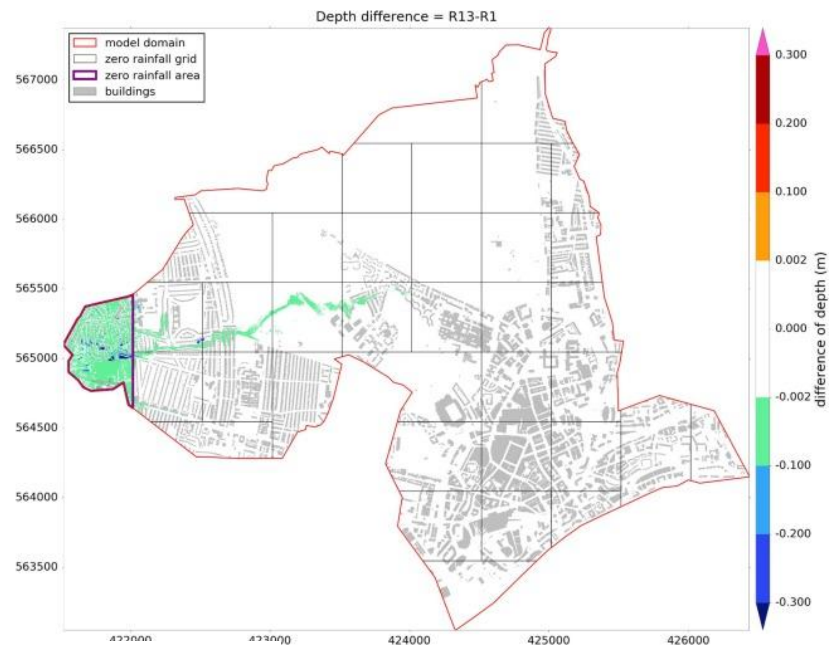
Effect – reduction of flood depth

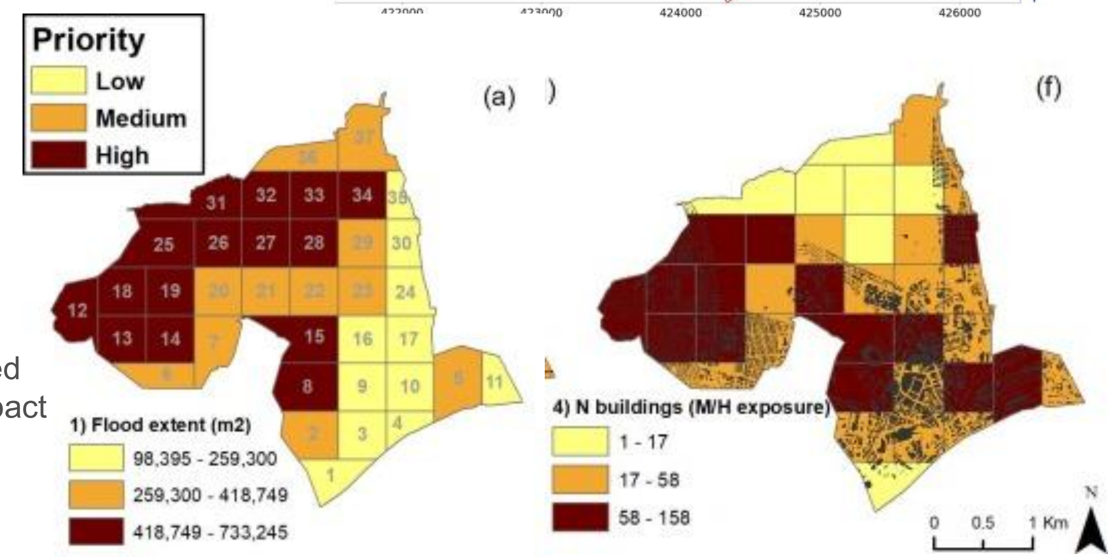
What is the best place to build Blue Green Infrastructure?

Newcastle University
UK | Malaysia | Singapore

Source-to-impact flood analysis

- Capturing (all) rainfall in cells simulated, one-by-one;
- Difference-maps between the maximum flood depths simulated in the baseline scenario and that simulated for each different cell scenario
- Systematically assessed for different types of impact (e.g. depth, no of buildings, roads affected)





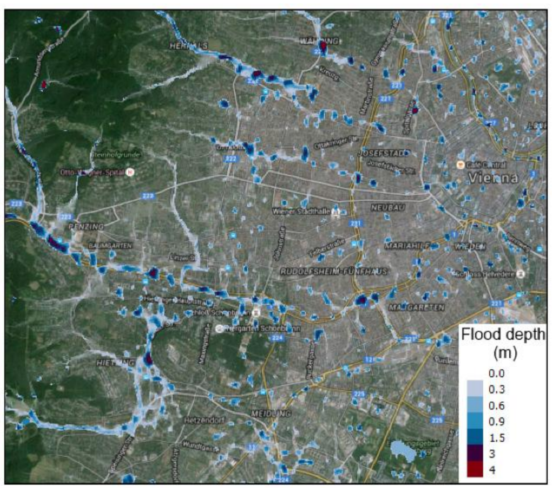
Developing spatial prioritization criteria for integrated urban flood management based on a source-to-impact flood analysis
[Vercruysse et al. 2019, https://doi.org/10.1016/j.jhydrol.2019.124038](https://doi.org/10.1016/j.jhydrol.2019.124038)

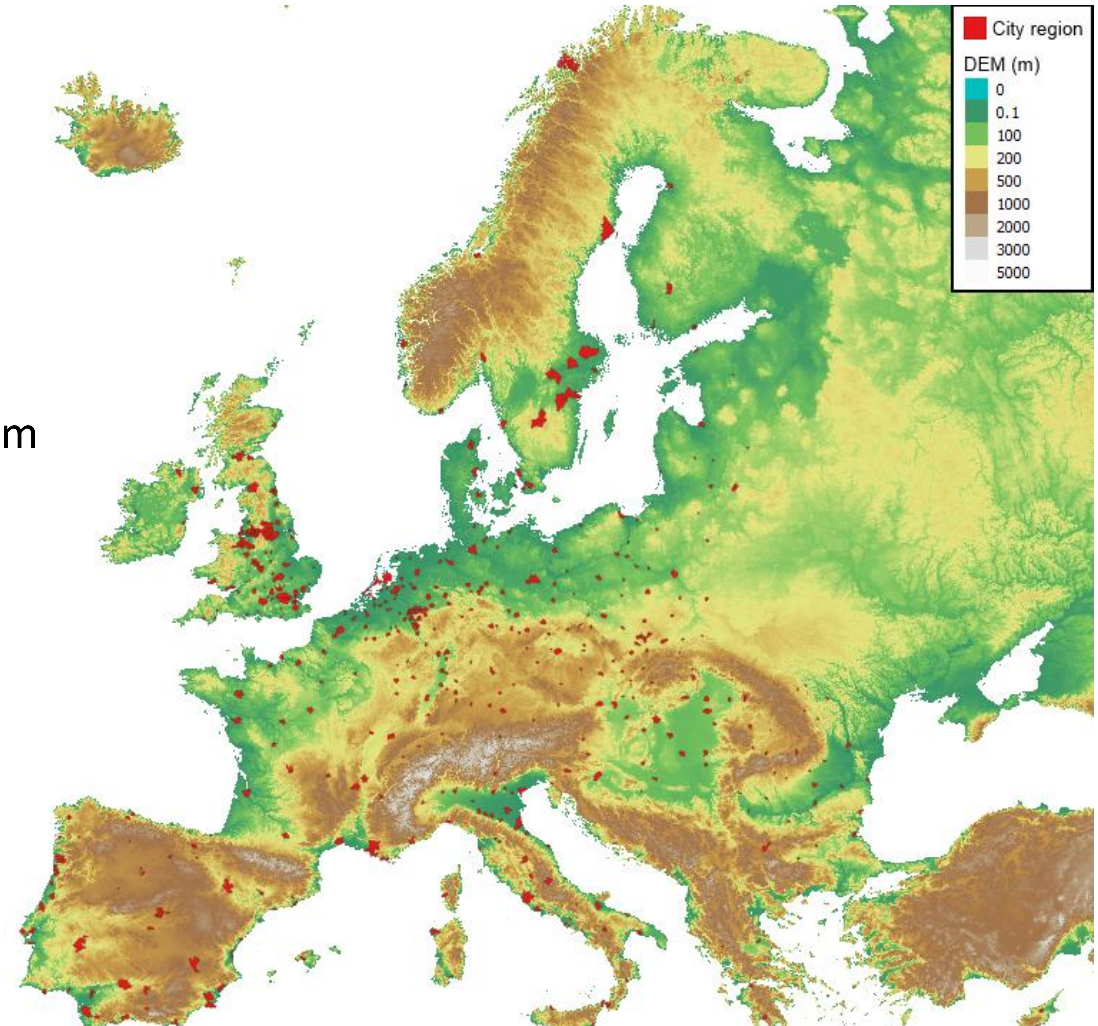
CityCat on Azure Cloud
- Modelling 571 European cities

Newcastle University
UK | Malaysia | Singapore

<u>EU RAMSES project</u>

571 cities across Europe
16 design storms
Total number of runs = 9,136
Simulation time on cloud reduced from ~3months to ~3days
Flood depths and areas simulated on 25m DEM, no sewer network





Guerreiro et al, 2017 Pluvial Flooding in European Cities—A Continental Approach to Urban Flood Modelling *Water* https://doi.org/10.3390/w9040296

Catchment flood modelling

Modelling system developed and assessed with auto set up

To assess :
- **various rainfall sources**
- **various DEMs**
- **treatment of channels and roughness**

To validate against :
- **Flood extent (easy!)**
- **Flood hydrographs (harder)**

Catchments modelled:
- **All in N England for 2015 Storm Desmond**
- **Mutiple large EU basins**
- **Jakarta**

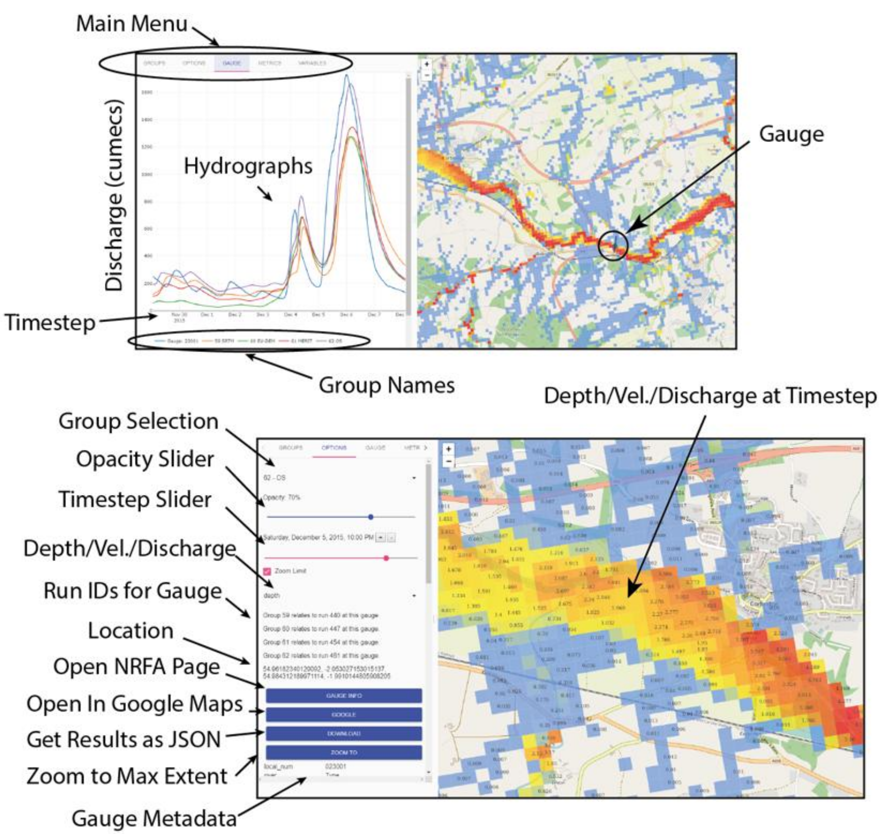


Figure 3-8 - Web application designed in AngularJS, using GeoServer, Leaflet and a Tornado backend.

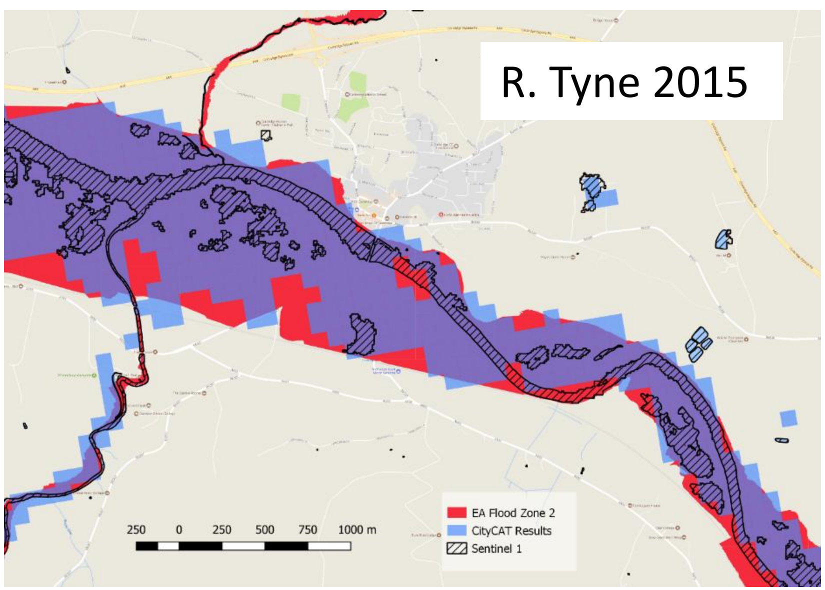
McClean, F., 2019 Broad-scale flood modelling in the cloud: validation and sensitivities from hazard to impact, *PhD thesis*, Newcastle University

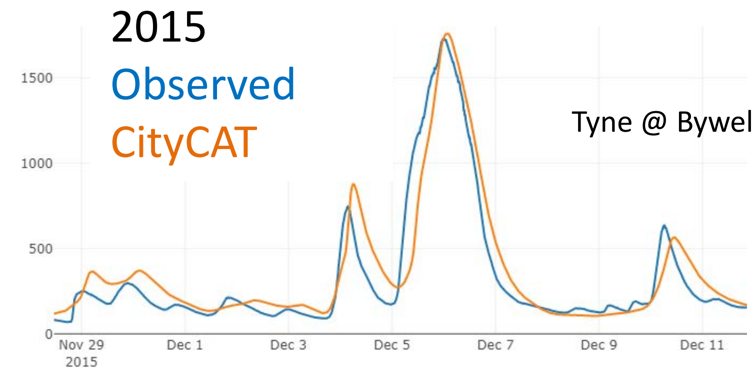
Catchment flood modelling: Validation against hydrographs

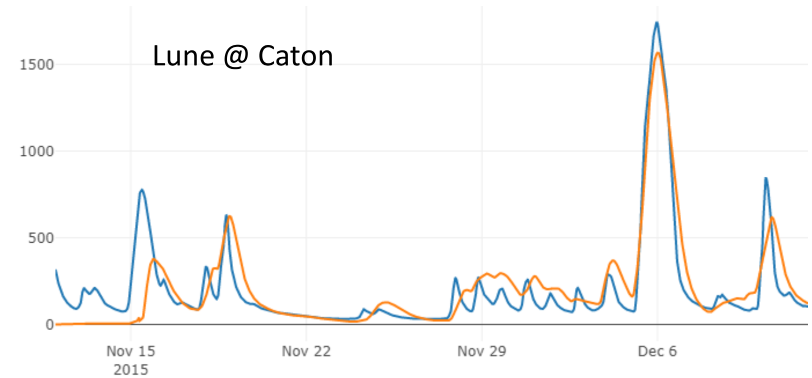
Newcastle University
UK | Malaysia | Singapore

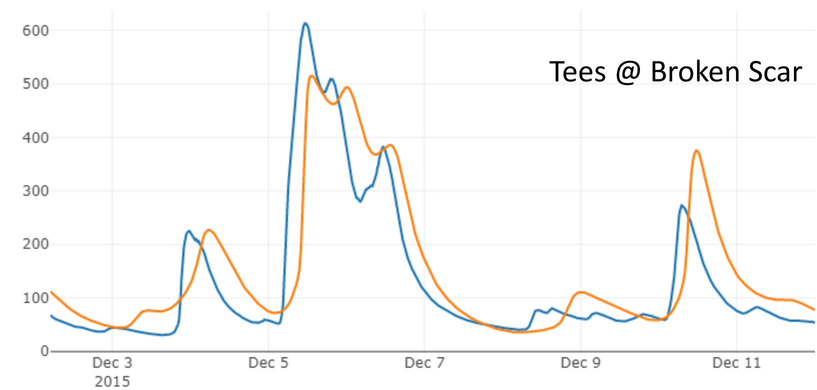
Modelling hydrograph is harder as:
- **Timing and routing need to be correct**
- **Gauging high flows is prone to error**

Modelling flood extent is constrained by flood plain geometry

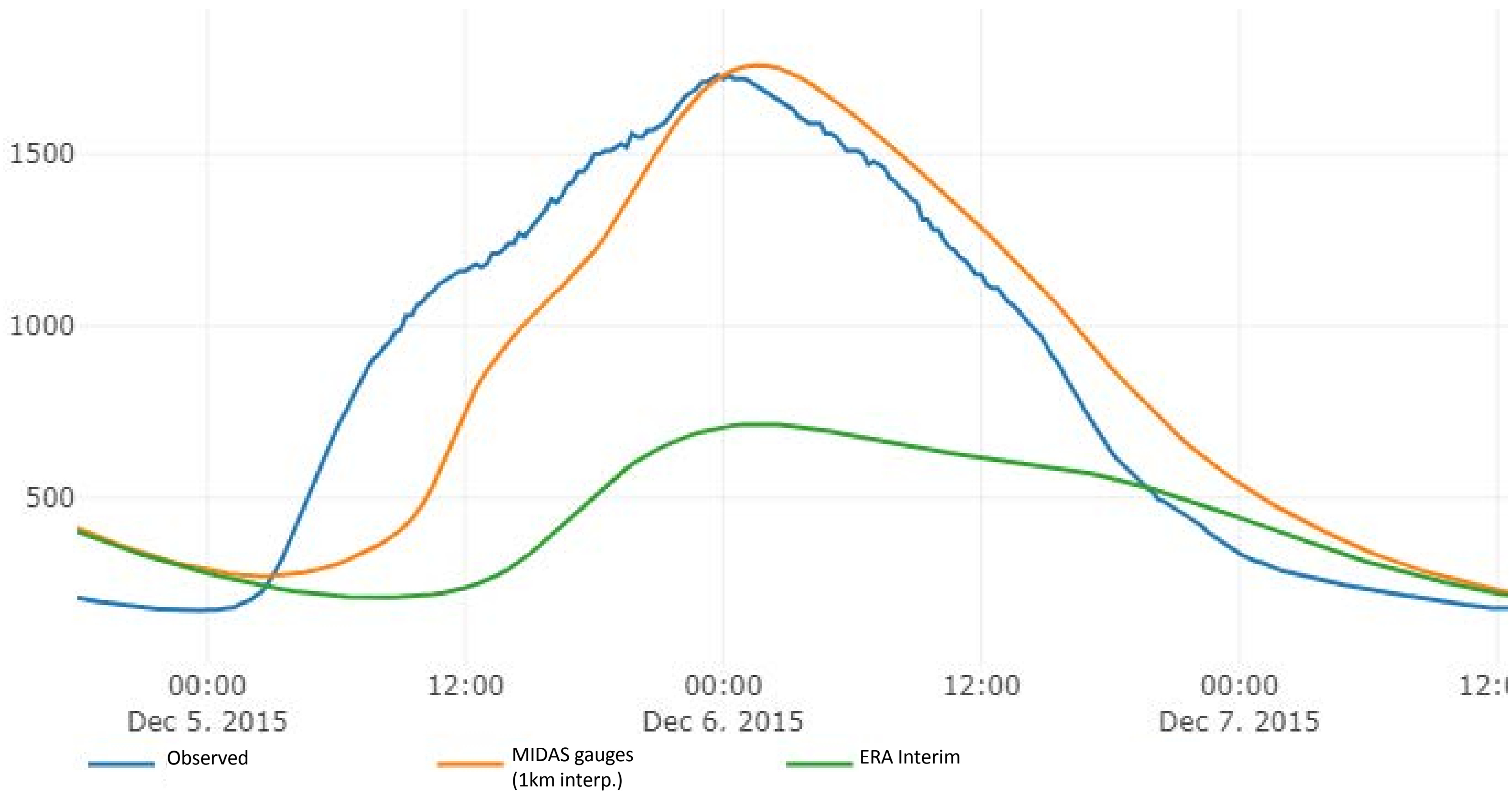




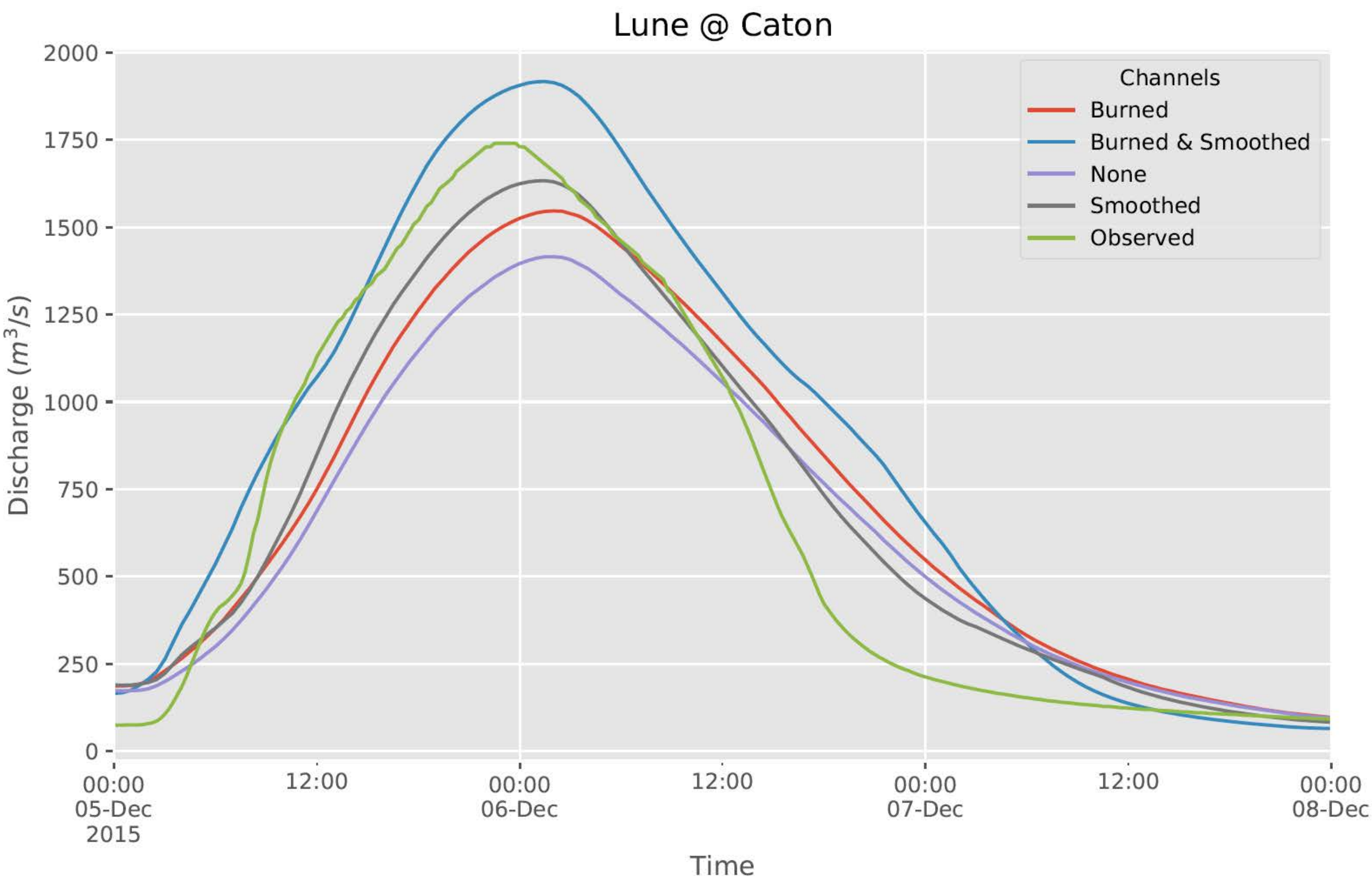




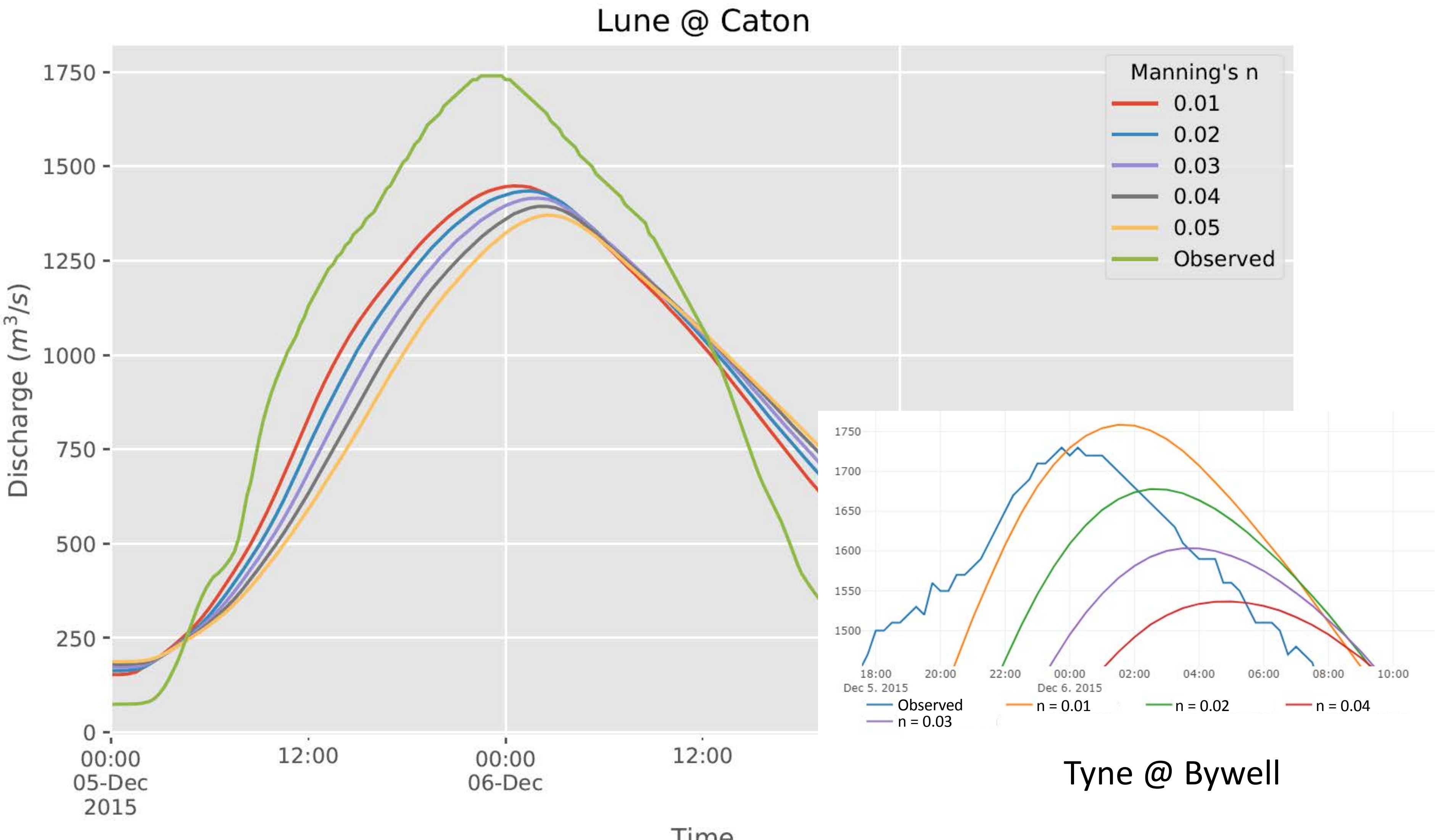
Catchment flood modelling
- Effect of rainfall inputs



Catchment flood modelling
- effect of river representation



Catchment flood modelling
- effect of channel roughness



Tyne @ Bywell

Conclusions

Accurate city and basin flood modelling at high resolution is now possible due to Cloud computing and availability of high resolution information such as lidar DEMs and building outlines.

The need for combining 2D models with 1D (river network) models can be avoided using high resolution DEMs – this is beneficial as complex 1D / 2D flood situations can be handled more easily

Models like CityCAT (accurate, shock-capturing) can achieve accurate results without calibration (of Mannings n) and can be validated against river flow time series (hard!) as well as flood extent (easy!)

The use of Cloud provides access to enough resources to carry **out a large ensemble of simulations** addressing the uncertainty and variability in the characteristics of present and future extreme rain storms

Cloud computing can provide **rapid and flexible access** to computational resources as and when needed without the need for significant financial outlay and continued expenses for maintaining the resources

Future work

Cities

- Digital twin: of city/catchment/infrastructure
- Analysis of best location for flood risk alleviation capturing flows (not rainfall)
- Representation of bridges, leaky barriers, NFM

Catchments

- Analysis of error sources : DEMs, channels, rainfall
- CAT models (uncalibrated)
- CAT models (validation against discharge)
- Implementing "hydrology" – lateral sub-surface transfers, geology a.k.a. integration with SHETRAN

Implementation

Web browser user interface to Cloud version

- Automatic set up
- Editing of DEM, land cover
- Import of sewer networks (from ICM)
- Generation of synthetic sewer networks (for design or accounting for effect of drainage)

We welcome collaborations in Europe !!!

References

Glenis V, Kutija V, Kilsby CG. A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions. *Environmental Modelling & Software* 2018, **109**, 272-292.

Bertsch R, Glenis V, Kilsby C. Urban Flood Simulation Using Synthetic Storm Drain Networks. *Water* 2017, **9**(12), 925.

Guerreiro SB, Glenis V, Dawson RJ, Kilsby C. Pluvial flooding in European cities - A continental approach to urban flood modelling. *Water* 2017, **9**(4), 296.

Vercruysse K, Dawson DA, Glenis V, Bertsch R, Wright N, Kilsby C. **2019** Developing spatial prioritization criteria for integrated urban flood management based on a source-to-impact flood analysis. *Journal of Hydrology*, 578, 124038.

Glenis V, Kutija V, Kilsby CG. A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions. *Environmental Modelling & Software* 2018, 109, 272-292.

Glenis V, McGough AS, Kutija V, Kilsby C, Woodman S. Flood modelling for cities using Cloud computing. *Journal of Cloud Computing: Advances, Systems and Applications* 2013, **2**(1), 7.

McClean, F., 2019 Broad-scale flood modelling in the cloud: validation and sensitivities from hazard to impact, *PhD thesis*, Newcastle University

Impact Assessment: pipe network & surface water (1D/2D)

Changing Pipe diameters (mm)

Existing ➔ increased
100 ➔ 200
150 ➔ 250
200 ➔ 300
225 ➔ 350
300 ➔ 400
375 ➔ 500
450 ➔ 600