Hydroinformatics in Urban Environment

Prof. Dragan Savic *FREng*

11 May 2014


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EXETER
THE SUNDAY TIMES
UNIVERSITY
OF THE YEAR
2012-13
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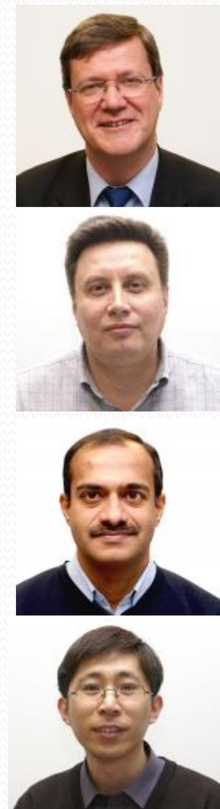
Centre for Water Systems

- Established in 1998
- 30+ members (9 academic staff, 8 post-docs, 20+ PhDs/EngDs, 1 administrator)
- Current projects (~£4M):
  - 5 EPSRC (UK Research Council)
  - 7 EU projects (FP7/STREP/ITN)
  - IDC: STREAM (12 x EngD)
  - CDT: WISE (20 x PhD over 5 years)
  - 3+ Knowledge Transfer Partnerships



Centre for Water Systems

- Part of the multidisciplinary College of Engineering, Mathematics & Physical Sciences
- Research interests across the urban water cycle, with particular emphasis on:
  - **hydroinformatics**
  - **urban water management**
- Consultancy – wide range of projects & partners
- MSc in Water Management

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Outline

- RAPIDS and CADDIES Projects(Intro)
- Case Studies
  - RAPIDS
    - Crossness, Portsmouth and Dorchester
  - CADDIES
    - Two EA Benchmark Test Cases
    - Two Real Test Case (up to 14 million cells)
    - Flooding from mains/sewers
- Summary

RAPIDS Project

RAdar Pluvial flooding Identification for Drainage System

- **Two sub-projects**
  - UKWIR – RTM Project (2011-12)
    - Real-time Machine Learning Approach to Near-term Assessment of Risk of Flooding in Urban Areas
  - EA – Bacti Project (2012-13)
    - Early Warning System for Prediction of Bacterial Concentration Exceedance in Tidal Waters

RAPIDS Team

Prof Dragan Savic

Prof Slobodan Djordjevic

Dr Edward Keedwell

Mr Andrew Duncan

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Acknowledgments

- **UKWIR – RTM Project**
  - HR Wallingford - Coordination
  - Richard Allitt Associates - Dorchester case study
  - Halcrow - Crossness case study
  - Mouchel - Portsmouth case study
  - University of Exeter - ANN models
  - UKWIR - Funding
- **Bacti Project**
  - Environment Agency SW - Requirements + Data + - Decision tree models
  - University of Exeter - ANN models
  - South West Water - Advice

HR Wallingford
raa
Halcrow
mouchel
UKWIR
Environment Agency
SOUTH WEST WATER

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Overview

1. UKWIR RTM: Machine learning models of urban flooding – 3 case studies
2. RAPIDS: Artificial Neural Network (ANN) model
3. Bacti: Adapting RAPIDS to predict bathing water quality
4. Rainfall prediction
5. Future plans

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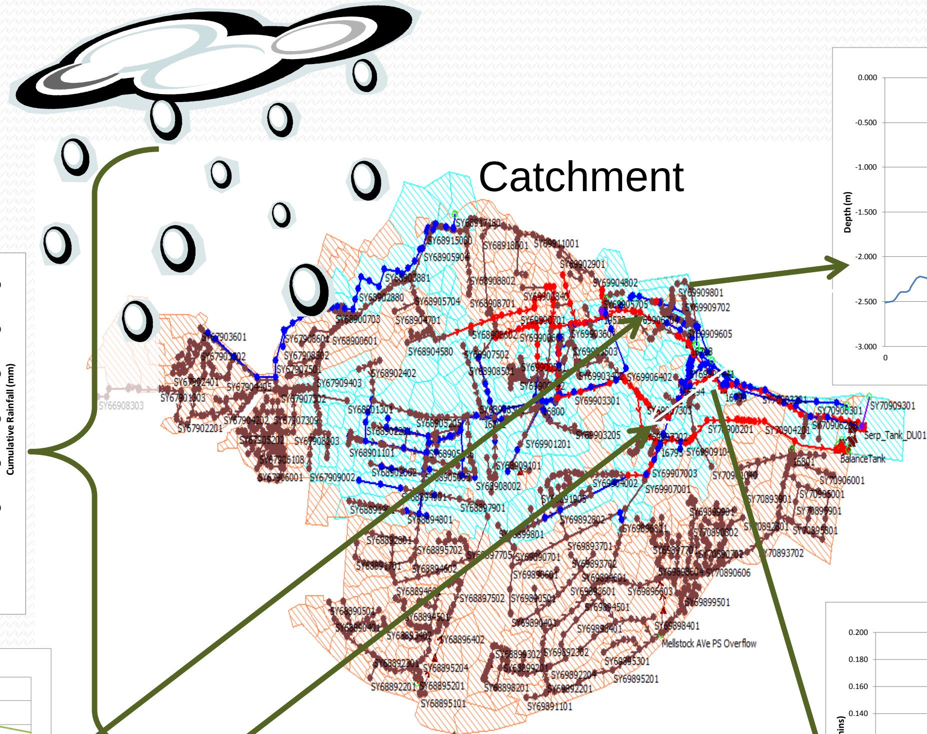
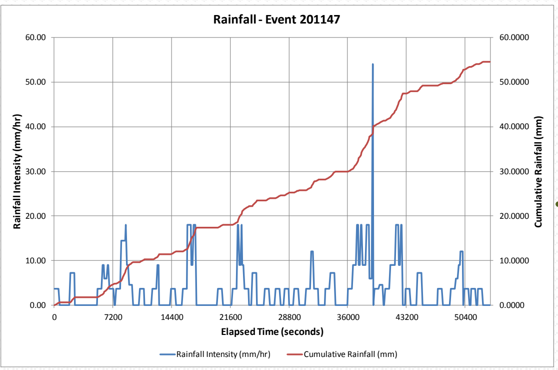
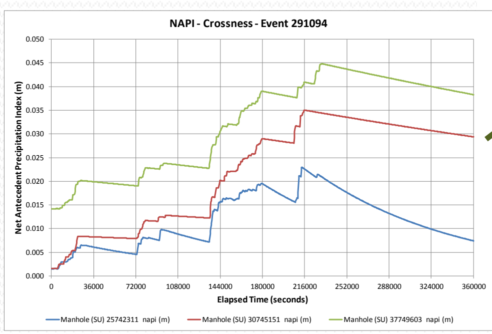
UKWIR RTM: machine learning models of urban flooding

- Scenario

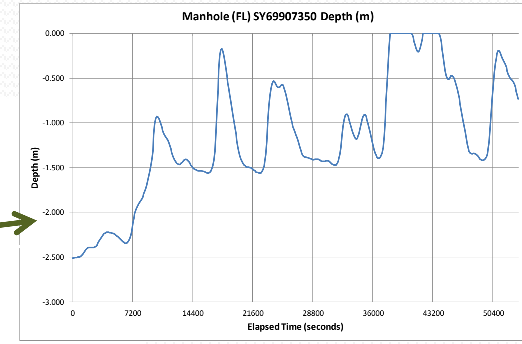


Rainfall Event



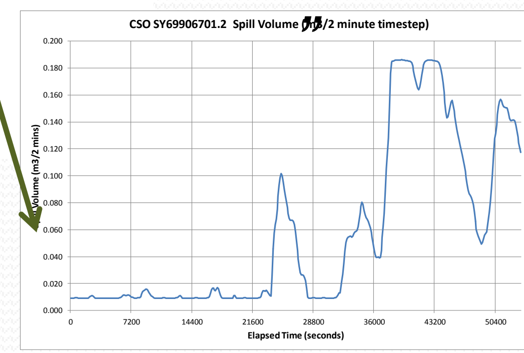


NAPI



Manhole Depth Hydrograph

"Targets"



CSO Spill Volume Hydrograph

Other Inputs: Tides, Pump States etc.

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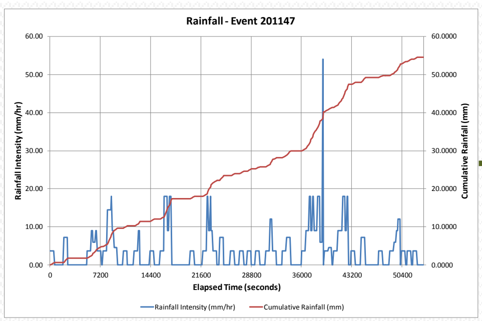
RAPIDS – Architecture

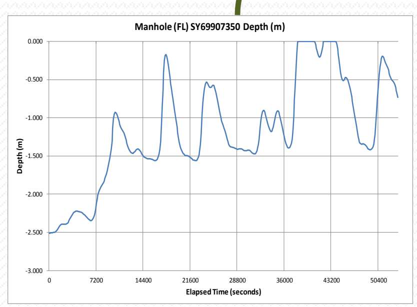
RAPIDS Program Setup Configuration Sheet Beta Version

Note: Only fill in cells highlighted in light blue (other cells may contain formulae)

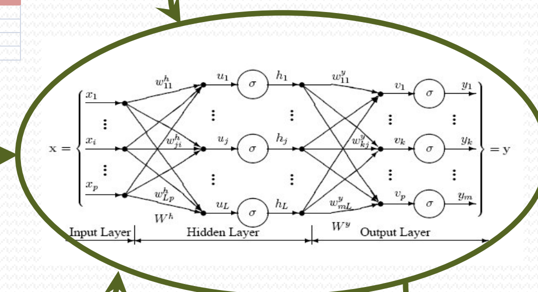
Catchment & Event Description	Value	Units
Training Event Data File	Stage2data\Crossness_Halcrow_data\Train\Stage_2_Crossness_Train_Surcharged_MHs_depthAD.xlsx	
Test Event Data File	Stage2data\Crossness_Halcrow_data\Test\Stage_2_Crossness_Test_Surcharged_MHs_depthAD.xlsx	
Catchment Name	Crossness	
Rainfall Type	Spatial	
Training Event Spatial Rainfall File	Stage2data\Crossness_Halcrow_data\Train\Stage_2_Crossness_Train_Spatial_rainfall_dataAD.xlsx	
Test Event Spatial Rainfall File	Stage2data\Crossness_Halcrow_data\Test\Stage_2_Crossness_Test_Spatial_rainfall_dataAD.xlsx	
Columns of Spatial Rainfall Data	23	
Project Stage	2	
Summary WorkSheet Name	Info	
Total Events (Test + Training)	50	
Target Header Range	A1:AS3	
Target Data Range	A4:AS1204	
Node Label Range	D2:AS2	
Columns of Input Data in Target Sheets	3	
NAPI Value Used as ANN Input	FALSE	
Separate NAPI data files?	TRUE	
Training Event NAPI File	Stage2data\Crossness_Halcrow_data\Train\Stage_2_Crossness_Train_NAPI_AD.xlsx	
Test Event NAPI File	Stage2data\Crossness_Halcrow_data\Test\Stage_2_Crossness_Test_NAPI_AD.xlsx	
Columns of NAPI Data	40	



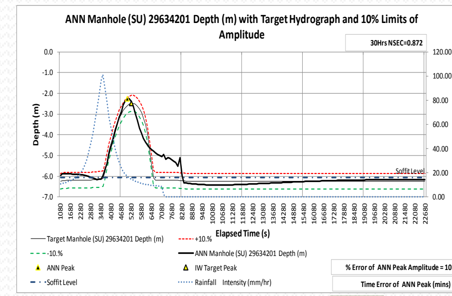
Input & Target Data Workbooks



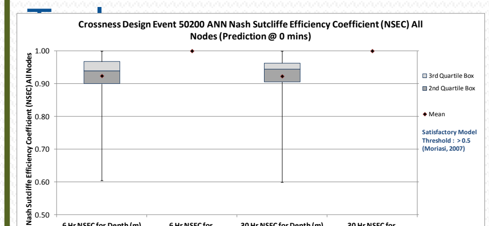
ANN (MATLAB)

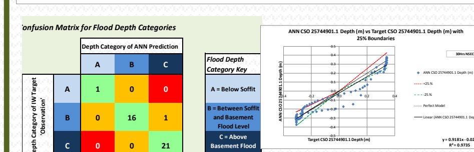


Trained Network Structures



HydroMAT Analysis Tool

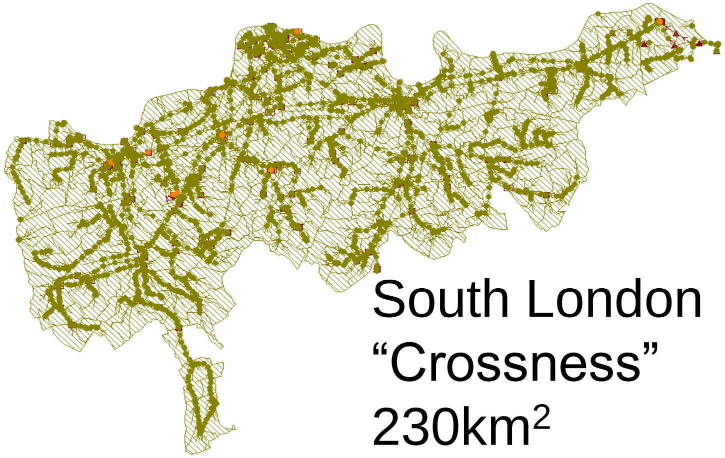




15 metrics

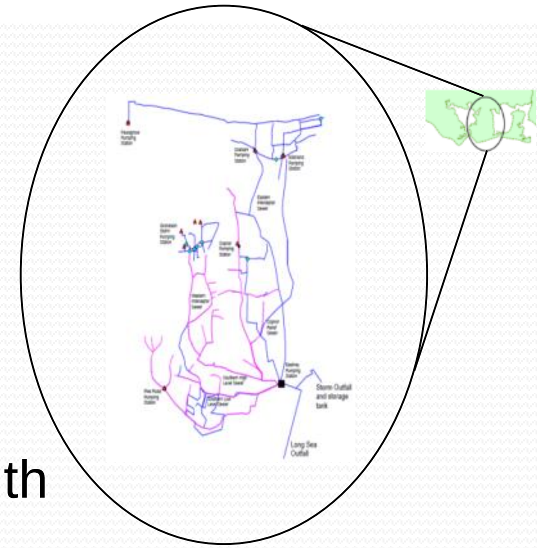
UKWIR RTM: 3 case study cities – focus of study

- **Crossness:**
  - Spatially variable rainfall
  - Up to 23 raingauges
- **Portsmouth:**
  - Predictive pump starting
  - Flood mitigation strategy
- **Dorchester:**
  - Relevance of soil moisture (NAPI) as model input



South London
"Crossness"
230km^2

Dorchester
6km^2



Portsmouth
29km^2

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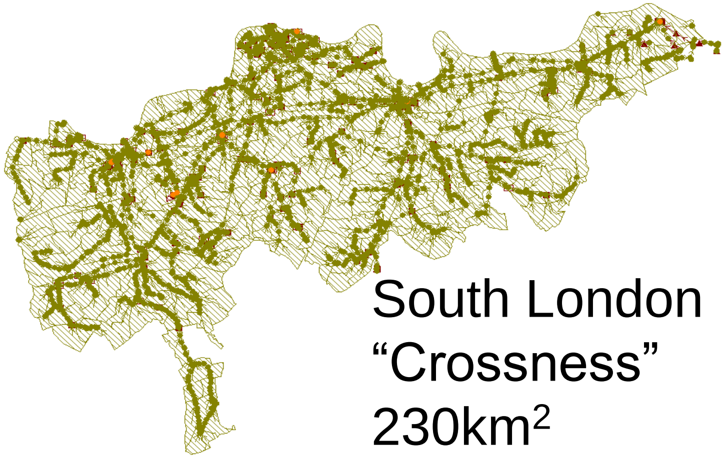
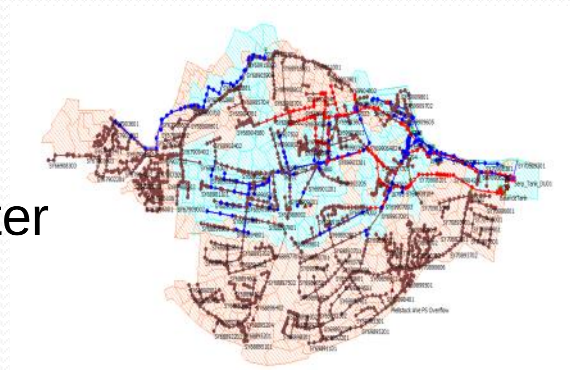
UKWIR RTM: 3 case study cities - modelling

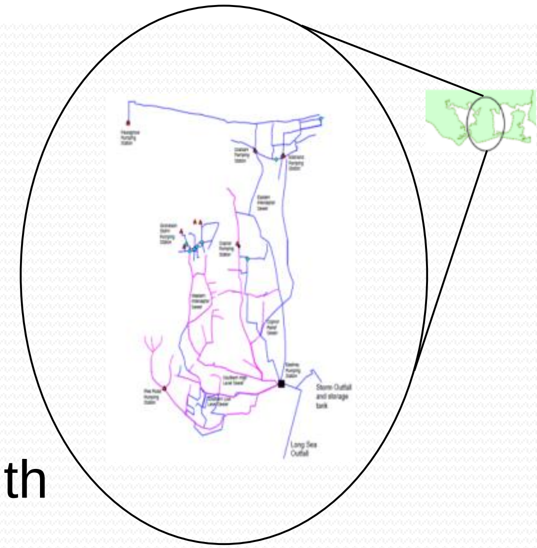
- **ANN Parameters:**
  - Input units (timesteps)
  - Hidden units
  - Optimisation strategies
- **Catchment Parameters:**
  - Times of concentration (ToC)
  - Hydrograph profiles
  - Rainfall events



South London
“Crossness”
230km^2



Dorchester
6km^2



Portsmouth
29km^2

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Results: Volume of data

Measurement Points:	Crossness	Portsmouth	Dorchester
Number of flooding manholes	20	17	20
Number of surcharged manholes	20	6	20
Number of CSOs	19	10	10

Measurement Parameters:

- Flooding volume
- Flooding depth
- CSO volume
- CSO depth
- Surcharged manhole depth

Number of Hydrographs:

Stage 1 = 952

Stage 2 = 1190

Total = 2142 !!!

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Results: ANN model performance metrics

Nash-Sutcliffe Efficiency Coefficient (NSEC)

$$E = 1 - \frac{\sum_{t=1}^{T} \left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q_o}\right)^2}$$

where Q_o is observed discharge, and Q_m is modelled discharge. Q_o^t is observed discharge at time t.

- Nash–Sutcliffe values can range from −∞ to 1.
- A value of 1 corresponds to a perfect match between Target and ANN model results.
- A value of 0 indicates that the ANN model predictions are as accurate as the mean of the Target data.
- A value less than zero occurs when the mean of the Target data is a better predictor than the ANN model.

Criteria used for results evaluation

0.9 to 1.0	**GOOD**
0.5 to 0.9	**ACCEPTABLE**
<0.5	**POOR**

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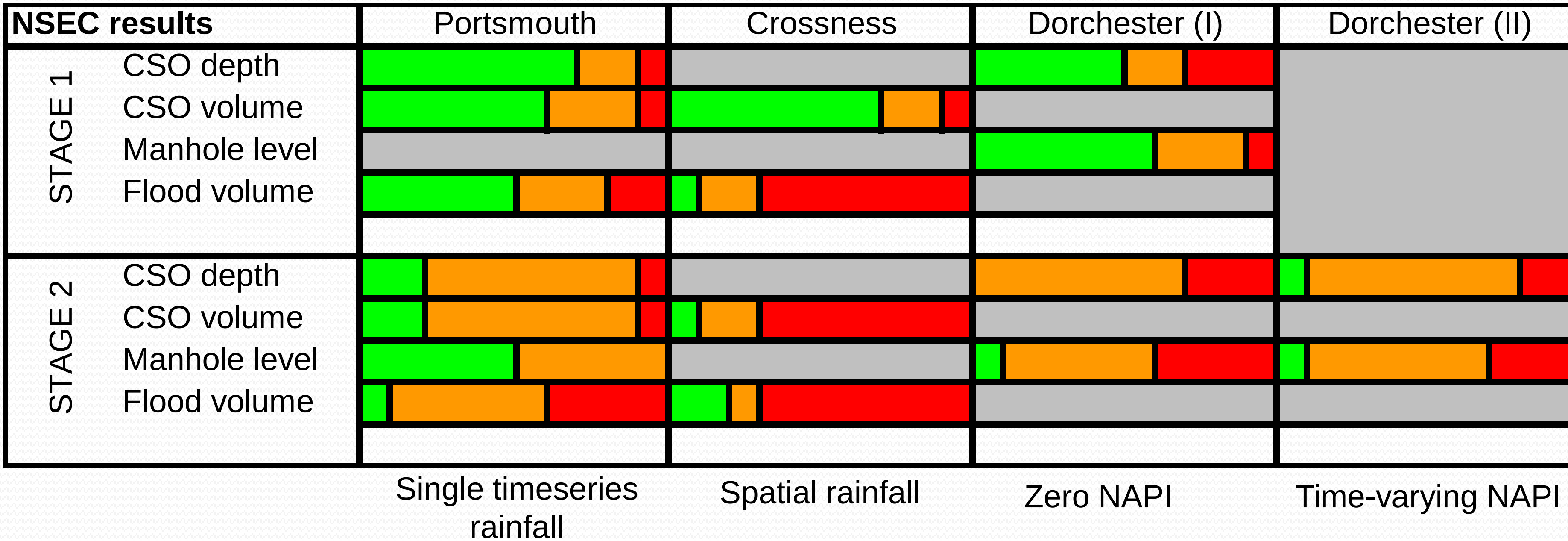
Results: Hydrograph goodness of fit (NSEC) results summary (~2000 results)



- Stage 1 (design rainfall) results better than stage 2 (time-series rainfall) – but still largely acceptable (e.g. Portsmouth)
- ANN not capturing spatial rainfall input/response (e.g. Crossness)
- NAPI signal has minor influence on ANN performance (e.g. Dorchester)

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Introduction

- Cellular Automata for 2D flood modelling
- 2 CA models
- Results comparison

EA Cases	Torquay Cases	Large Case
Multiple Models Multiple Hardware	InfoWorks ICM 3.0	~~InfoWorks ICM 3.0~~
UIM		UIM

UIM: in-house physical based
non-inertial urban inundation model

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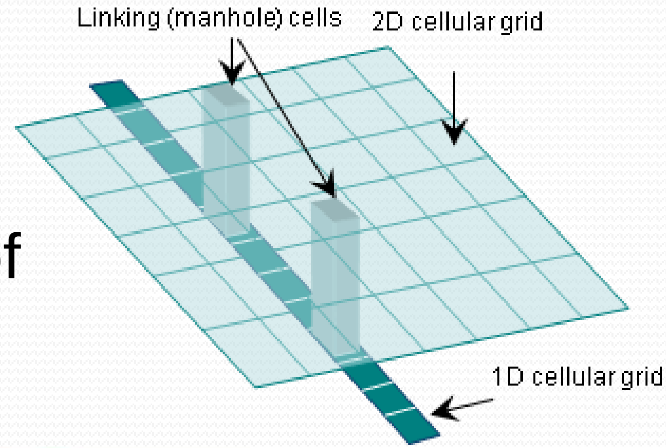
CADDIES Project

- £500k project funded by the UK EPSRC and industry (2010-2013)
  - Rapid, simplified dual-drainage modelling algorithms
  - Realistically capture the nature of flood dynamics over large urban areas



EPSRC Engineering and Physical Sciences Research Council
Environment Agency
Halcrow
HR Wallingford Working with water
mouchel
City of Bradford MDC www.bradford.gov.uk
UKWIR
SOUTH WEST WATER
Thames Water
United Utilities
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TORBAY COUNCIL
raa Richard Allitt Associates Ltd
NORTHUMBRIAN WATER
YorkshireWater

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MWH BUILDING A BETTER
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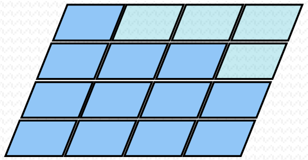
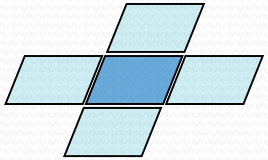
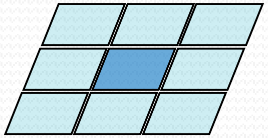
Models

Cellular Automata



1. Discrete space
2. Cell states: discrete, continuous
3. Neighbourhood type

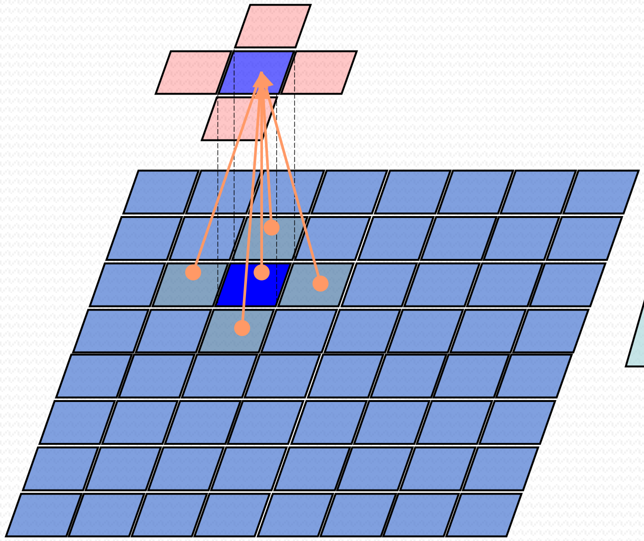


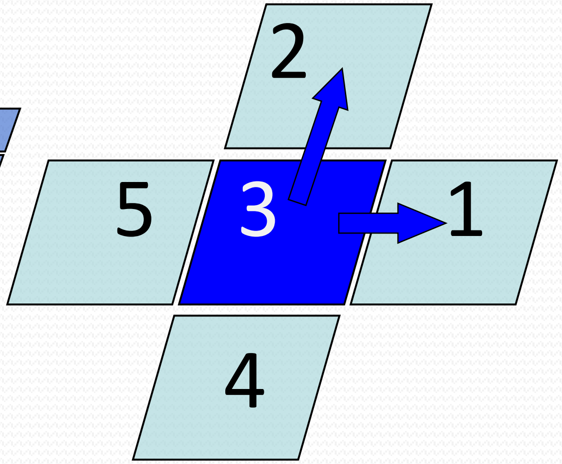


4. Local rules (deterministic and uniform)
5. Independent cell state updating (parallel)

CADDIES 2D Models

- The 2D CA models describes the surface flow using discretised cell states





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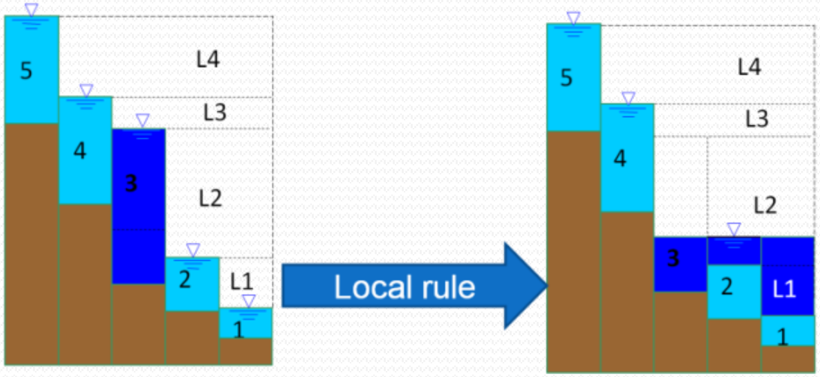
CADDIES 2D Models

- CA2D: **First model (2011/2012)**
  - Ranking technique to compute the volume of water transferred
  - Expensive ranking algorithm
  - Oscillation problems



Formulation of a Fast 2D Urban Pluvial Flood Model Using a Cellular Automata Approach. *J. Hydroinformatics* (2013)

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CADDIES 2D Models

- Weighted CA2D: **Improved model (2013)**
  - Quicker weight-based system to compute the volume of water transferred
  - Manning's equation applied to limit flux
  - Quicker with same accuracy of CA2D
  - Journal paper (under review):

    CADDIES: a Streamlined, Weighted Cellular Automata 2D Inundation Model for Rapid Flood Analysis, submitted to

    J. Env. Mod. & Soft.

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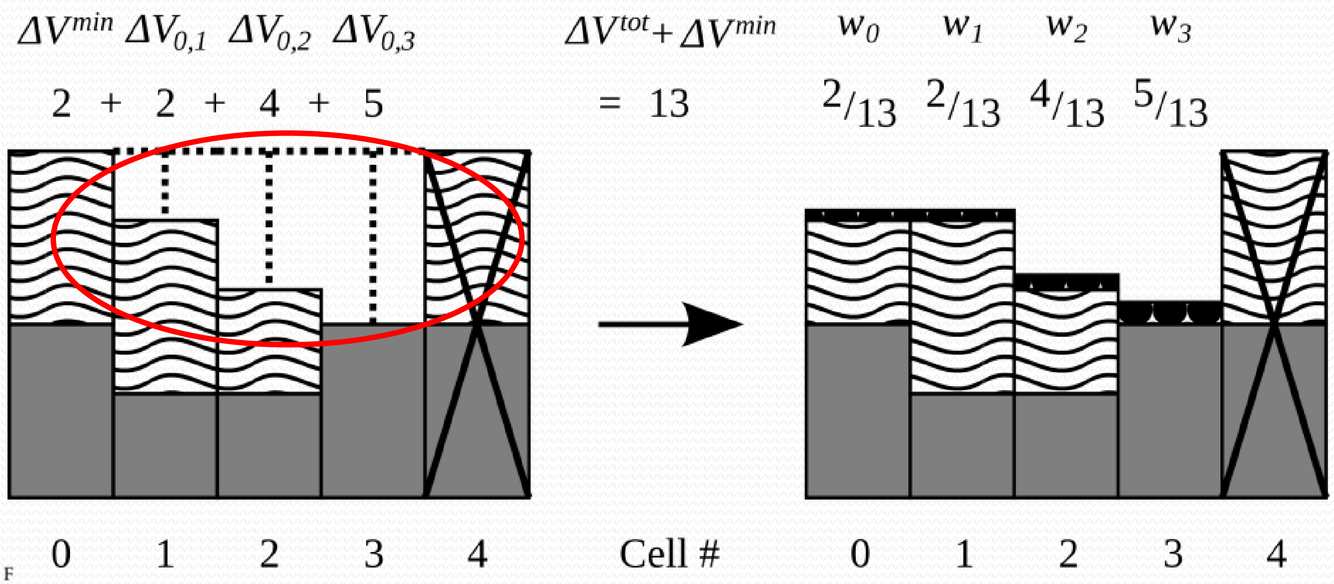
WCA2D Methodology

- For each neighbour cell:
  - Compute a weight that depends on the difference in water volume with the main cell



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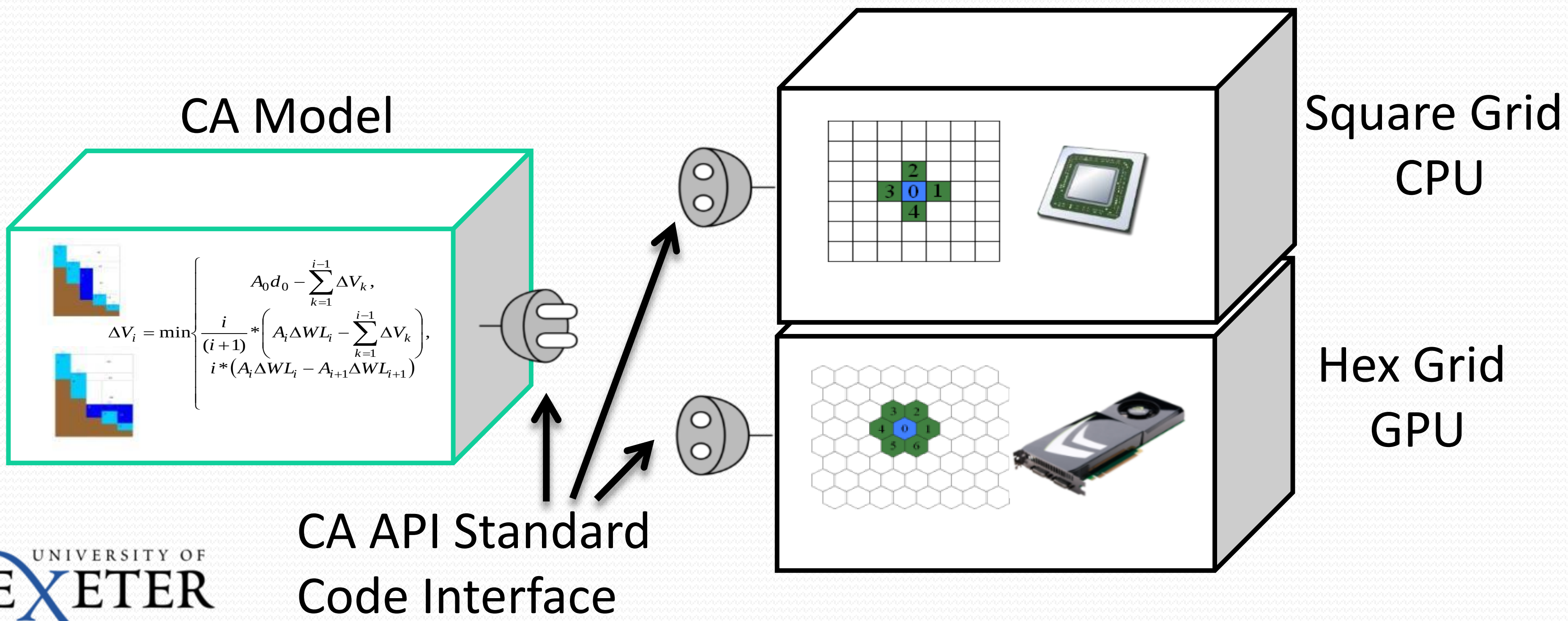
WCA2D Methodology

- The volume transferred between cells is capped by the Manning's formula
- The calculation is only applied to the neighbour cell with the largest weight to save computational cost
- Calculated once per cell

CADDIES Software Platform

- Integrates the numerical models with modern computing techniques



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Results
EA Benchmarks

Benchmarking model

Urban Inundation Model (UIM), a physically based non-inertial 2D model based on shallow water equations

$$\frac{\partial d}{\partial t}+\frac{\partial ud}{\partial x}+\frac{\partial vd}{\partial y}=q$$

$$\frac{\partial (d+z)}{\partial x}+\frac{n^2 u\sqrt{u^2+v^2}}{d^{\frac{4}{3}}}=0$$

$$\frac{\partial (d+z)}{\partial y}+\frac{n^2 v\sqrt{u^2+v^2}}{d^{\frac{4}{3}}}=0$$

where,

q : lateral source term

u : velocity in x-direction

v : velocity in y-direction

d : flow depth

z : bed elevation

n : Manning's Roughness

x,y,t : space and time coordinates

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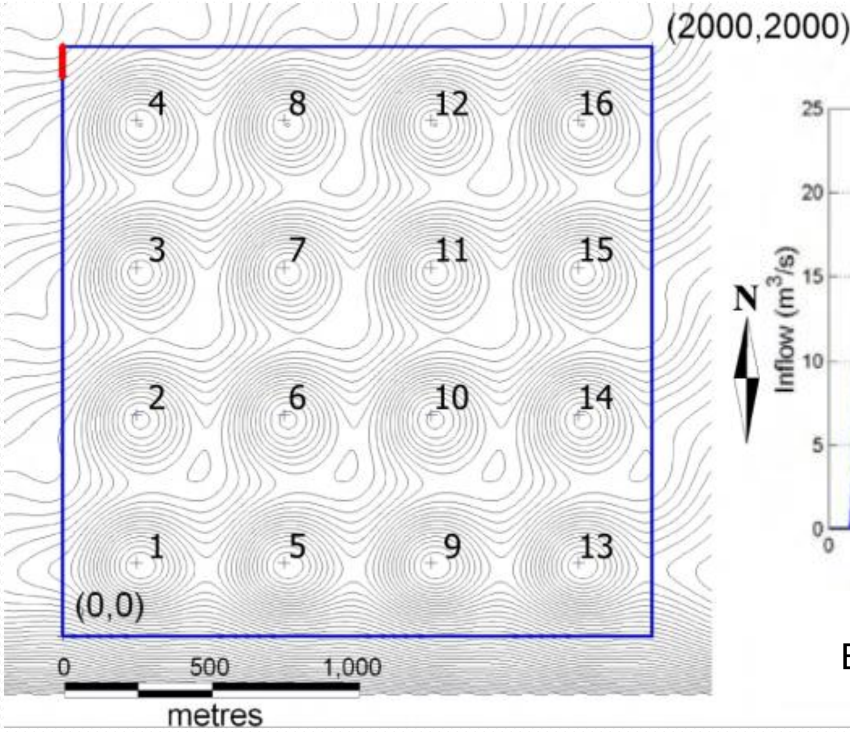
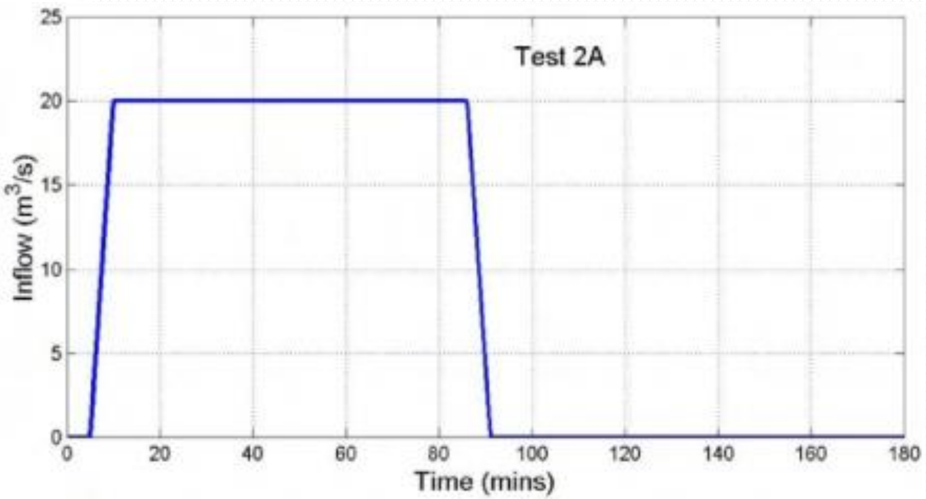
EA Benchmarks
Test cases

EA Benchmarking TEST2

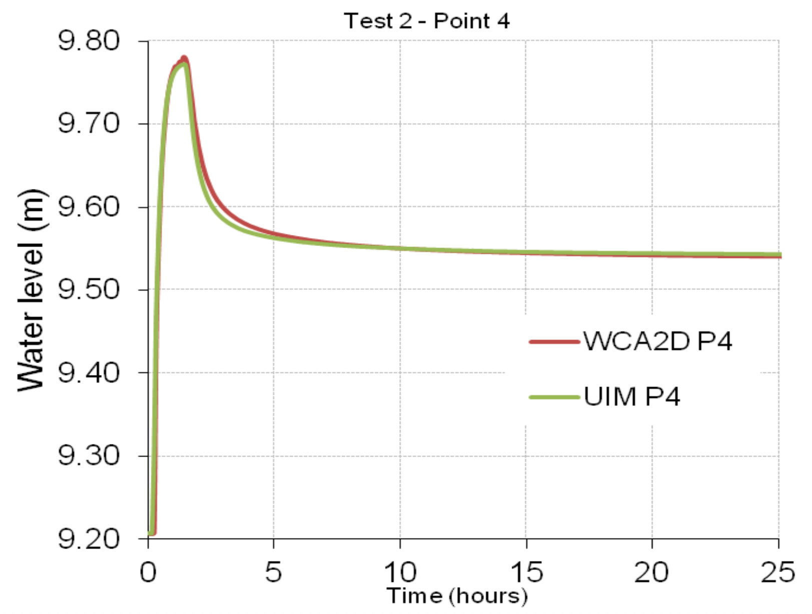
Terrain (plan) gently sloping (NW to SE) area with 4x4 matrix of ~0.5m deep depressions

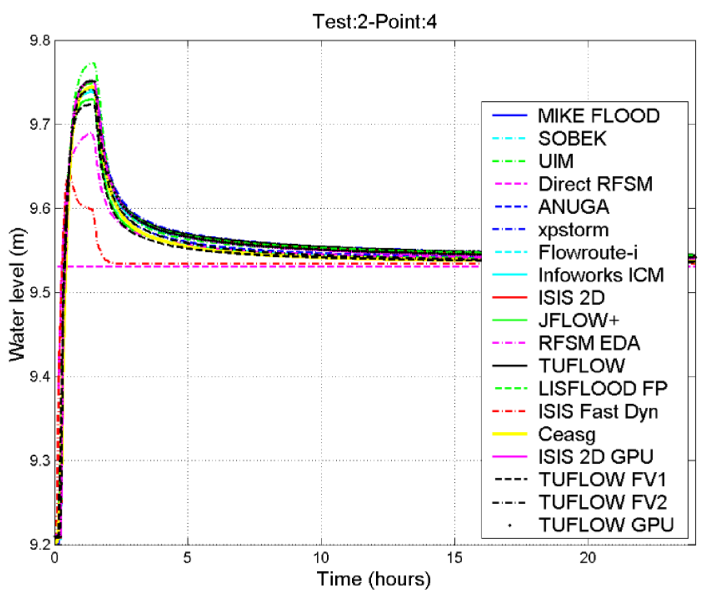




Boundary Condition: Inflow

Results: WCA2D – EAT2

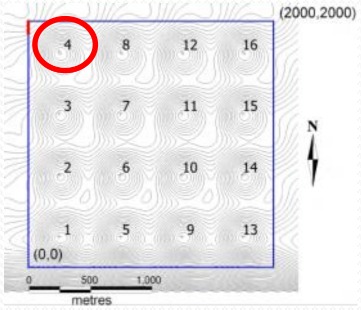




WCA2D And UIM

Multiple Models

Point 4



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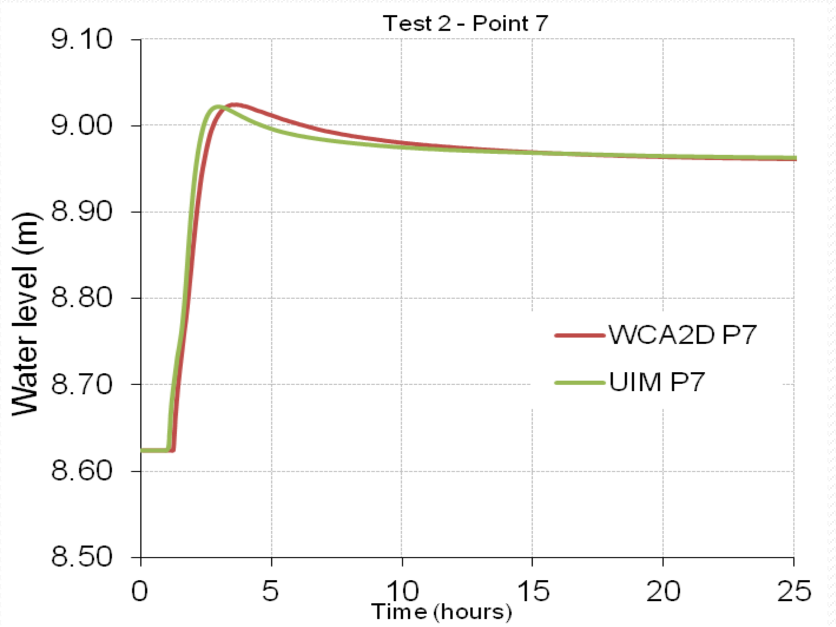
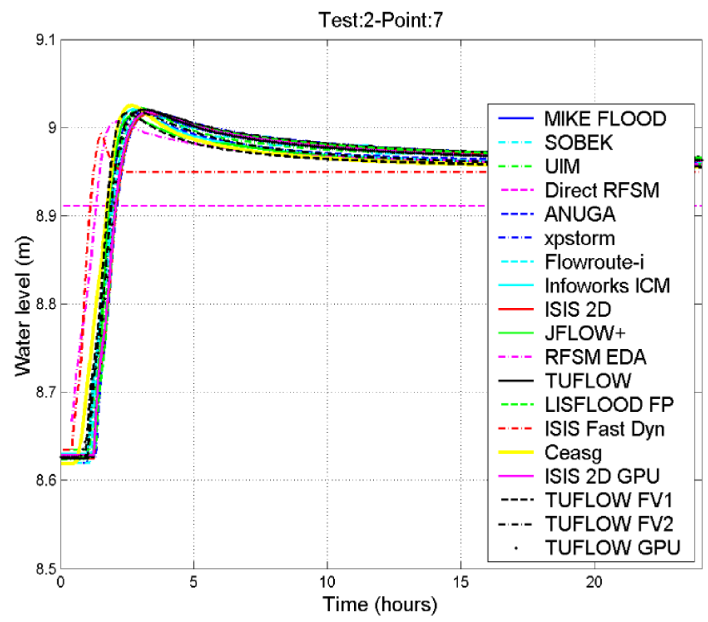
Results: WCA2D – EAT2

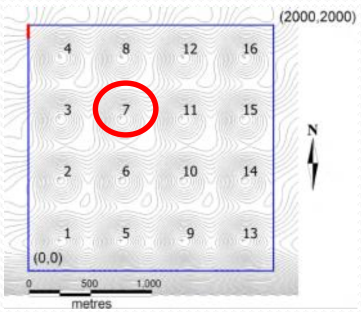


WCA2D And UIM



Multiple Models

Point 7



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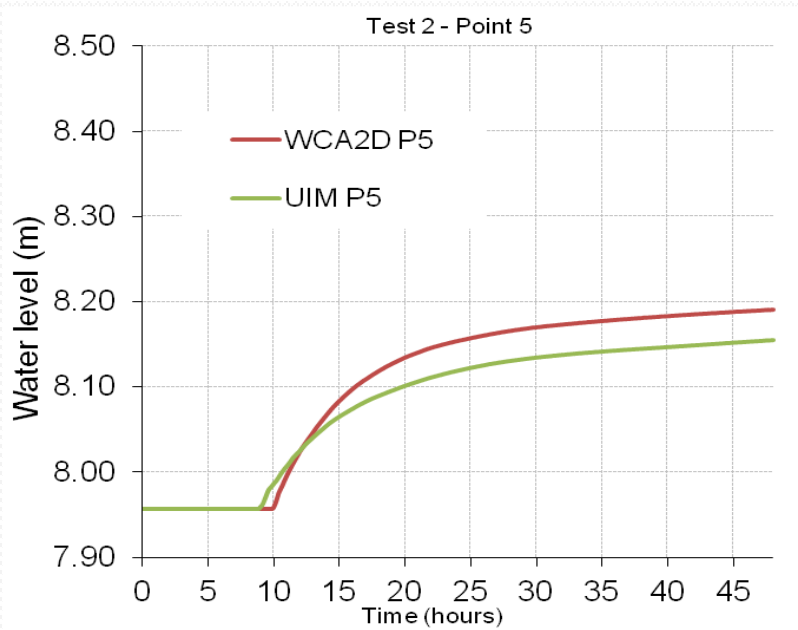
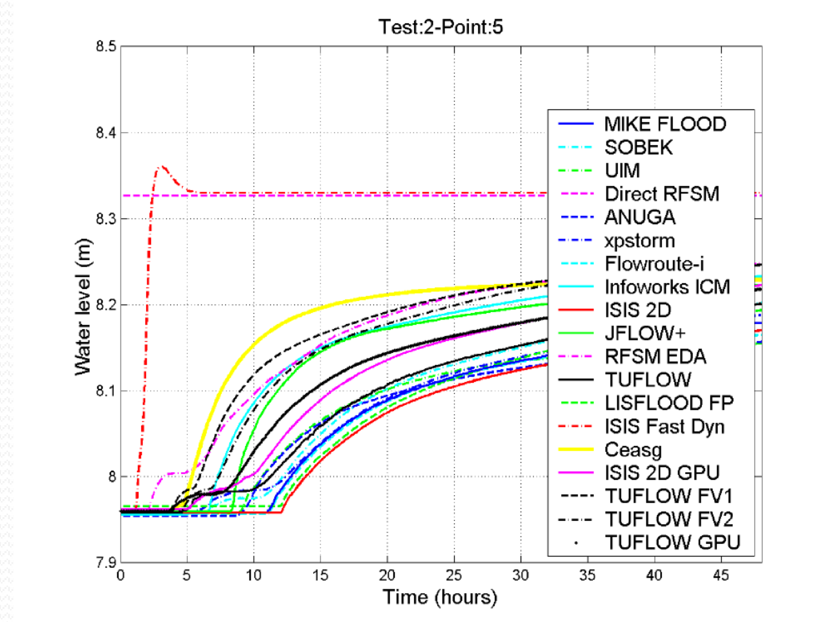
Results: WCA2D – EAT2

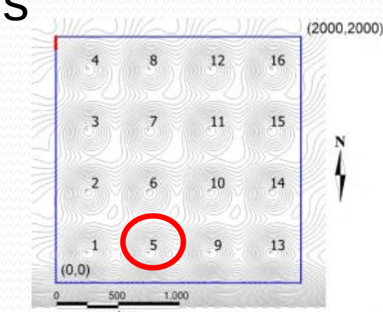


WCA2D And UIM



Multiple Models

Point 5



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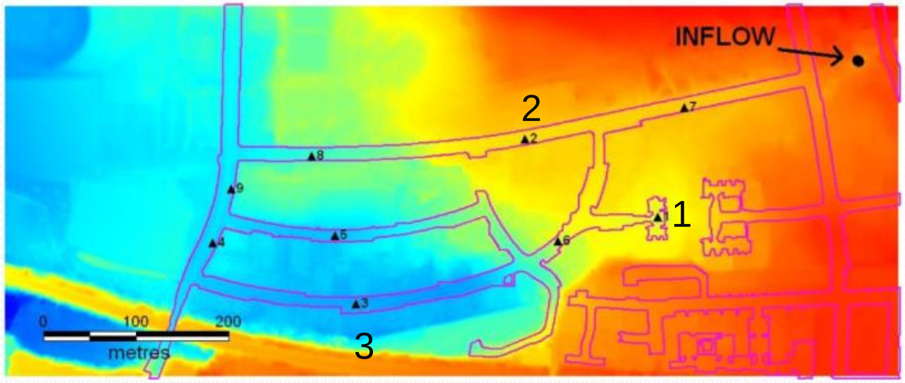
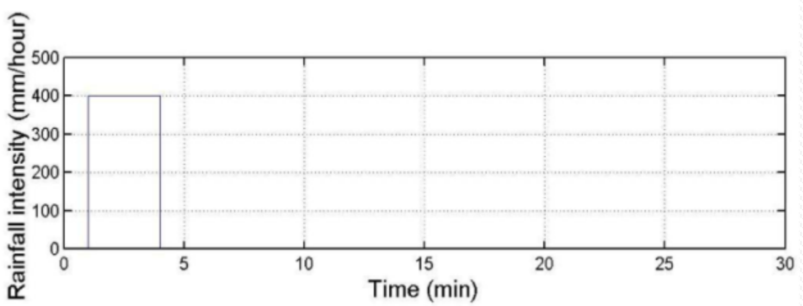
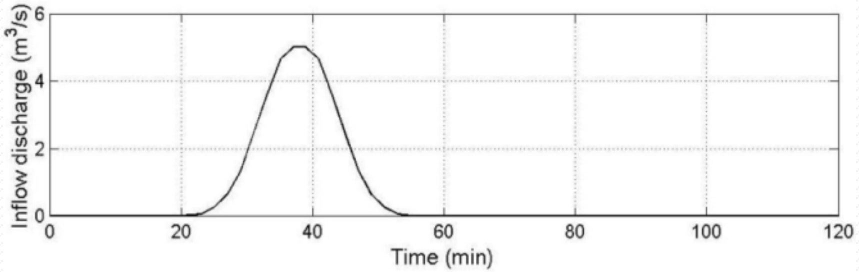
EA Benchmarking TEST8a

Terrain an approximately 0.4 km by 0.96 km urban area in Glasgow, UK







Boundary Condition : Rain (top), Inflow (bottom)

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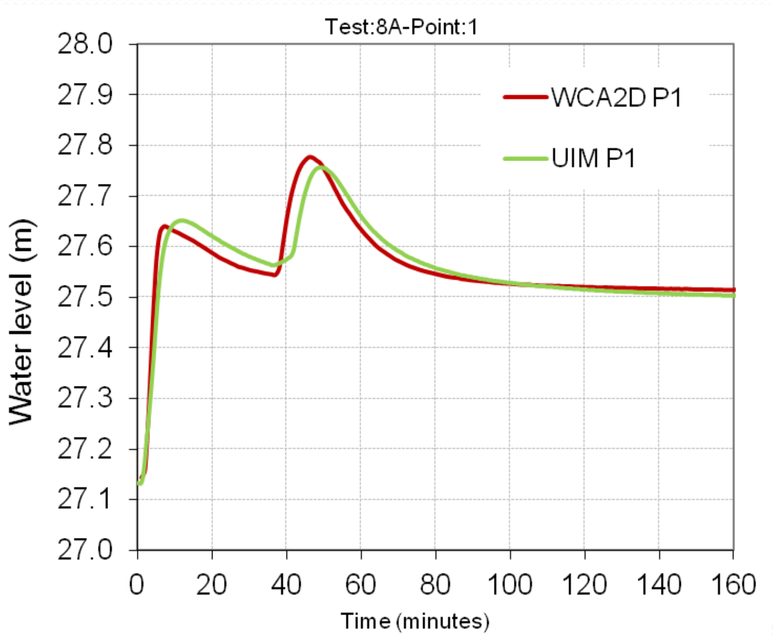
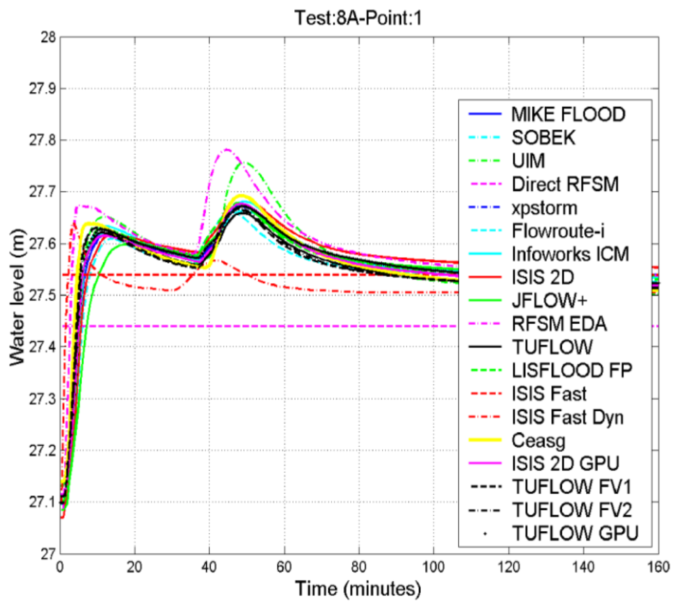
Results: WCA2D – EAT8a

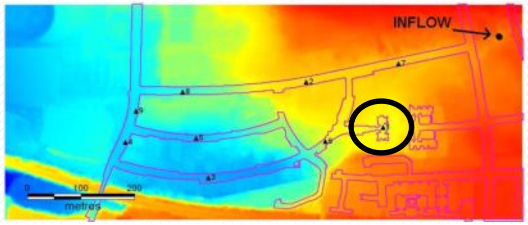


WCA2D And UIM



Multiple Models

Point 1



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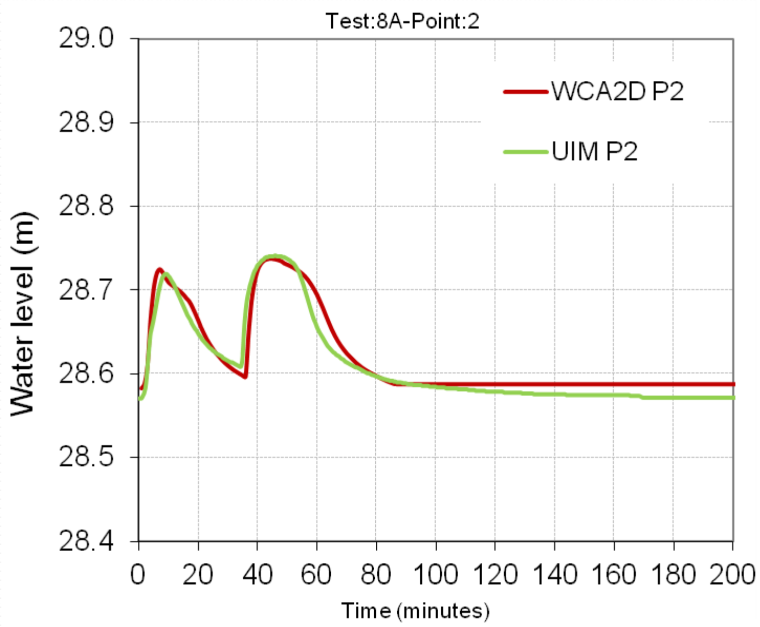
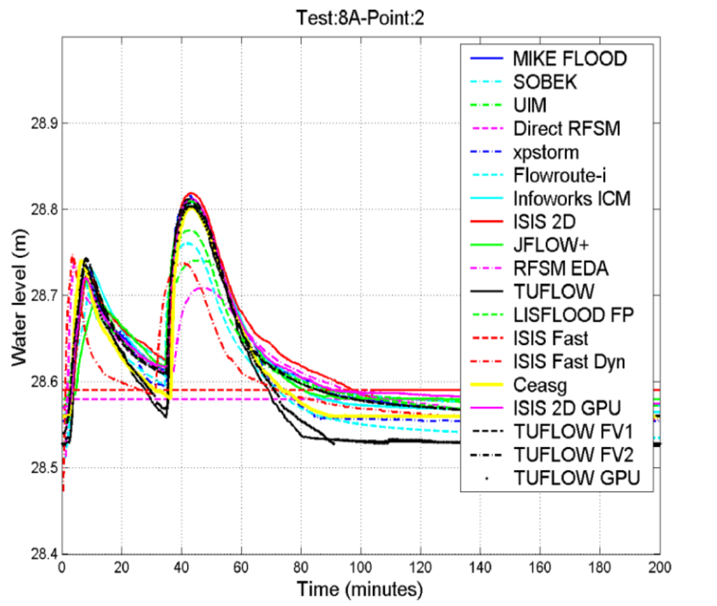
Results: WCA2D – EAT8a

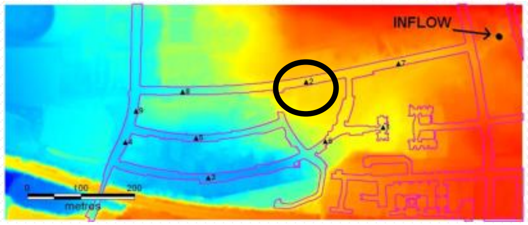


WCA2D And UIM



Multiple Models

Point 2



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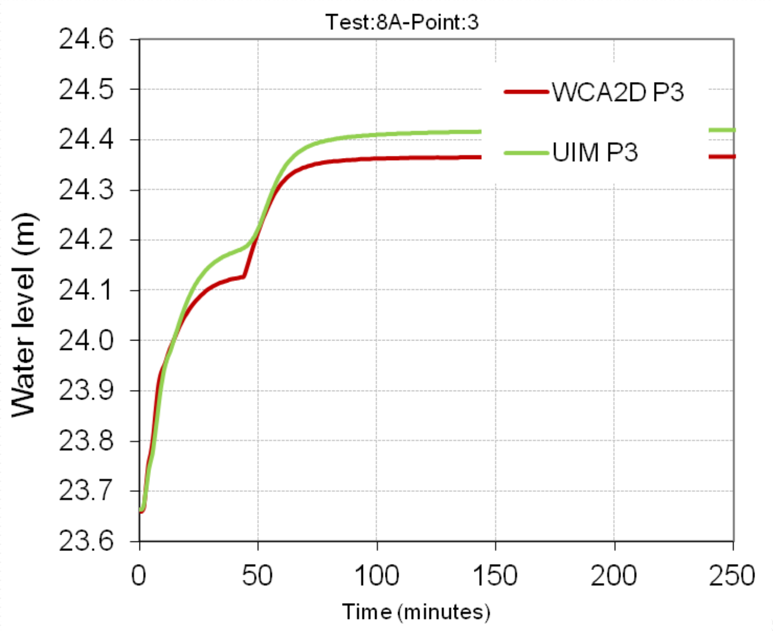
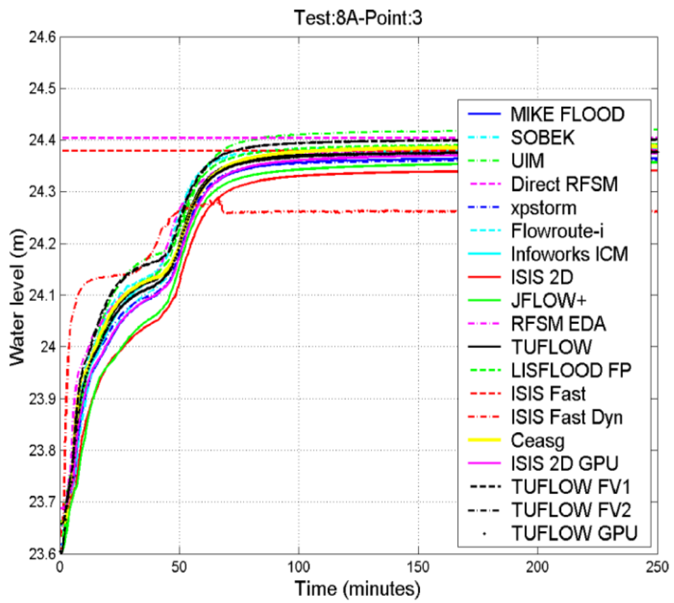
Results: WCA2D – EAT8a

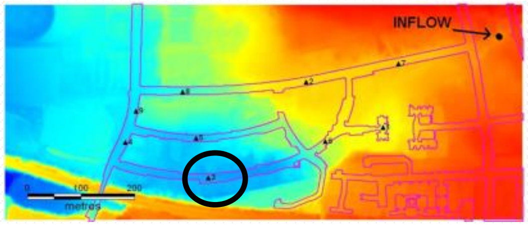


WCA2D And UIM



Multiple Models

Point 3



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Computation Time

- EA report contains run times
- Achieved using different hardware
- Table shows the minimum, median and first quartile run time obtained by all models

	Run Time	
	EAT2	EAT8a
Minimum	2 s	66.0 s
Median	12.1 s	297.5 s
1st Quartile	9.6 s	88.5 s
WCA2D GPU	3.84 s	33.9 s

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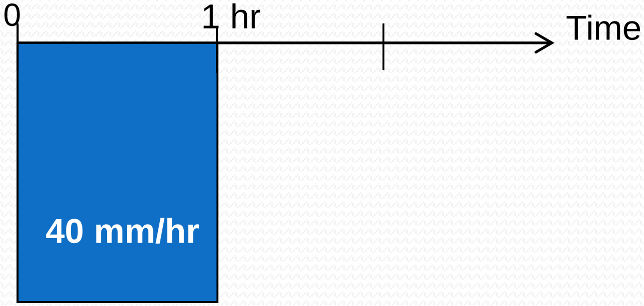
Results
Torquay test cases

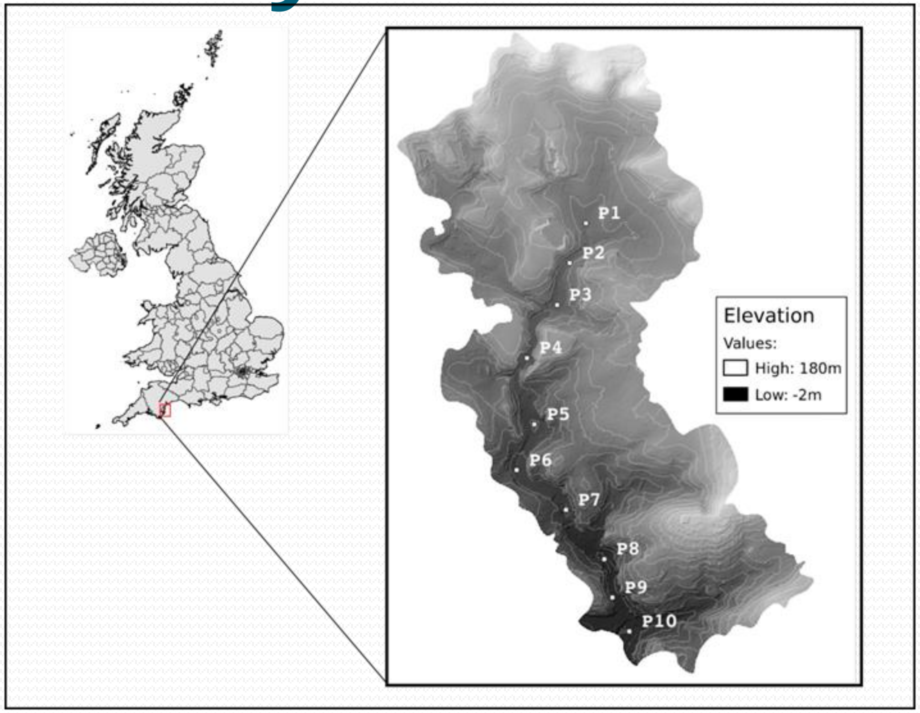
Torquay case study

<u>Boundary Condition</u>

Open boundaries

Rainfall: 40 mm/hr





- 8m resolution: ~120,000 cells
- 4m resolution: ~500,000 cells
- 2m resolution: ~2,000,000 cells

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Results analysis

- Compared WCA2D
  - InfoWorks ICM 3.0
- Using three metrics:
  - Maximum absolute error (MAD)
  - Root mean square error (RMSE)
  - R-squared (R^2)

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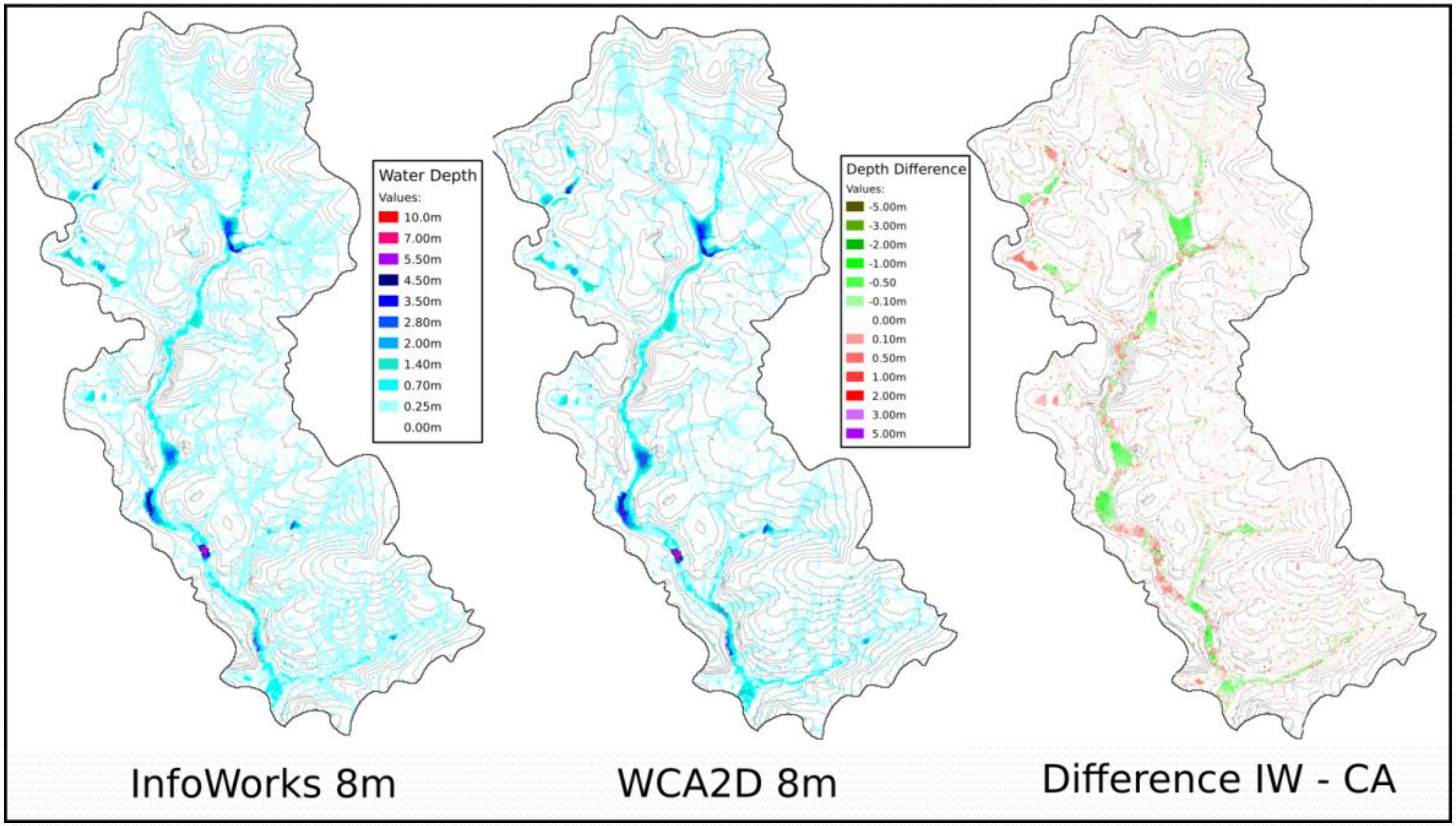
Maximum Inundation Depth



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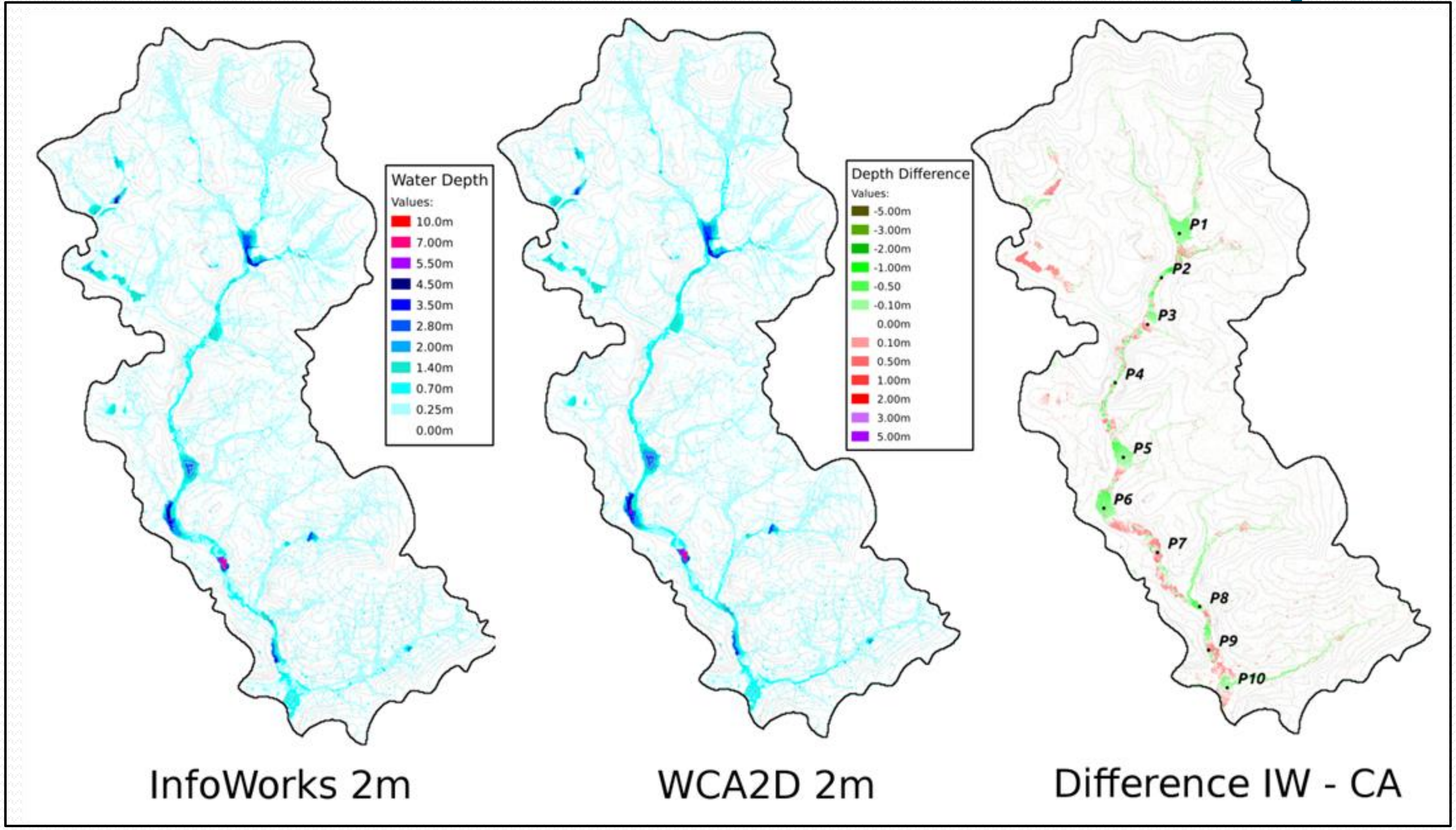
Maximum Inundation Depth

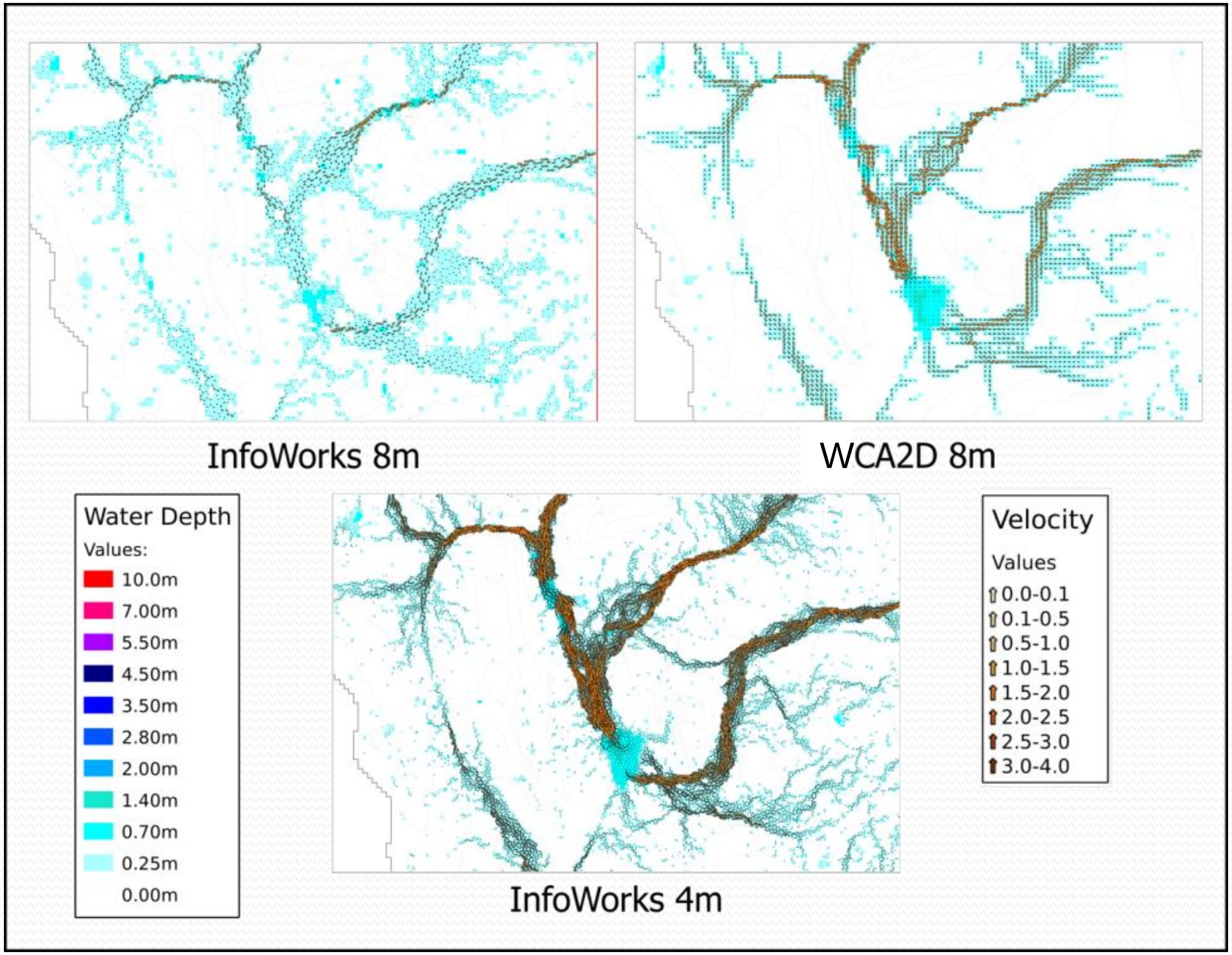


Results vs InfoWorks

Models comparison time / attribute	IW 8m – WCA2D 8m			IW 4m – WCA2D 4m			IW 2m – WCA2D 2m		
	MAD	RMSE	R2	MAD	RMSE	R2	MAD	RMSE	R2
30 Min.	2.12 m	0.08 m	0.77	2.42 m	0.05 m	0.92	1.52 m	0.04 m	0.96
60 Min.	2.59 m	0.11 m	0.89	2.86 m	0.08 m	0.95	2.80 m	0.06 m	0.97
90 Min.	3.35 m	0.27 m	0.94	5.52 m	0.26 m	0.95	4.73 m	0.25 m	0.95
120 Min.	4.14 m	0.24 m	0.97	3.11 m	0.16 m	0.99	3.39 m	0.12 m	0.99
360 Min.	3.56 m	0.27 m	0.98	3.11 m	0.14 m	0.99	2.75 m	0.10 m	0.99
720 Min.	3.54 m	0.28 m	0.98	3.11 m	0.14 m	0.99	2.73 m	0.11 m	0.99
Max. Depth	4.08 m	0.13 m	0.92	3.12 m	0.09 m	0.97	3.41 m	0.07 m	0.98
Max. Speed	3.42 m/s	0.35 m/s	0.81	3.71 m/s	0.39 m/s	0.83	5.36 m/s	0.44 m/s	0.84

- $R^2 > 0.95$ good agreement
- RMSE < 0.10m - max depth at 4m and 2m
- Only water depth at 30 Min. for 8m test case and maximum speed non satisfactory

Depth and Velocity at 30 min



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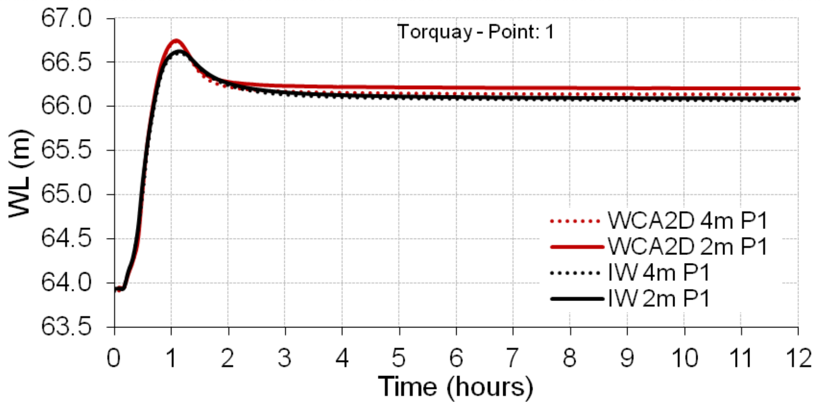
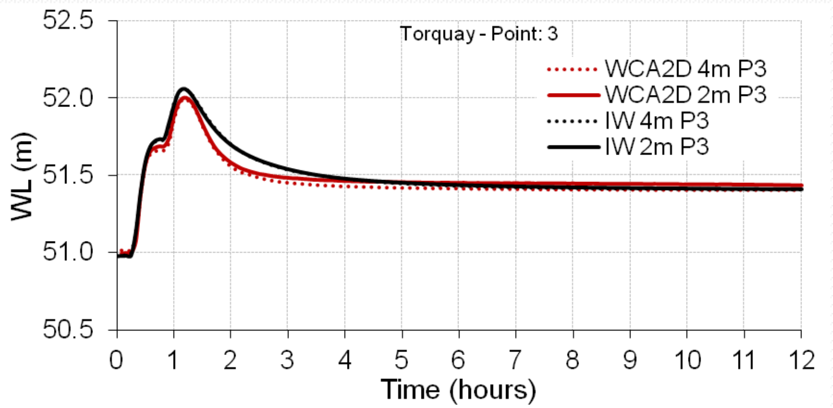
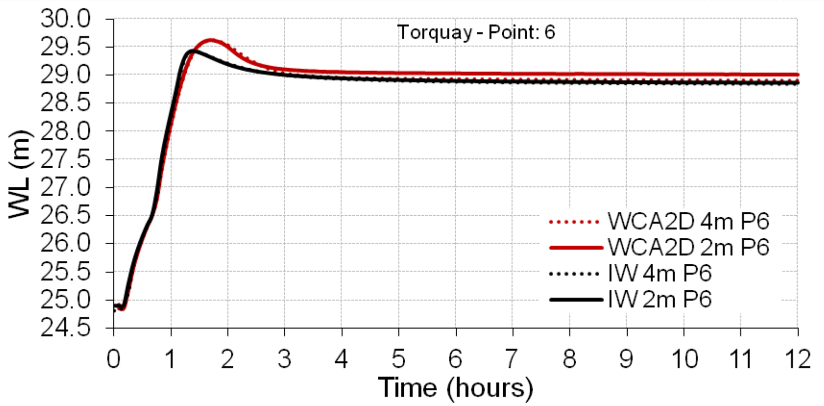
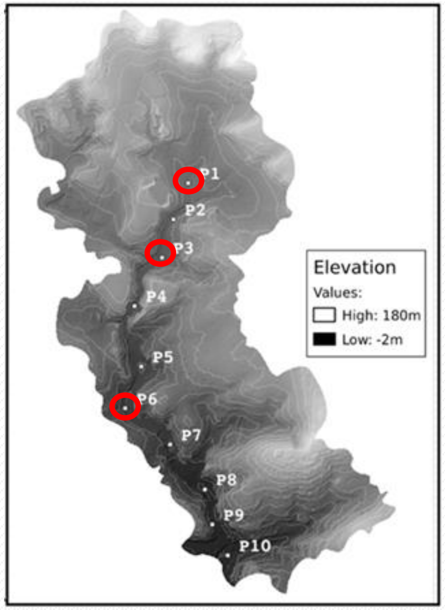
Results: Upstream Points









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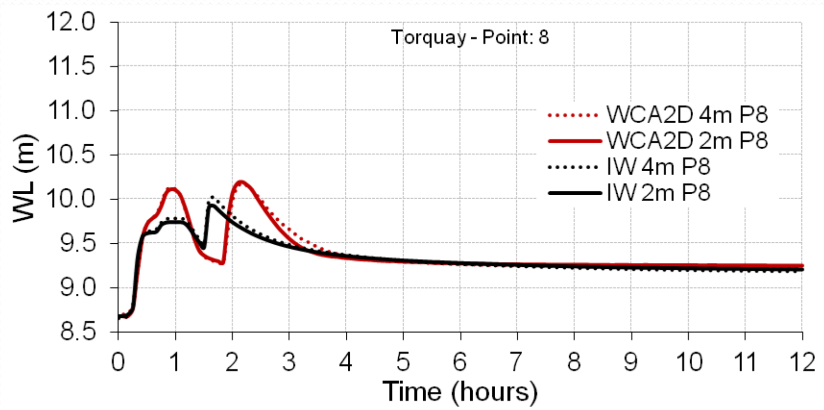
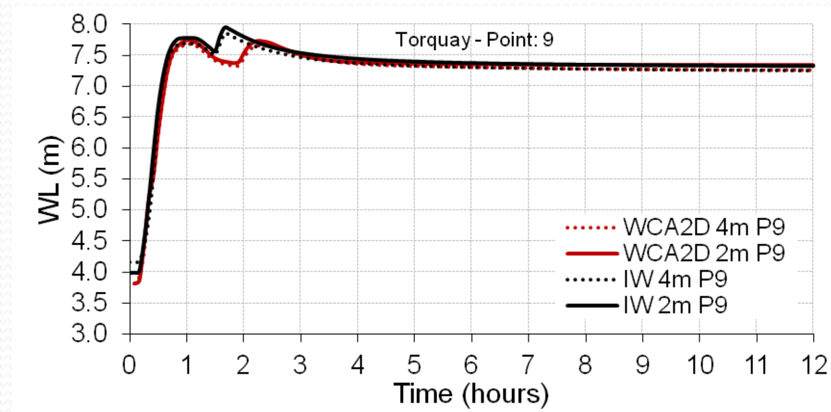
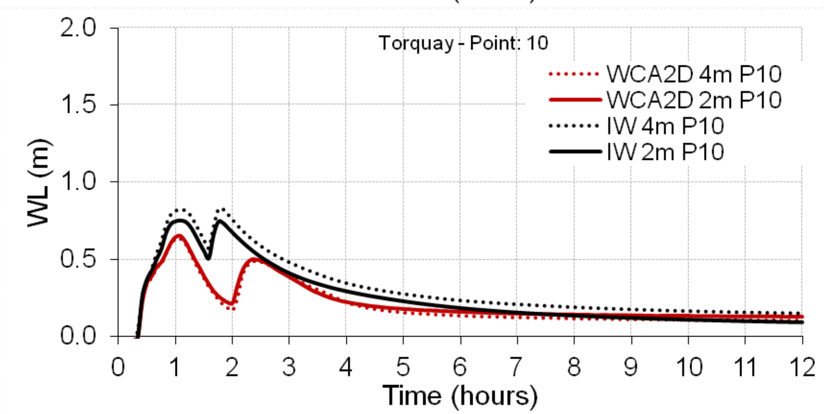
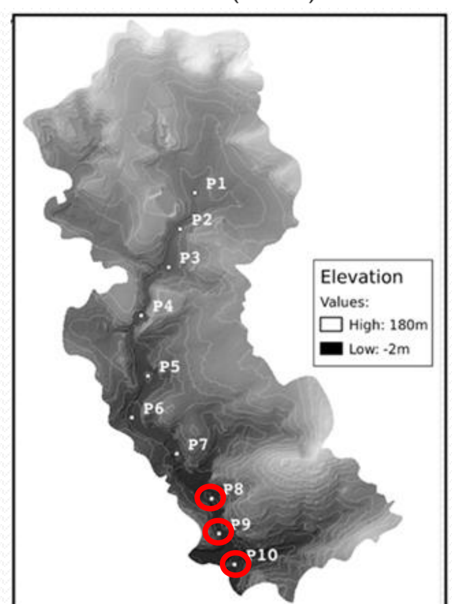
Results: Downstream Points









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Computation Time

	WCA2D 8m		IW 8m		WCA2D 4m		IW 4M		WCA2D 2m		IW 2m	
Memory	~12MB		~230MB		~45MB		~900MB		~280MB		~3600MB	
Type	MC	GPU	MC	GPU	MC	GPU	MC	GPU	MC	GPU	MC	GPU
Time (Min)	1.63	0.21	8.82	1.83	16.63	1.99	64.55	9.91	252.93	27.90	600.47	77.28
Sp vs IW	5.41	8.71	---	---	3.80	4.98	---	---	2.37	2.77		

- Run on multi-core CPU and GPU
- From 3x to over 8x faster then InfoWorks
- WCA2D use around 10 times less memory

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Results
Very Large Test case

Munich RE Data

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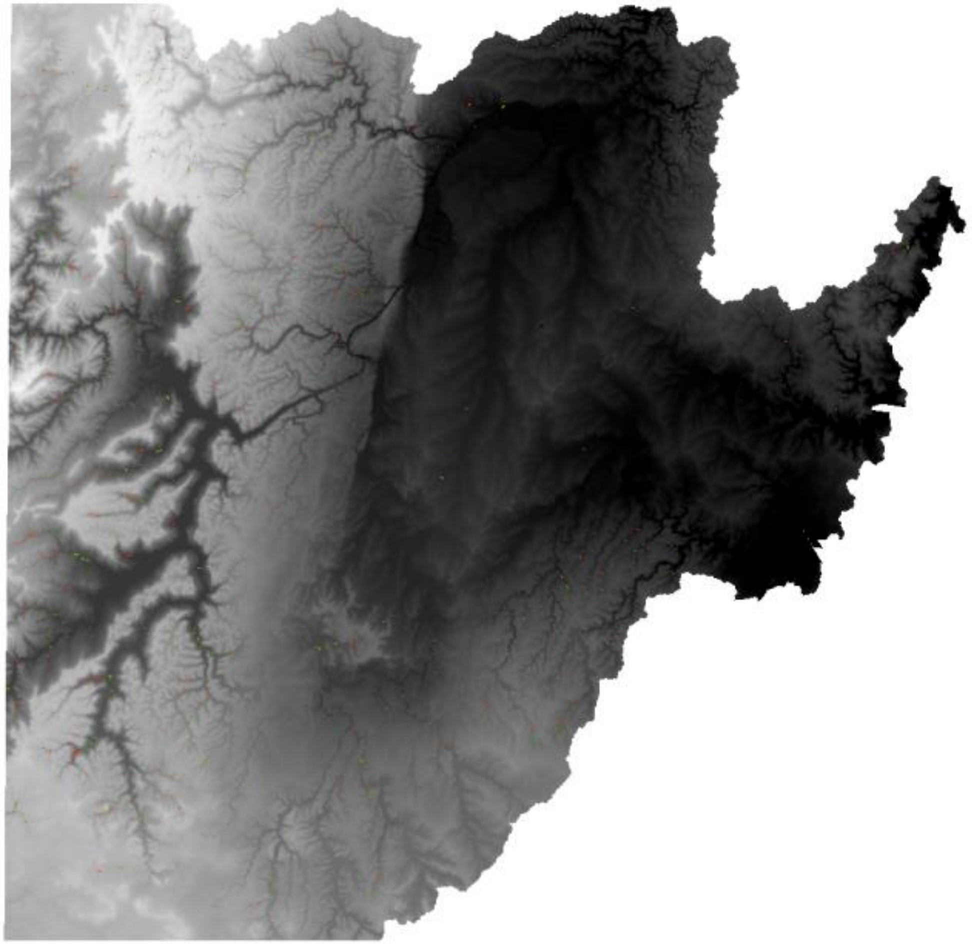
Sydney, Australia

- 3700 x 3700 cells
- ~14 million cells
- 30m x 30m



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Hardware

 

Name	Machine 1	Machine 2
Processor(s)	Intel i5-2500K 3.60GHz	2 x Intel Westmere 2.80GHz
Number of Cores	4	2 x 6
Memory	4 GB	24GB
Graphics Card	GeForce 550TI 192 Cores 1GB	N/A
Operating System	Windows 7, 64 bits	Linux, 64 bit
Note		1 Node of the Supercomputer

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Simulation Information

- WCA2D (Machine 1)
  - 4 cores CPU version
  - GPU version 24 hrs simulation

- UIM (Machine 2)
  - 12 cores CPU version
  - 24 hours simulation

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Results Case A and B

Name	WCA2D MC A	WCA2D GPU A	UIM A
Run Time Min.	Tot. (Model) 21 (14)	Tot. (Model) 11 (4)	Tot. 2091
RMSE > 0.01m	0.51m		---
Correlation	0.926		

Name	WCA2D MC B	WCA2D GPU B	UIM B
Run Time	Tot. (Model) 22 (15)	Tot. (Model) 11 (4)	Tot. 1972
RMSE > 0.01m	0.61m		---
Correlation	0.922		

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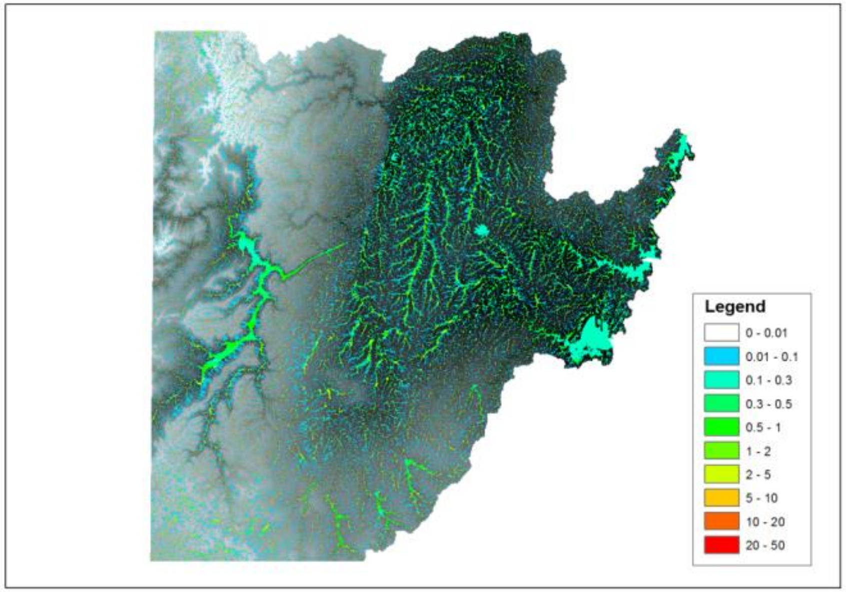
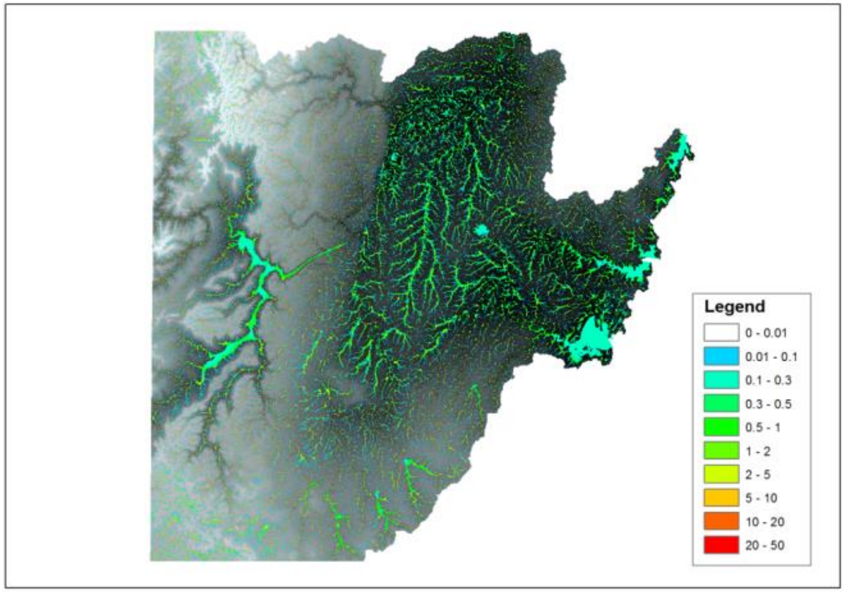
Results Case A

UIM / Case A / Peak Values



(a)

ICA2D / Case A / Peak Values



(b)

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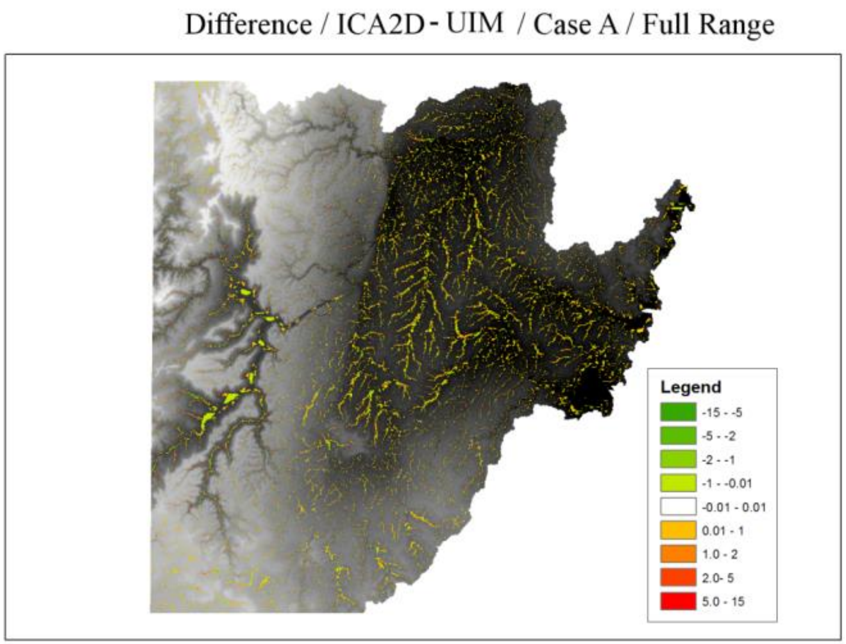
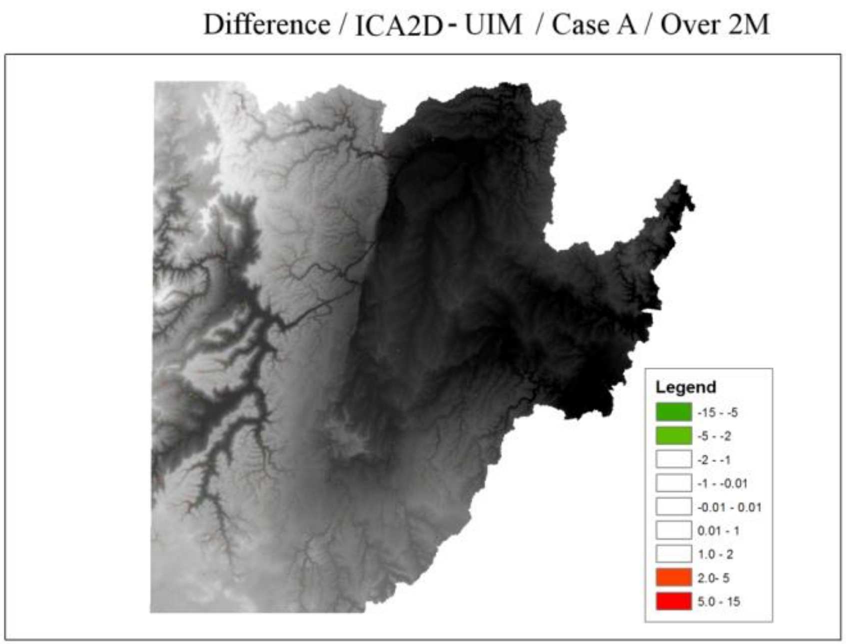
Results Case A Difference



(c)



(d)

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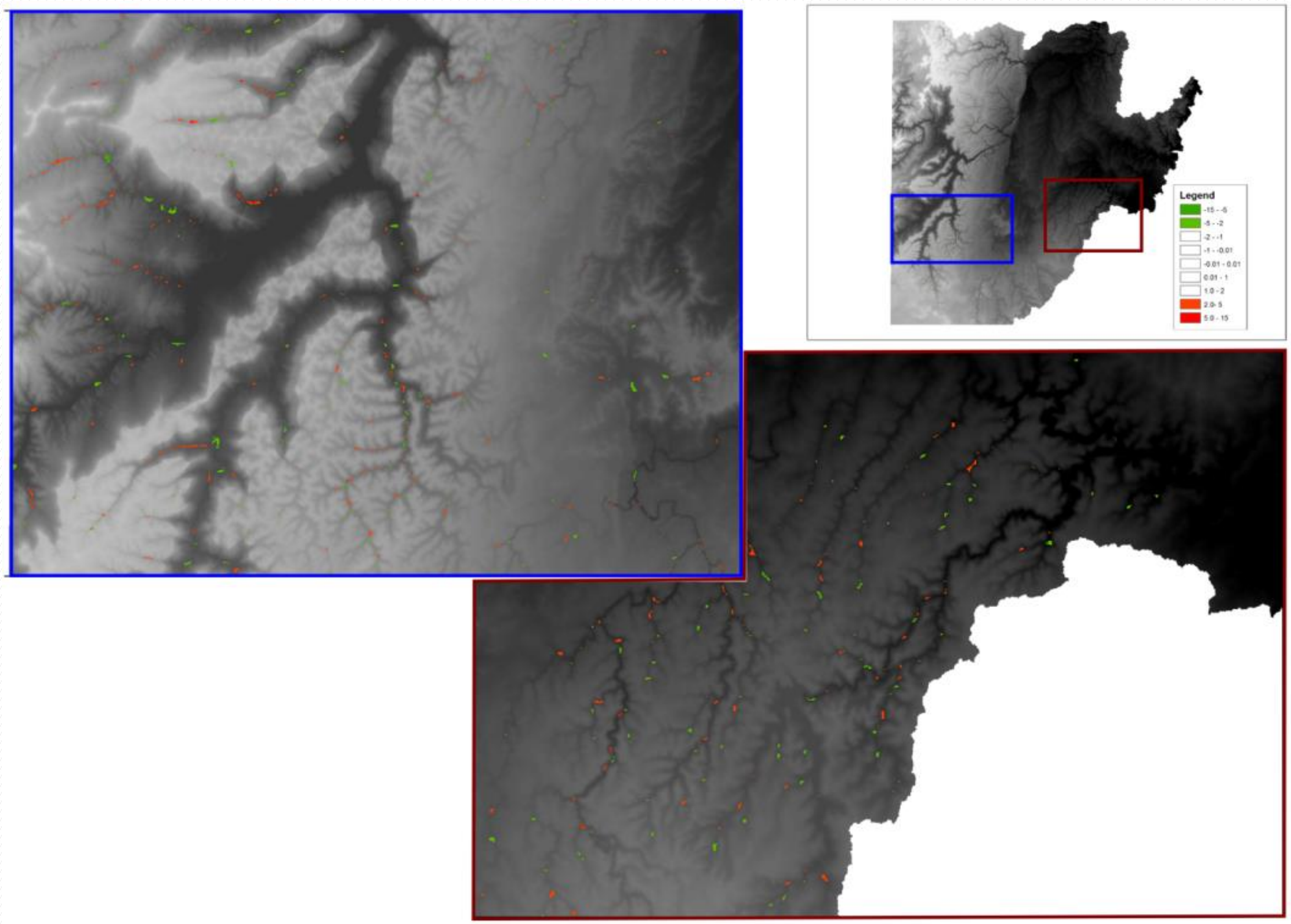
Results Case A Zoom



Extra Simulations

- Planned extra comparisons (on Machine 1)
  - InfoWorks ICM 3.0
- ICM was not able to complete a simulation due to memory limitation on the machine
  - When set with 6M triangles
  - Compared to around 10M of WCA2D
- Worked with 2.5M triangles
  - Run time was around 6 hours (4 cores)

1D vs. 2D risk of flooding from pipes

ICS Consultants Ltd.

University of Exeter
Centre for Water Systems

Ageing assets… Thames Water £4m bill for Herne Hill flood after burst water main – August 2013

Herne Hill was swamped when an 88-year-old main burst

Consequences - 1D Flood Routing

Consequences - 1D versus 2D Flood Risk

Consequences - 1D versus 2D Flood Risk

Summary

- Developed a fast 2D flood model that uses a CA technique
- Rules (not SWE) developed manually, based on problem physics
- Produced results comparable to UIM and InfoWorks
- Runs quicker than UIM and InfoWorks in the examples showed

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Future Work

- A new advance version of the model
  - Spatial roughness, infiltration, rainfall
  - Batch execution
  - Further ~30% faster and more accurate
- Automatic generation of transition rules
  - Genetic Programming

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Thank You
Questions?

d.savic@exeter.ac.uk