Benchmarking of 2D hydraulic modelling packages RESULTS

This report summarises how the software package (described in the table below) performed in the benchmark tests developed during the Joint Defra / Environment Agency research programme. The report from the research project was published in June 2010 and is available from the Environment Agency (summary and report). To access the test specification and datasets email fcerm.evidence@environment-agency.gov.uk.

Software name:	**TUFLOW** **TUFLOW GPU Module**	**TUFLOW FV**
Software version:	2012-05-AA	2012.000b
Software developer:	BMT WBM Pty Ltd TUFLOW Flood and Tide Simulation Software Web: www.tuflow.com Forum: http://www.tuflow.com/forum/index.php Wiki: http://wiki.tuflow.com/ Tutorial/Demo Model: http://www.tuflow.com/Tutorial%20Model.aspx	
Report completed by:	Bill Syme, Ian Teakle, Greg Collecutt, Phillip Ryan	
Report completed on:	15 June, 2012	
Report supersedes:	TUFLOW: Supersedes 2010 Report TUFLOW GPU Module: First Report TUFLOW FV: Supersedes 2010 Report	

Report contents

Contents

Software and hardware details

Name of software	TUFLOW		TUFLOW FV
	"Classic"	**GPU Module**	
Version of software	2012-05-AA		2012.000b
Software developer	BMT WBM Pty Ltd	BMT WBM Pty Ltd	BMT WBM Pty Ltd
Numerical scheme of software	**2D:** 2nd order finite difference alternating direction implicit scheme over a regular grid of square elements. 2D scheme solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity. **1D:** Finite difference Runge-Kutta explicit scheme. 1D scheme solves all terms of the St Venant equations.	Finite volume scheme over a regular grid of square elements. Several order options, with 1st order spatial, 4th order time used. 2D scheme solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity.	Finite volume 1st and 2nd order schemes over a flexible mesh of triangular and/or quadrilateral elements. 2D scheme solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity.
Shock capturing scheme	1D and 2D schemes automatically switch between upstream and downstream controlled flow regimes to represent shocks.	Finite volume shock capturing capability used.	Finite volume shock capturing capability used.

1D-2D linkages	Yes. Range of 1D/2D linkages based on one of: • Full 2D solution across 1D/2D interface that preserves momentum for downstream controlled regimes, and automatically switches with upstream controlled regimes (eg. weir or supercritical flow). • 2D sink/source ideally suited to linking drains/gully traps/pits/manholes and small culverts under embankments. TUFLOW 2D scheme is linked with the internal scheme (ESTRY), ISIS and XP-SWMM 1D. ESTRY is also linked with ISIS via ISIS-TUFLOW-PIPE.	Not yet available.	Embedding of 1D stage discharge relationships to model structures available. More advanced 1D/2D linking similar to TUFLOW “Classic” under development.
For any queries or additional information on TUFLOW or TUFLOW FV, please email support@tuflow.com.			

Hardware details

Minimum recommended hardware specification	**Make**	Any Windows based or compatible PC.		
	Model	No restrictions.		
	Type	No restrictions.		
	Cores	No minimum requirement. TUFLOW FV is parallelised and a simulation will run faster if more than one core is available.		
	RAM	2GB		
	Operating system	Any Windows O/S, but only later ones (Windows 2000 onwards) recommended. TUFLOW FV compiled for Linux, but not yet commercially available under Linux.		
	CPU processing	32 or 64-bit		
	Graphics card	No restrictions for TUFLOW “Classic” and TUFLOW FV. TUFLOW GPU Module presently only functional for latter NVidia GPUs.		
Hardware specification used to carry out tests	**Software**	**TUFLOW**	**TUFLOW GPU**	**TUFLOW FV**
	Make	Dell	Dell	Dell
	Model	Intel Core i7-2600 3.4GHz	Intel Xeon X5355 2.66 GHz	Intel Xeon X5690 3.47 GHz
	Type	Desktop	Desktop	Desktop
	CPU Cores	4	8	12
	RAM	16GB	8GB	24GB
	Operating system	Windows 7	Windows 7	Windows 7
	CPU processing	64-bit	64-bit	64-bit
	Graphics card	ATI Radeon HD 5450	NVidia Tesla C2075	NVidia Quadro FX3800

Tests completed

Test	Description	Test complete / reason for not completing			Justification
		TUFLOW	TUFLOW GPU	TUFLOW FV	
1	Flooding a disconnected water body	Yes	Yes	Yes	
2	Filling of floodplain depressions	Yes	Yes	Yes	
3	Momentum conservation over a small (0.25m) obstruction.	Yes	Yes	Yes	
4	Speed of flood propagation over an extended floodplain.	Yes	Yes	Yes	
5	Valley flooding	Yes	Yes	Yes	
6A	Dam break	Yes	Yes	Yes	
6B	Dam break	Yes	Yes	Yes	
7	River to floodplain linking	Yes	No	No	For TUFLOW GPU and TUFLOW FV, linked 1D River + 2D Floodplain modelling not supported (in development).
8A	Rainfall and sewer surcharge flood in urban areas	Yes	Yes	Yes	
8B	Rainfall and sewer surcharge flood in urban areas	Yes	No	No	For TUFLOW GPU and TUFLOW FV, linked 1D Pipe + 2D Floodplain modelling not supported (in development).

Test results

Test 1: Flooding a disconnected water body

Objective:

The objective of the test is to assess basic capabilities such as handling disconnected water bodies and wetting and drying of floodplains.

Description:

This test consists of a sloping topography with a depression as illustrated in Figure (a). The modelled domain is a perfect 700m x 100m rectangle. A varying water level, see Figure (b), is applied as a boundary condition along the entire length of the left-hand side of the rectangle, causing the water to rise to level 10.35m. This elevation is maintained for long enough for the water to fill the depression and become horizontal over the entire domain. It is then lowered back to its initial state, causing the water level in the pond to become horizontal at the same elevation as the sill, 10.25m.

Figure (a): Plan and profile of DEM used in Test1. The area modelled is a perfect rectangle extending from X=0 to X=700m and from Y=0 to Y=100m as shown.

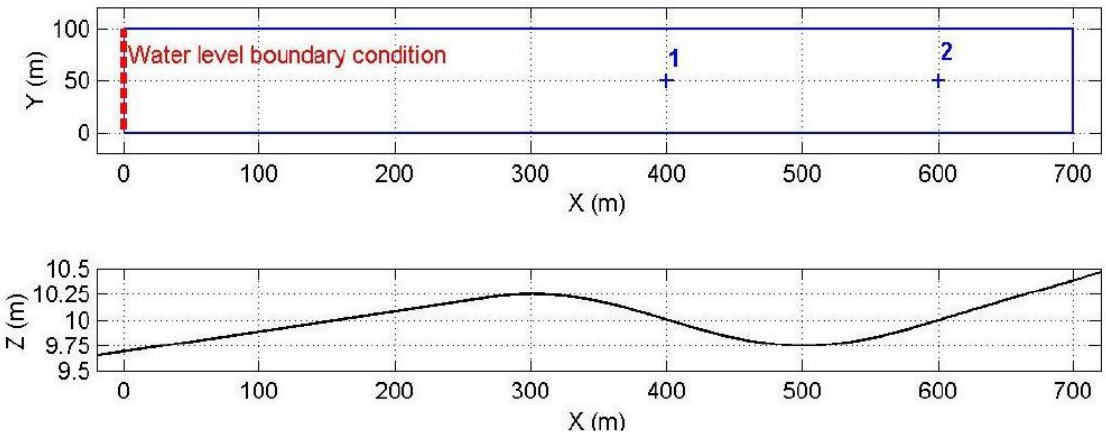
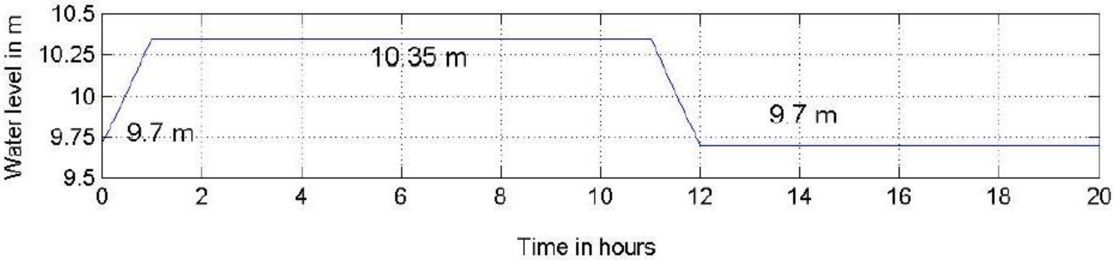


Figure (b): Water level hydrograph used as a boundary condition (table provided as part of the test input dataset)



Boundary and initial conditions:

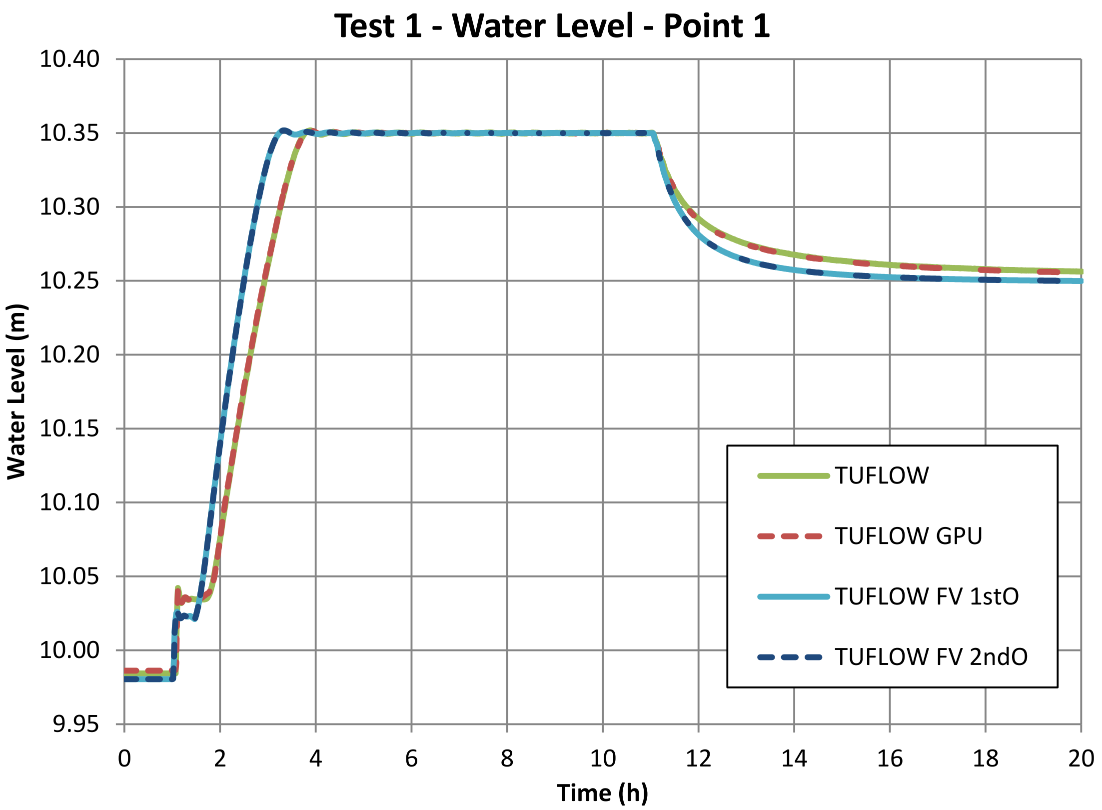
- Varying water level along dashed red line shown in figure (a). Figures provided as part of the test input dataset;
- All other boundaries closed;
- Initial condition: water elevation = 9.7m.

Parameter values:

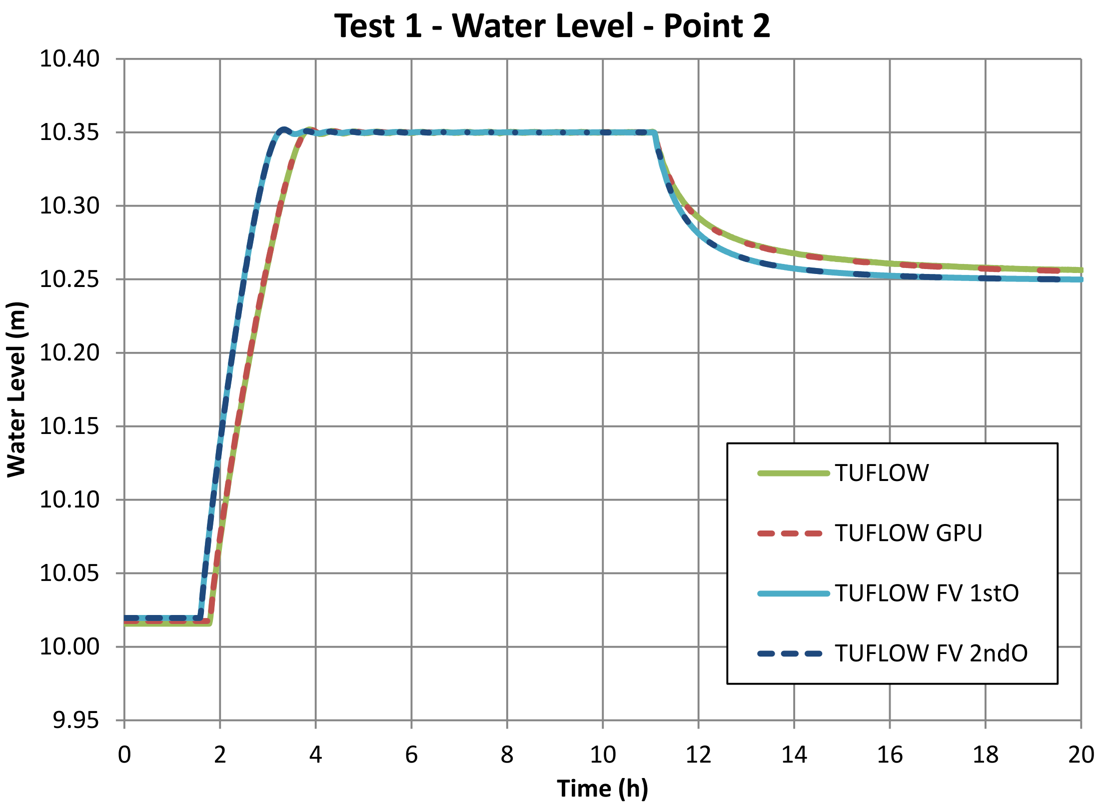
- Manning's n: 0.03 (uniform)
- Model grid resolution: 10m (or 700 nodes in modelled area)
- Time of end: model is to be run until time t = 20 hours

Results:

Test 1, point 1: Water level versus time (output frequency 60s)



Test 1, point 2: Water level versus time (output frequency 60s)



Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.03	0.03	0.03	0.03
Grid	10m	10m	10m	10m
Time-stepping	Adaptive (15 to 60s)	Adaptive (1.7 to 2.1s)	Adaptive (~1.9s)	Adaptive (~1.9s)
Total simulation time (hrs)	0.0006 (2.1s) 1 CPU Core	0.0056[1] (20s) 448 GPU Cores	0.0012 (4.4s) 12 CPU Cores	0.0019 (6.7s) 12 CPU Cores

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: No distinguishable change in results from the 2010 report. However, enhancements in the 2012-05-AA release means the model can be run on larger timesteps, with or without adaptive time-stepping, and with no significant mass error (-0.6% in 2010 vs 0.0% in 2012).

TUFLOW GPU: Gives near identical results to TUFLOW.

TUFLOW FV: Further developments to the 2nd Order solution have produced a quicker response from that in the 2010 report.

Test 2: Filling of floodplain depressions

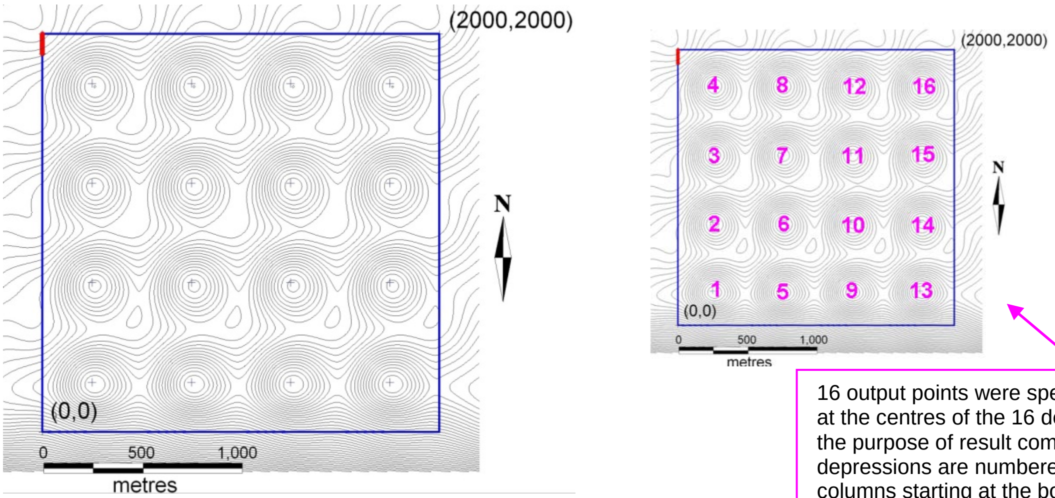
Objective:

The test has been designed to evaluate the capability of a package to determine inundation extent and final flood depth, in a case involving low momentum flow over a complex topography.

Description:

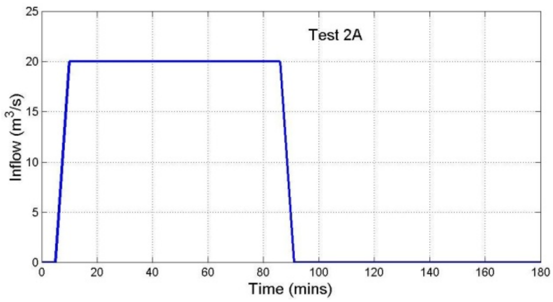
The area modelled, shown in Figure (a), is a perfect 2000 m x 2000 m square and consists of a 4 x 4 matrix of ~0.5 m deep depressions with smooth topographic transitions. The DEM was obtained by multiplying sinusoids in the North to South and West to East directions and the depressions are all identical in shape. An underlying average slope of 1 : 1500 exists in the North to South direction, and of 1 : 3000 in the West to East direction, with a ~2m drop in elevation along the North-West to South-East diagonal. The inflow boundary condition is applied along a 100m line running South from the North Western corner of the modelled domain, see Figure (a). A flood hydrograph with a peak flow of 20m3/s and time base of ~85mins is used (figure b)). The model is run for 2 days (48 hours) to allow the inundation to settle to its final state.

Figure (a): Map of the DEM showing the location of the upstream boundary condition (red line), ground elevation contour lines every 0.05 m, and output point locations (crosses).



16 output points were specified, located at the centres of the 16 depressions. For the purpose of result comparison the depressions are numbered 1 to 16 in columns starting at the bottom left

Figure (b): Inflow hydrograph used as upstream boundary condition.



Boundary and initial conditions:

- Inflow along the red line in Figure (a). Location and tables provided as part of dataset.
- All other boundaries are closed.
- Initial condition: Dry bed.

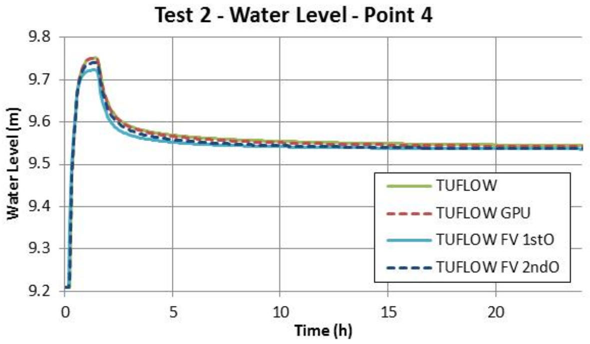
Parameter values:

- Manning's n: 0.03 (uniform)
- Model grid resolution: 20m (or ~10000 nodes in the area modelled)
- Time of end: model is to be run until time t = 48 hours

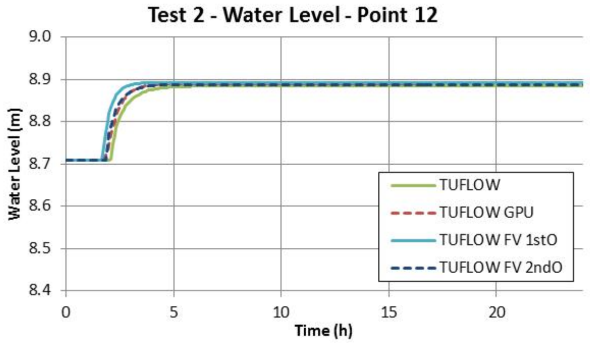
Results:

Water level versus time (output frequency 300s)

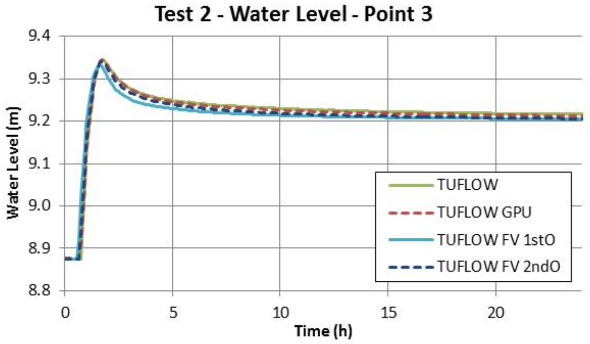
Test 2, point 4:



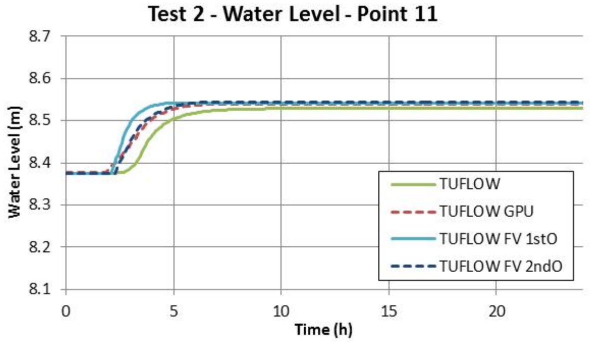
Test 2, point 12:



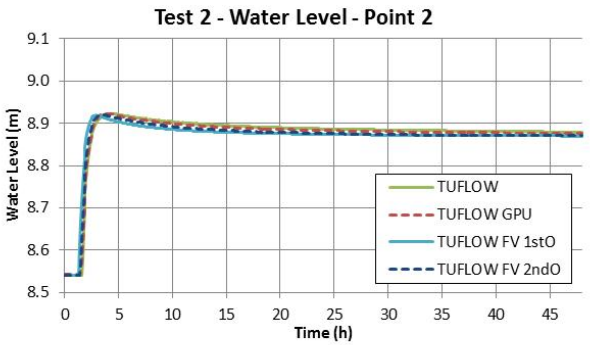
Test 2, point 3:



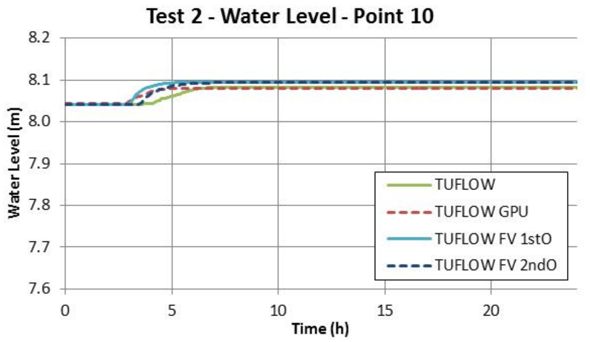
Test 2, point 11:



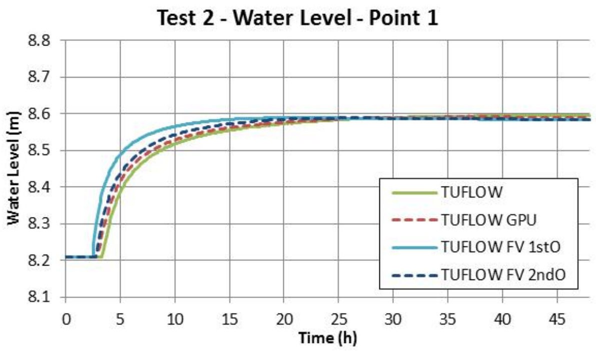
Test 2, point 2:



Test 2, point 10:



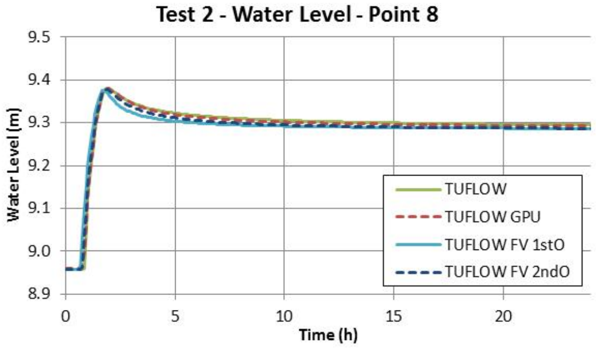
Test 2, point 1:



Test 2, point 9:

All models remain dry.

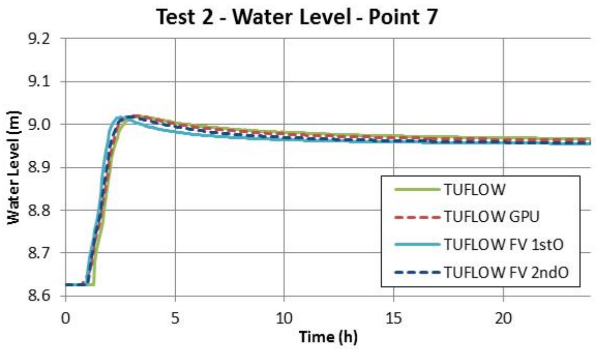
Test 2, point 8:



Test 2, point 16:

All models remain dry.

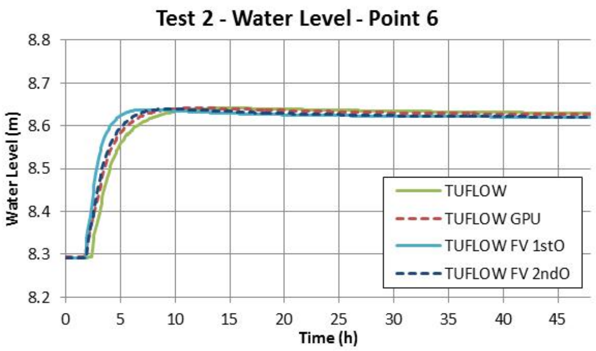
Test 2, point 7:



Test 2, point 15:

All models remain dry.

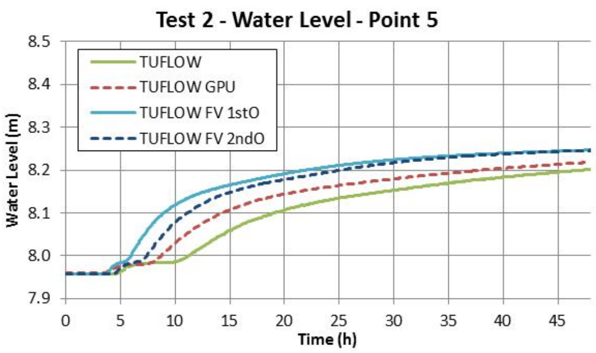
Test 2, point 6:



Test 2, point 14:

All models remain dry.

Test 2, point 5:



Test 2, point 13:

All models remain dry.

Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.03	0.03	0.03	0.03
Grid	20m	20m	20m	20m
Total volume of water left on the flood plain at the end of the simulation	97,195	97,200	97,192	97,189
Time-stepping	Adaptive (5s to 120s)	Adaptive (4s to 5s)	Adaptive (~5s)	Adaptive (~5s)
Total simulation time (hrs)	0.0020 (7.3s) 1 CPU Core	0.0061[1] (22s) 448 GPU Cores	0.0073 (26s) 12 CPU Cores	0.0115 (41s) 12 CPU Cores

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: No distinguishable change in results from the 2010 report for the first depressions to fill up, however, the 2012 build starts to fill the latter depressions slightly earlier than the 2010 build. However, when compared with the wide spread of results for all schemes in the 2010 report this is of little consequence. Importantly, the enhancements in the 2012-05-AA release means the model can be run using single precision (2010 needed double precision to keep mass error below 1%), on larger timesteps, with or without adaptive time-stepping, and no significant mass error (-0.1% in 2010 using DP vs 0.0% in 2012 using SP). "Number Iterations == 4" was specified to give improved convergence of the solution, especially during the initial phase where there are rapid changes in the inflow hydrograph.

TUFLOW GPU: Generally gives similar results to TUFLOW with slightly quicker filling of depressions, and very close with TUFLOW FV 2nd Order.

TUFLOW FV: Results consistent with other full 2D solvers. 1st order solution disperses more quickly than the 2nd order solution.

Test 3: Momentum conservation over a small obstruction

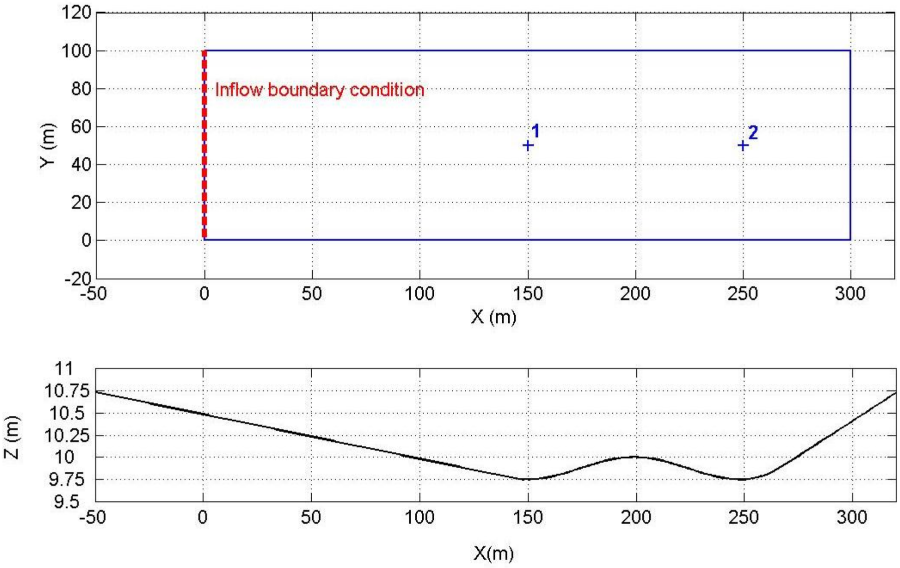
Objective:

The objective of this test is to assess the package's ability to conserve momentum over an obstruction in the topography. This capability is important when simulating sewer or pluvial flooding in urbanised floodplains. The barrier to the flow is designed to differentiate the performance of packages without inertia terms and 2D hydrodynamic packages with inertia terms. With inertia terms, some of the flood water will pass over the obstruction.

Description:

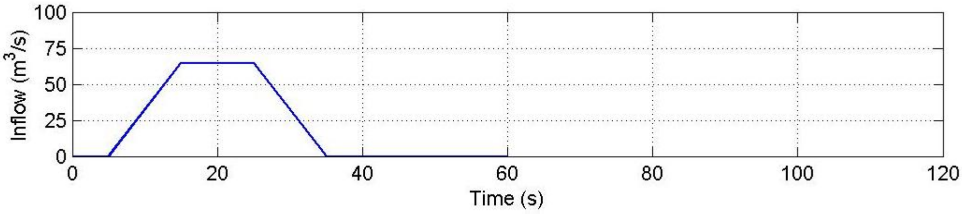
This test consists of a sloping topography with two depressions separated by an obstruction as illustrated in figure (a). The dimensions of the domain are 300m longitudinally (X) and 100m transversally (Y). A varying inflow (see figure (b)) is applied as an upstream boundary condition on the left-hand end, causing a flood wave to travel down the 1:200 slope. While the total inflow volume is just sufficient to fill the left-hand side depression at x=150m, some of the volume is expected to overtop the obstruction because of momentum conservation and settle in the depression on the right-hand side at x=250m. The model is run until time T=900s (15mins) to allow the water to settle.

Figure (a): plan and profile of DEM used in test 3. The area modelled is a perfect rectangle extending from X=0 to X=300m and from Y=0 to Y=100m.



Location	X	Y
1	150	50
2	250	50

Figure (b): inflow hydrograph used as an upstream boundary condition.



Boundary and initial conditions:

- Inflow boundary condition along the dashed red line in figure (a). Table provided as part of the dataset;
- All other boundaries are closed;
- Initial condition: dry bed.

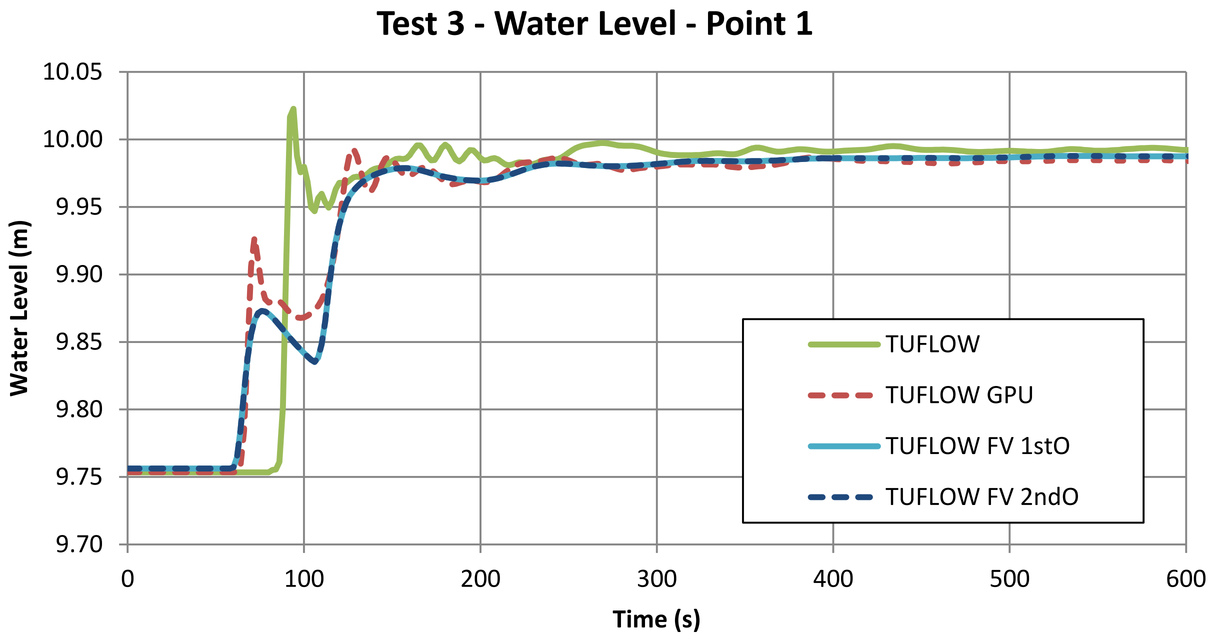
Parameter values:

- Manning's n: 0.01 (uniform);
- Model grid resolution: 5m (or ~1200 nodes in the area modelled);
- Time of end: the model to be run until T=15mins (900s).

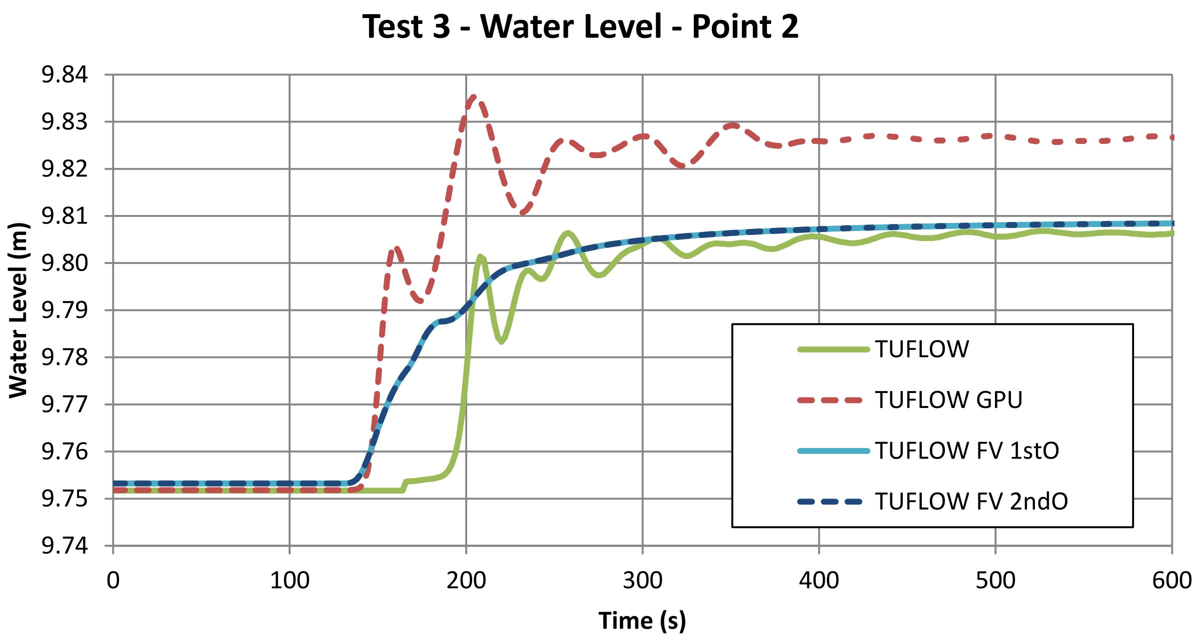
Results:

Water level time series:

Test 3, point 1: water level versus time (output frequency 2s)

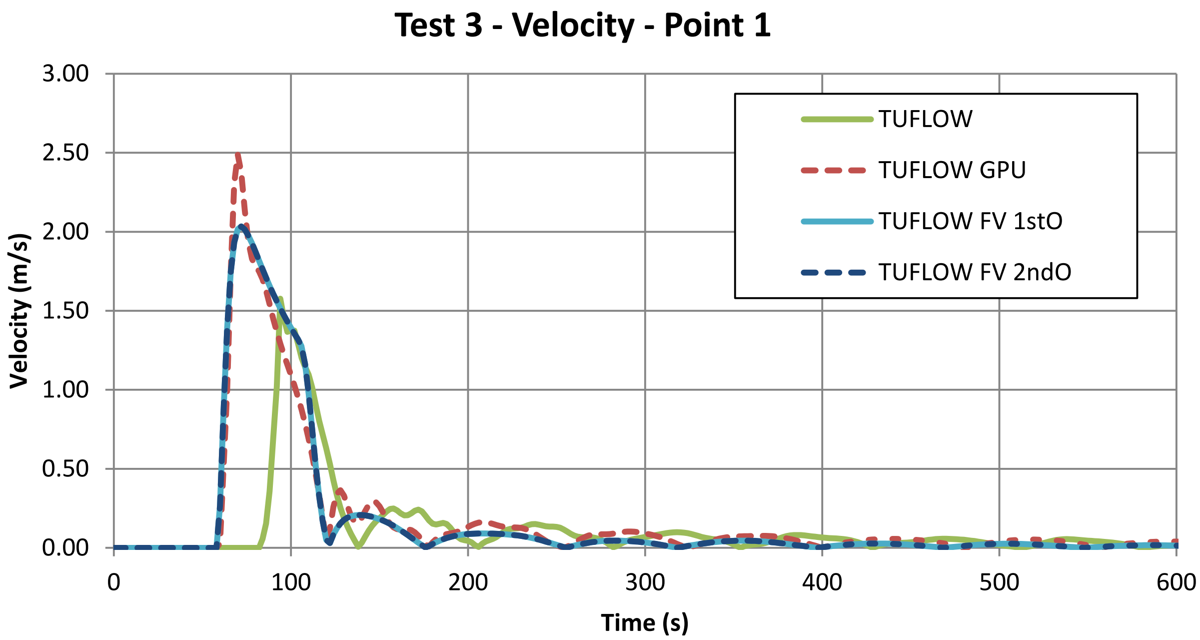


Test 3, point 2: water level versus time (output frequency 2s)



Velocity time series:

Test 3, point 1: velocity versus time (output frequency 2s)



Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.01	0.01	0.01	0.01
Grid	5m	5m	5m	5m
Time-stepping	2s	Adaptive (0.2 to 1.5s)	Adaptive (~0.2s)	Adaptive (~0.2s)
Total simulation time (hrs)	0.0005 (1.8s) 1 CPU Core	0.0006[1] (2s) 448 GPU Cores	0.0004 (1.3s) 12 CPU Cores	0.0004 (1.5s) 12 CPU Cores

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: The enhancements in the 2012-05-AA release provide an improvement on the 2010 report results in terms of stability and mass error (-0.15% in 2010 using DP vs 0.0% in 2012). Use of the “Mass Balance Corrector == ON” and “Mass Balance Corrector Iterations == 6” options seem to provide the best results, and were used for the results presented in this report.

TUFLOW GPU: The results are the most diverged from TUFLOW and to a lesser extent TUFLOW FV compared with all the other tests in this report. TUFLOW GPU fills the second depression higher than TUFLOW and TUFLOW FV by around 0.02m (2cm).

TUFLOW FV: Results similar to those from the 2010 report.

Test 4: Speed of flood propagation over an extended floodplain

Objective:

The objective of this test is to assess the package’s ability to simulate the celerity of propagation of a flood wave and predict transient velocities and depths at the leading edge of the advancing flood front. It is relevant to fluvial and coastal inundation resulting from breached embankments.

Description:

The test is designed to simulate the rate of flood wave propagation over a 1000m x 2000m floodplain following a defence failure (figure (a)). The floodplain surface is horizontal, at elevation 0m. One inflow boundary condition is used in the test, simulating the failure of an embankment by breaching or overtopping, with a peak flow of 20m^3/s and time base of ~6hours. The boundary condition is applied along a 20m line in the middle of the western side of the floodplain.

Figure (a): modelled domain, showing the location of the 20m inflow, 6 output points, and possible 10cm and 20cm contour lines at time 1hr (dashed) and 3hr (solid).

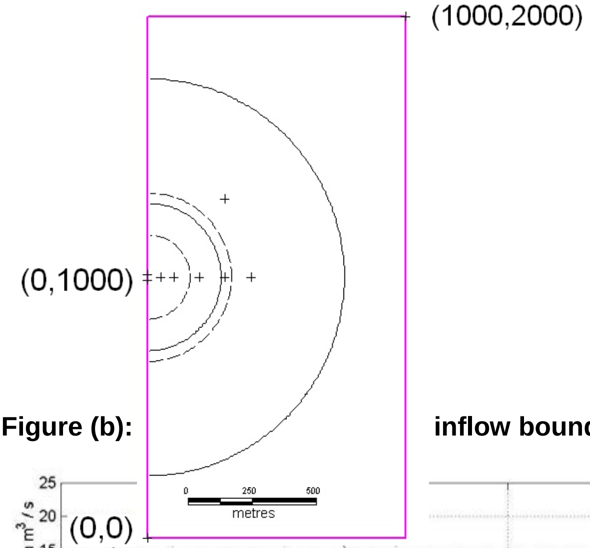
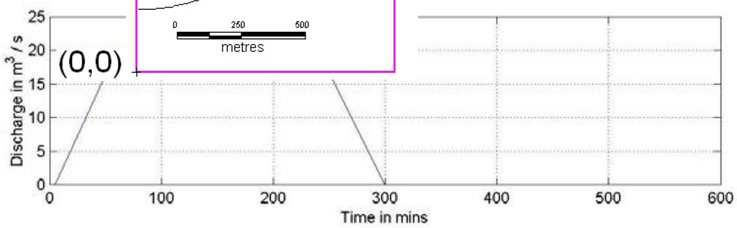


Figure (b): inflow boundary condition.



Boundary and initial conditions:

- Initial boundary condition as shown in figure (b). Table provided as part of the test dataset.
- All other boundaries are closed.
- Initial conditions: dry bed.

Parameter values:

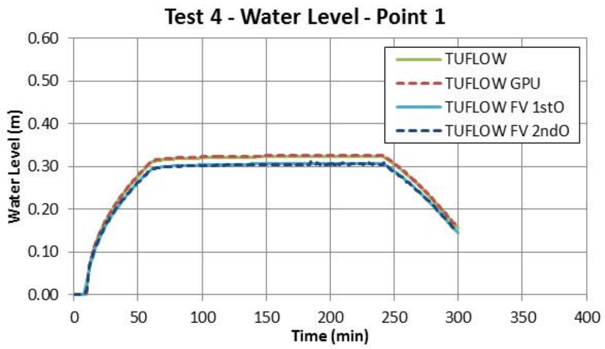
- Manning’s n: 0.05 (uniform).
- Model grid resolution: 5m (or ~80000nodes in the area modelled).
- Time of end: the model is to be run until time t=5hrs (if an alternative end time is used, run times must be reported for t=5hrs).

Results:

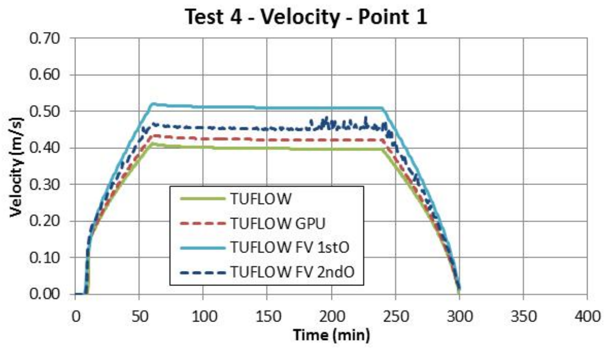
Water level (depth) and velocity time series:

Water level (depth) time series:	Velocity time series:

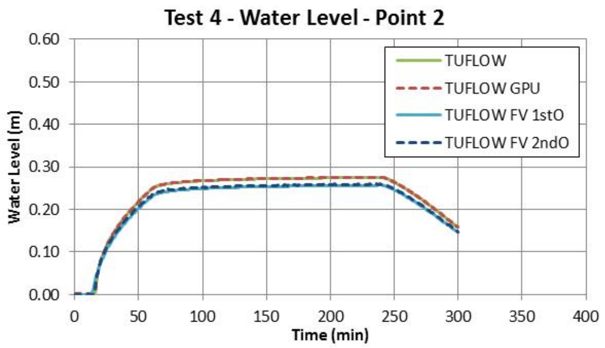
Test 4, point 1:



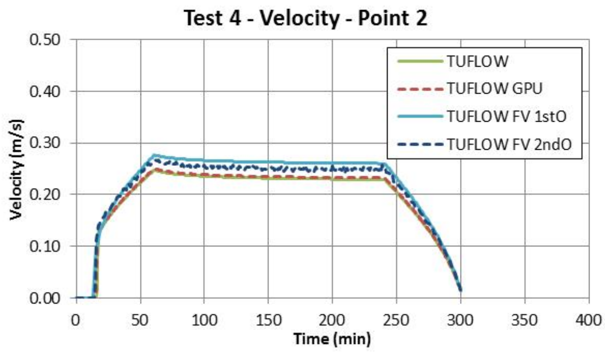
Test 4, point 1:



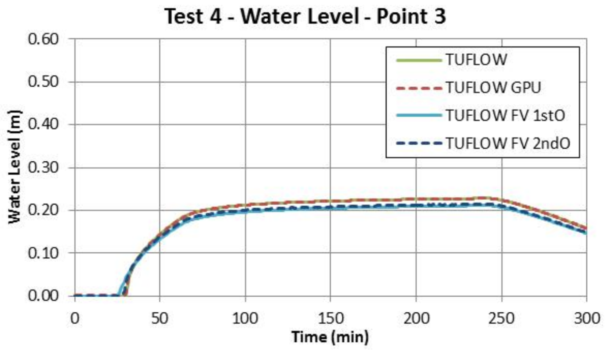
Test 4, point 2:



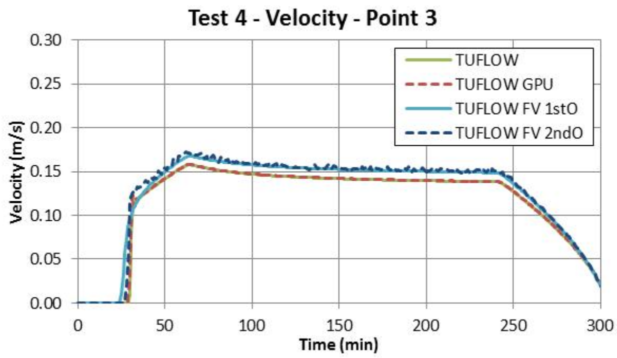
Test 4, point 2:



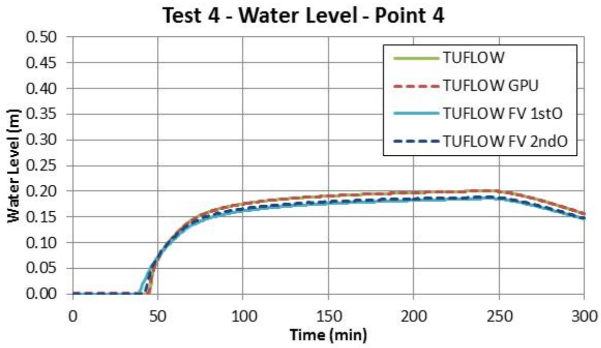
Test 4, point 3:



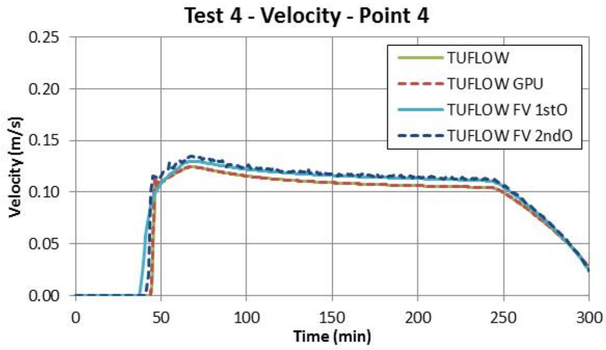
Test 4, point 3:



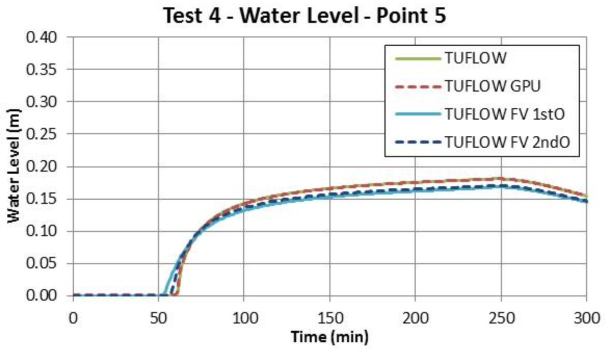
Test 4, point 4:



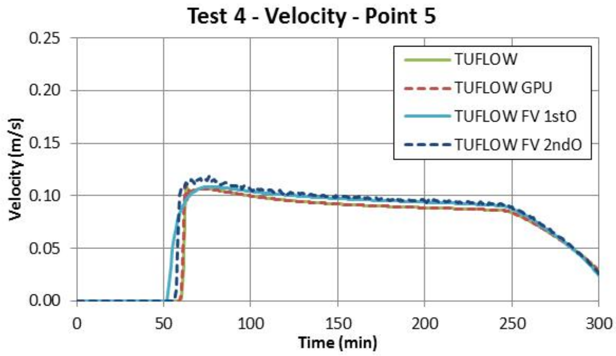
Test 4, point 4:



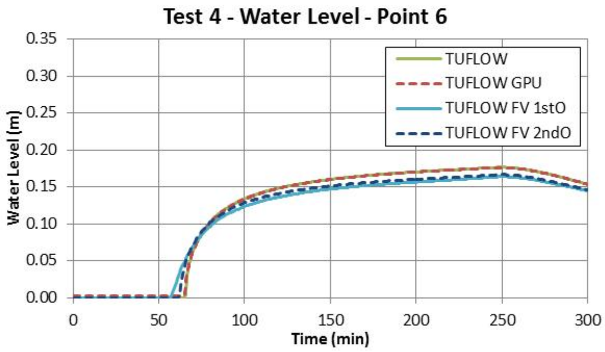
Test 4, point 5:



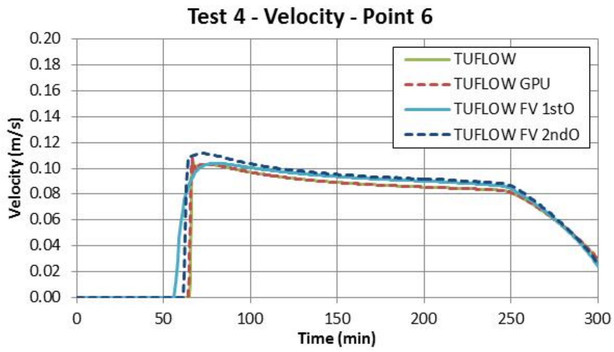
Test 4, point 5:



Test 4, point 6:

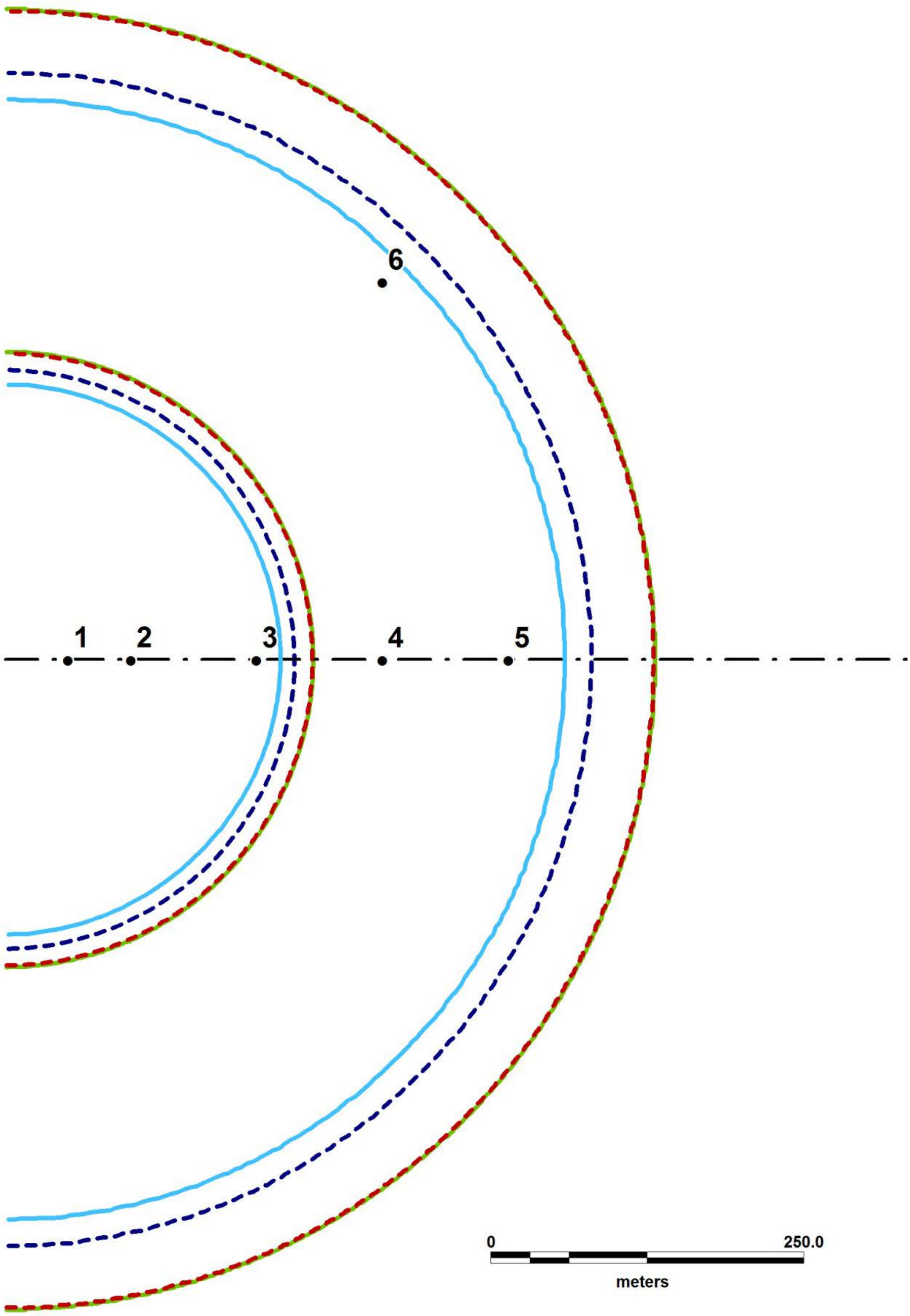


Test 4, point 6:

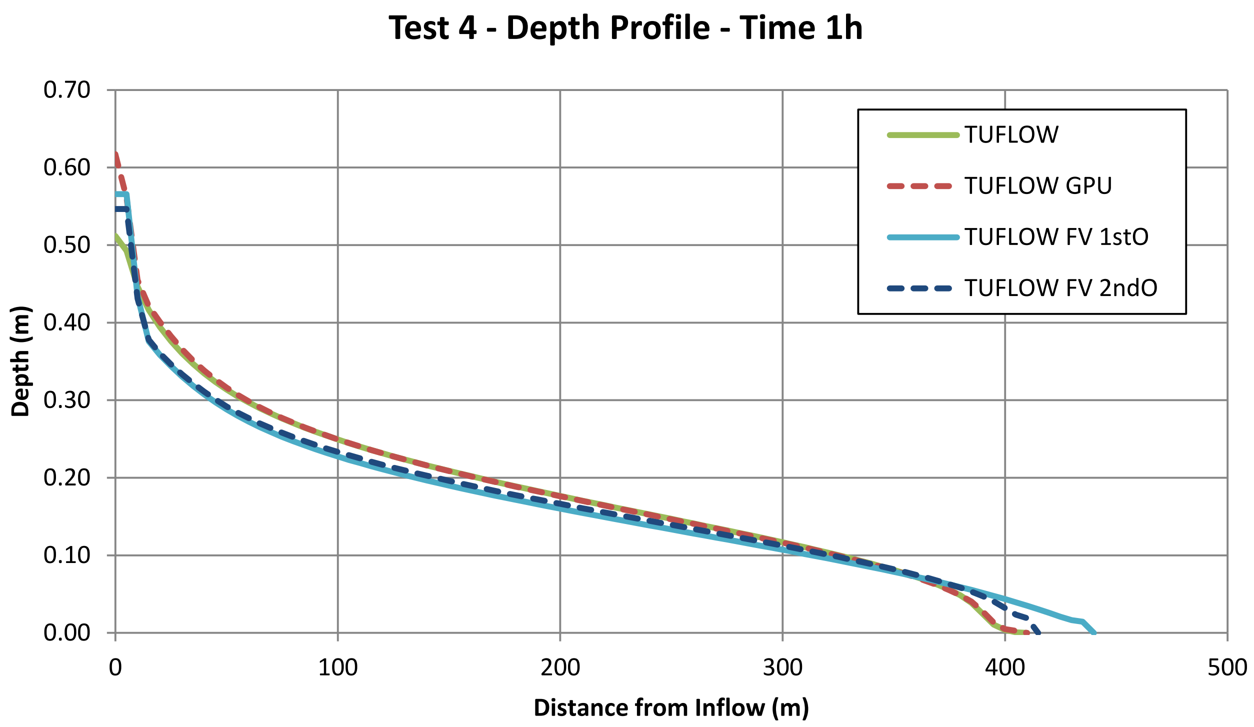


Output in raster format:

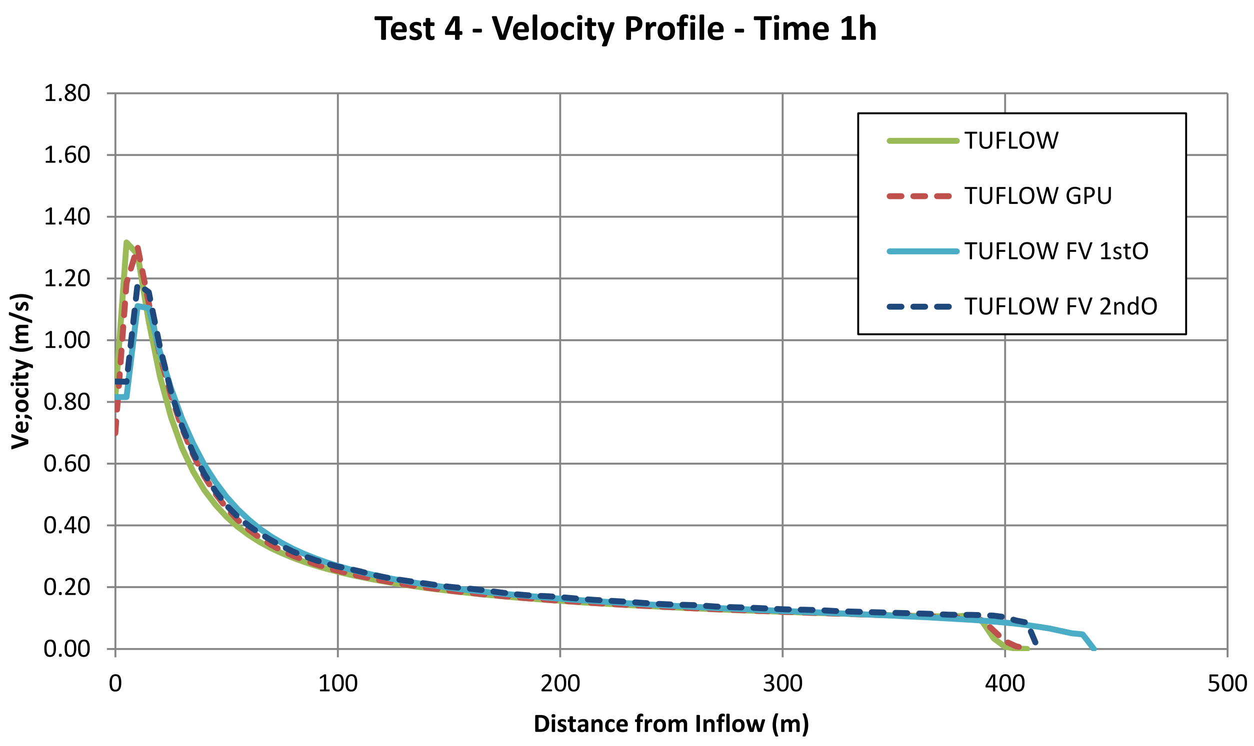
0.15m depth contours at times 1hr (left) and 3hr (right). The colour coding is consistent with the one used in the rest of this report. Cross-sections shown in the two following figures were taken along the black dashed line, which starts at the left boundary and runs through output points 1 to 5.



Cross-section of depths along dotted line in previous figure, at t=1hr:



Cross-section of velocities along dotted line in previous figure, at t=1hr:



Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.05	0.05	0.05	0.05
Grid	5m	5m	5m	5m
Time-stepping	Adaptive (1 to 30s)	Adaptive (0.8 to1.7s)	Adaptive (~0.7s)	Adaptive (~0.4s)
Total simulation time (hrs)	0.0131 (47s) 1 CPU Core	0.0086[1] (31s) 448 GPU Cores	0.0394 (142s) 12 CPU Cores	0.1335 (481s) 12 CPU Cores

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: No distinguishable change in results from the 2010 report except that the "initial sharp peak" in the velocity graphs as reported on in the 2010 report are not evident. The enhancements in the 2012-05-AA release allows the model to be run on larger timesteps, with or without adaptive time-stepping, while yielding little or no mass error.

TUFLOW GPU: Gives near identical results to TUFLOW.

TUFLOW FV: Results similar to other full 2D solutions. 1st order disperses more quickly with slightly faster propagation speeds.

Test 5: Valley flooding

Objective:

This tests a package's capability to simulate major flood inundation and predict flood hazard arising from dam failure (peak levels, velocities, travel times).

Description:

This test is designed to simulate flood wave propagation down a river valley following the failure of a dam. The valley DEM (figure (a)) is ~0.8km by ~17km and the valley slopes downstream on a slope of ~0.01 in its upper region, easing to ~0.001 in its lower region. The inflow hydrograph (figure (b)) applied as a boundary condition along a ~260m long line at the upstream end is designed to account for a typical failure of a small embankment dam and to ensure that both super-critical and sub-critical flows will occur in different parts of the flow field.

Figure (a): DEM used, with cross-section along the centre line, and location of the output points. The red line indicates the location of the boundary condition and the blue polygon is the modelled area.

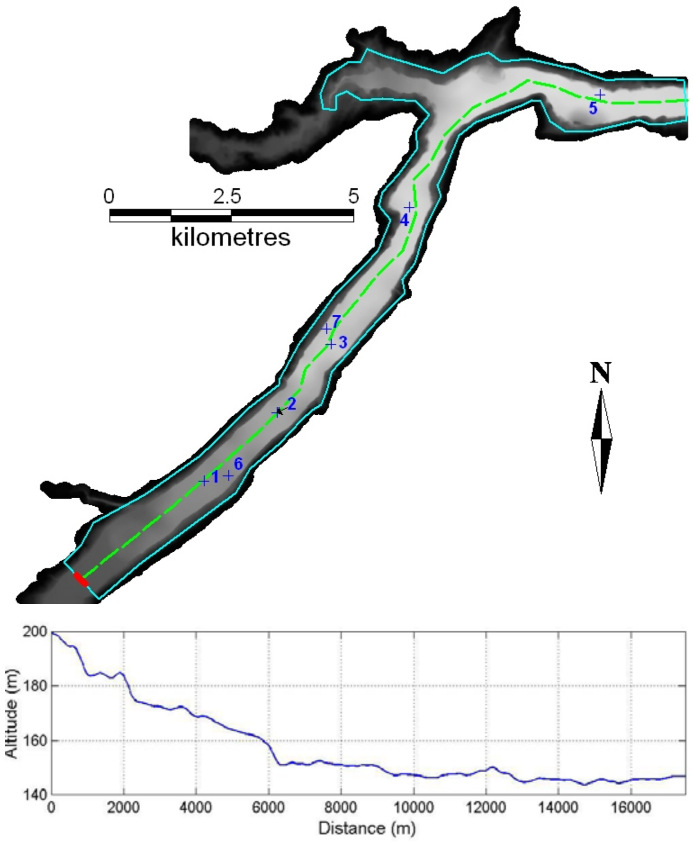
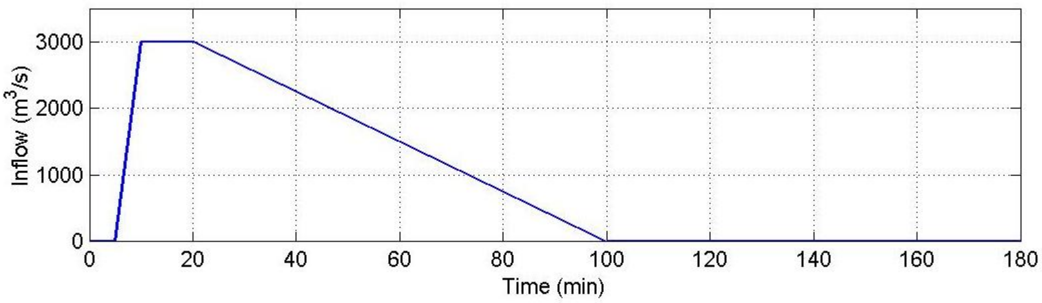


Figure (b): inflow hydrograph applied



Boundary and initial conditions:

- Initial boundary condition along the dashed red line in figure (a). Table provided as part of the dataset.
- All other boundaries are closed.

- Initial condition: dry bed.

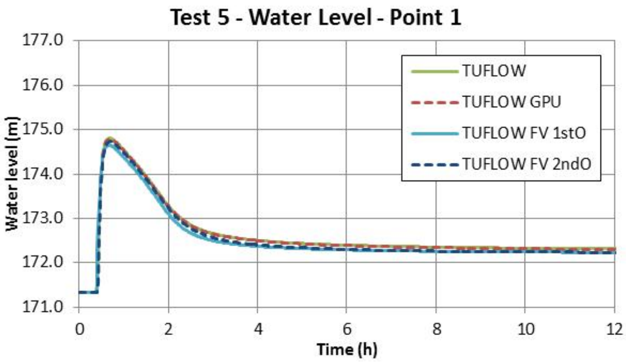
Parameter values:

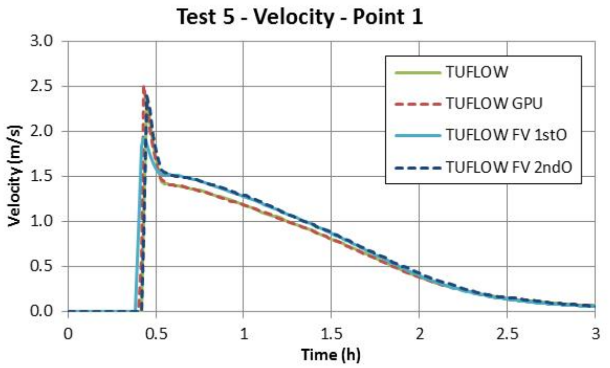
- Manning's n: 0.04 (uniform)
- Model grid resolution: 50m (or ~7600nodes in the 19.02km^2 area modelled)
- Time of end: the model is to be run until T=30hrs (if an alternative is used run times must be reported for T=30hrs)

Results:

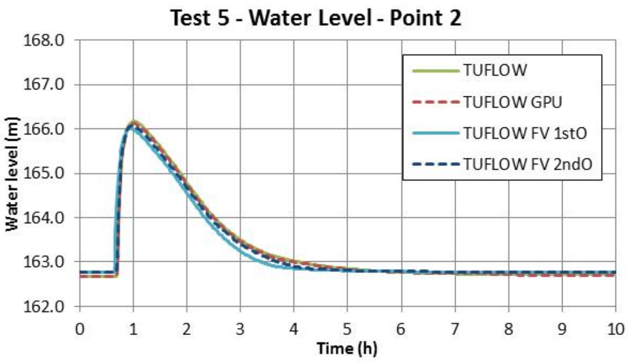
Water level (depth) and velocity time series:

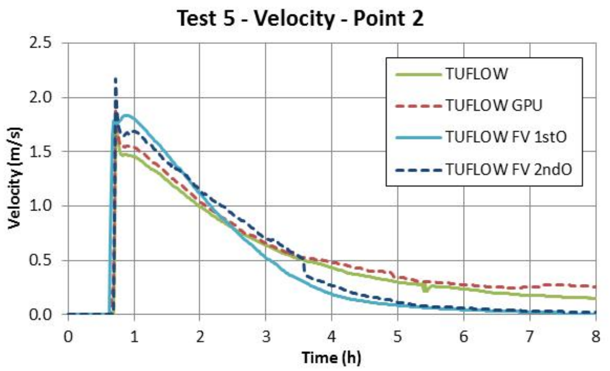
Water level (depth) time series:	**Velocity time series:**
Test 5, point 1:	**Test 5, point 1:**



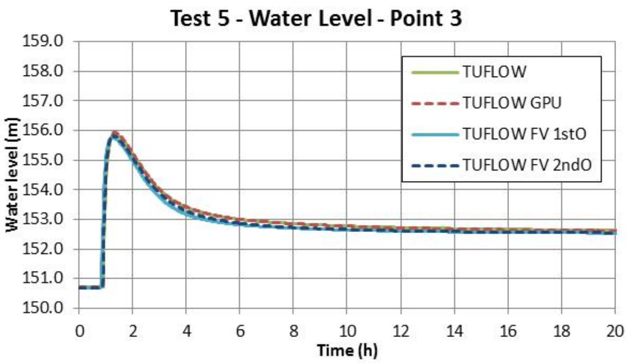


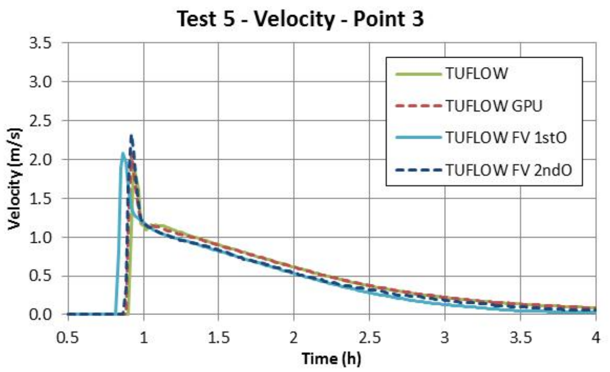
Test 5, point 2:	**Test 5, point 2:**



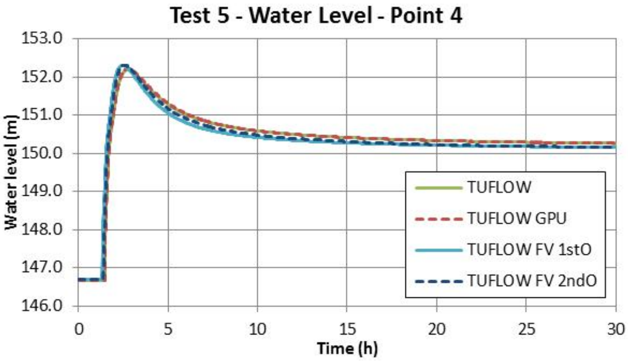


Test 5, point 3:	**Test 5, point 3:**

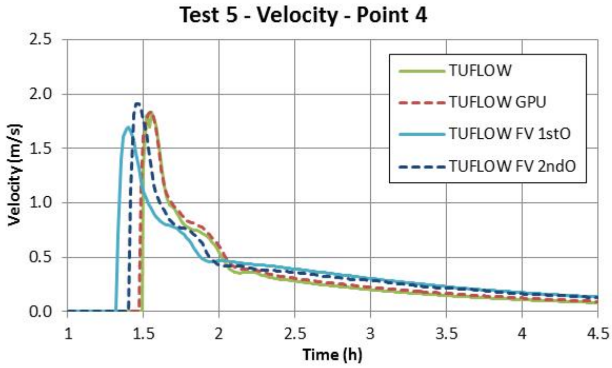




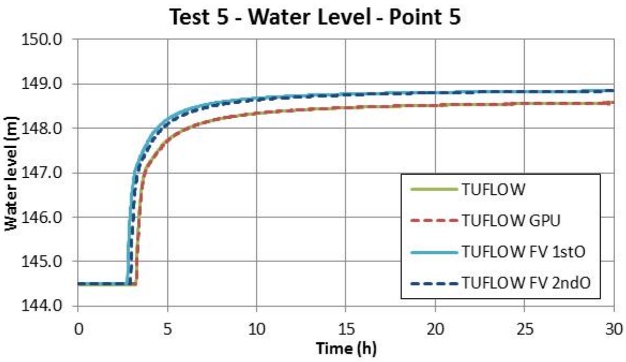
Test 5, point 4:



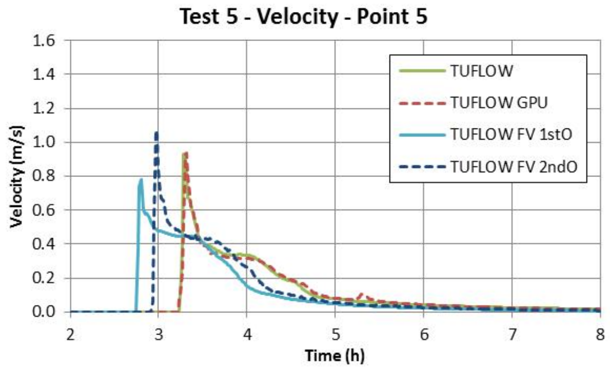
Test 5, point 4:



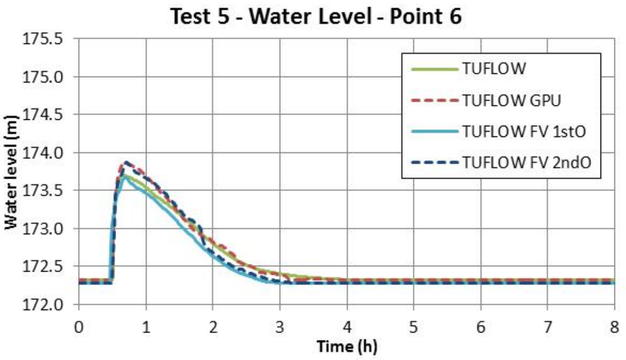
Test 5, point 5:



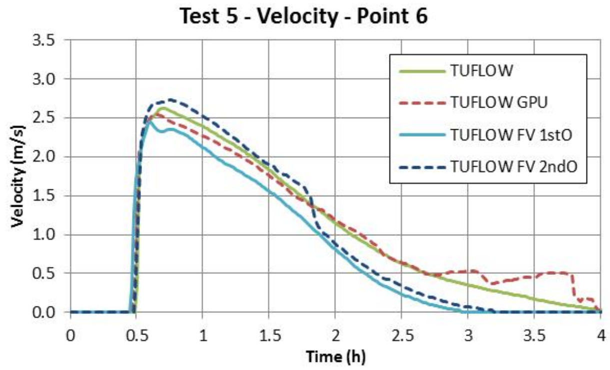
Test 5, point 5:



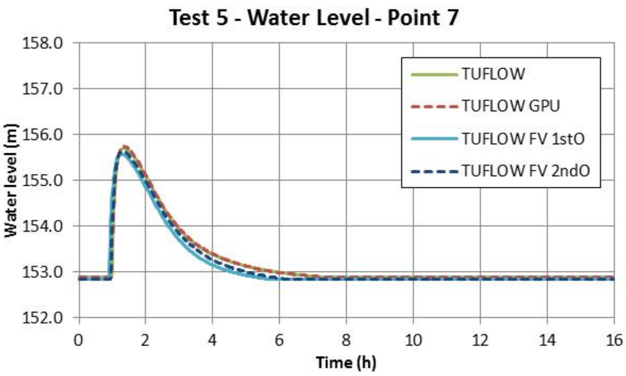
Test 5, point 6:



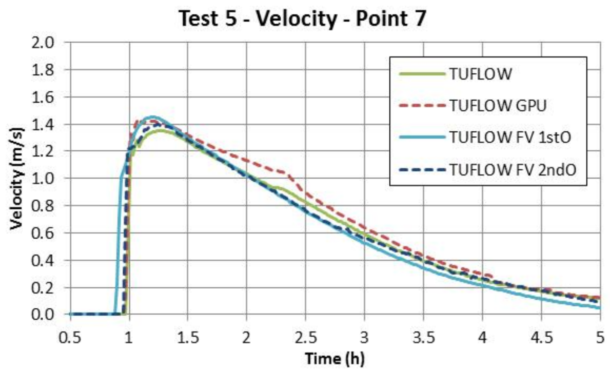
Test 5, point 6:



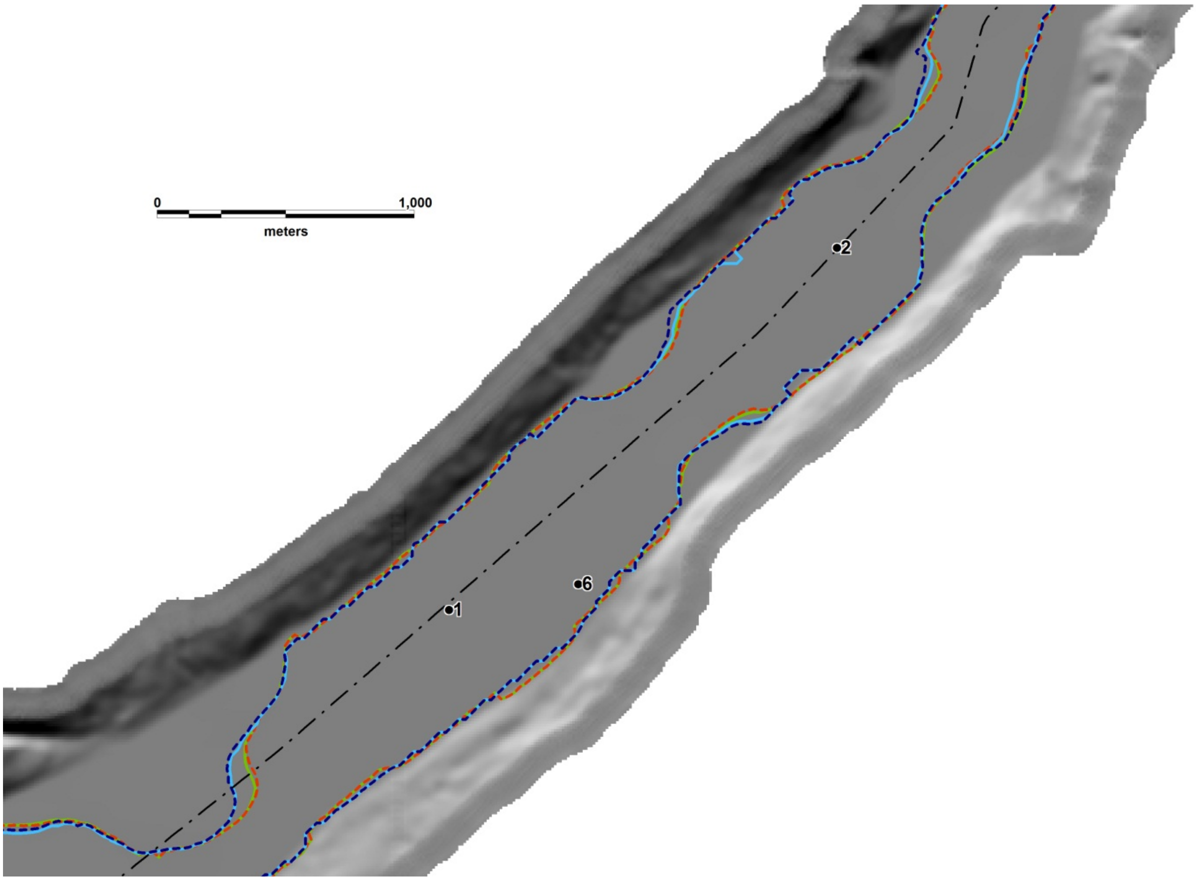
Test 5, point 7:



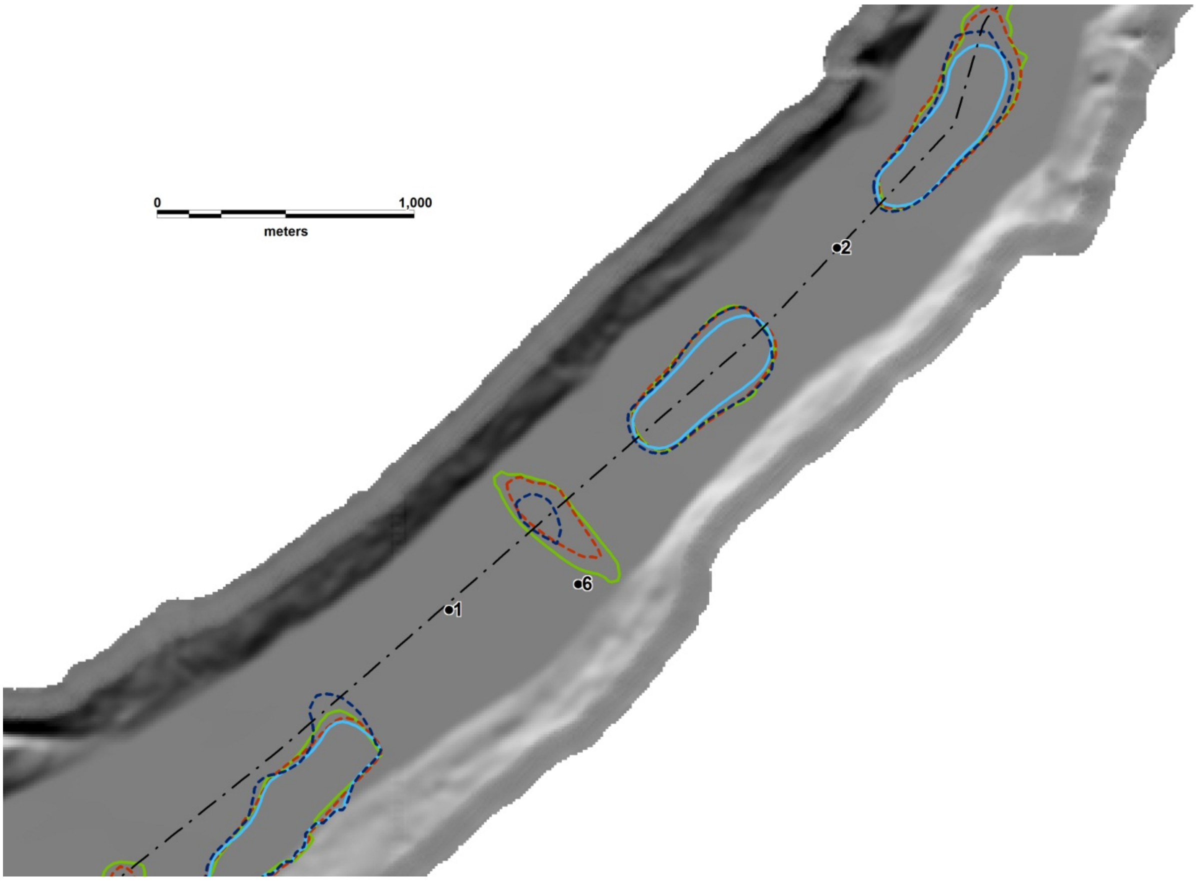
Test 5, point 7:



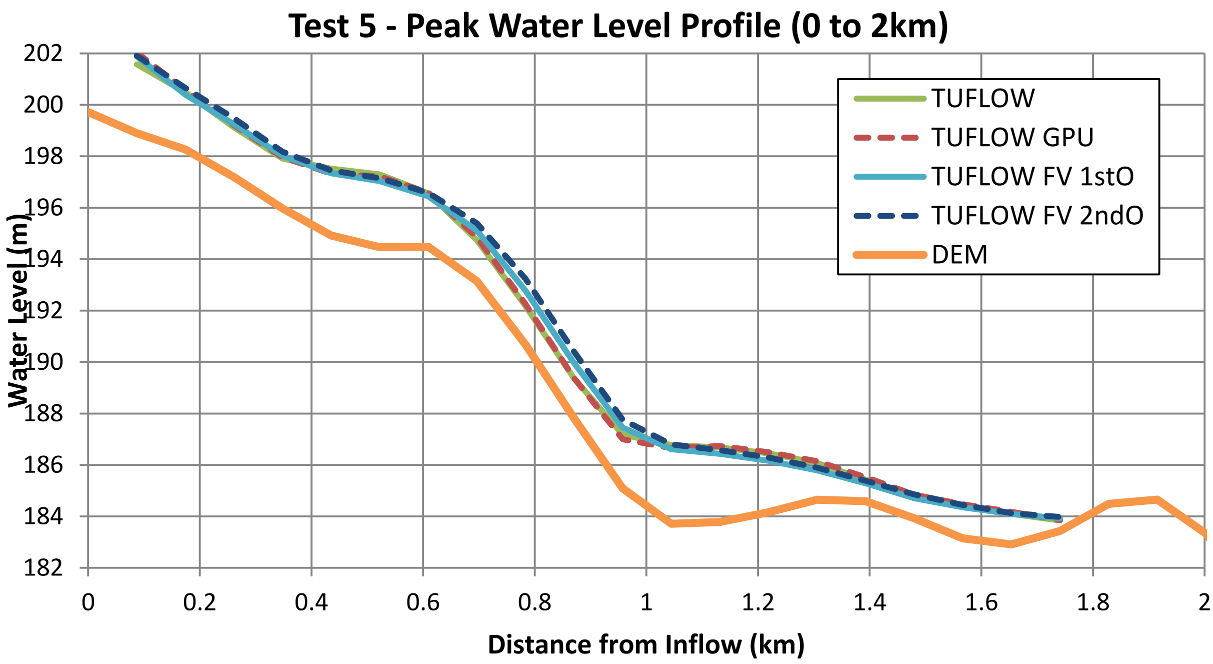
0.5m contour lines of peak depths for a section of floodplain around points 1, 2 and 6:



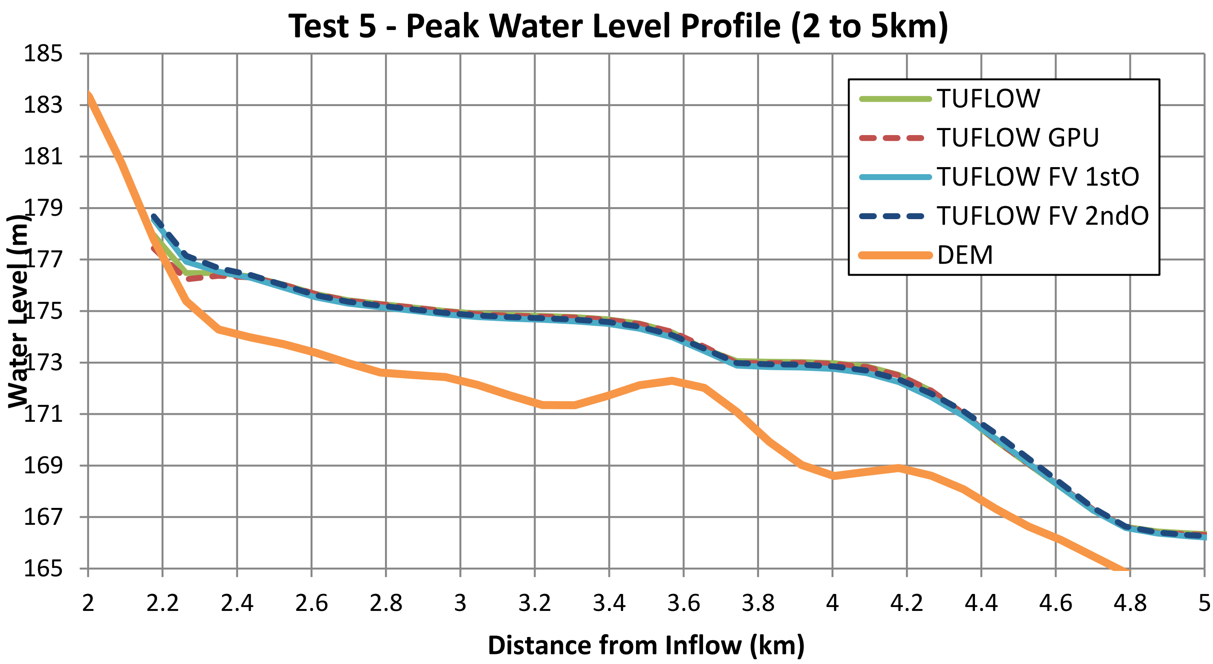
3m contour lines of peak depths for a section of floodplain around points 1, 2 and 6:



Cross section of predicted peak levels (0 to 2km) along valley centre line:

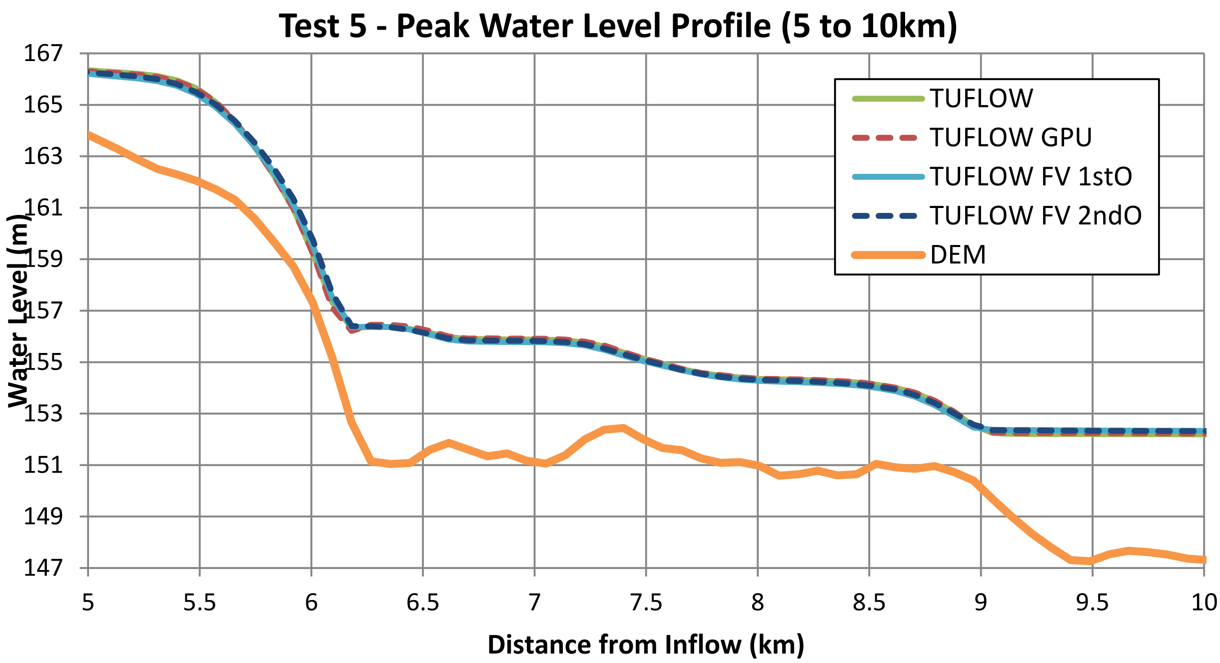


Cross section of predicted peak levels (2 to 5km) along valley centre line:

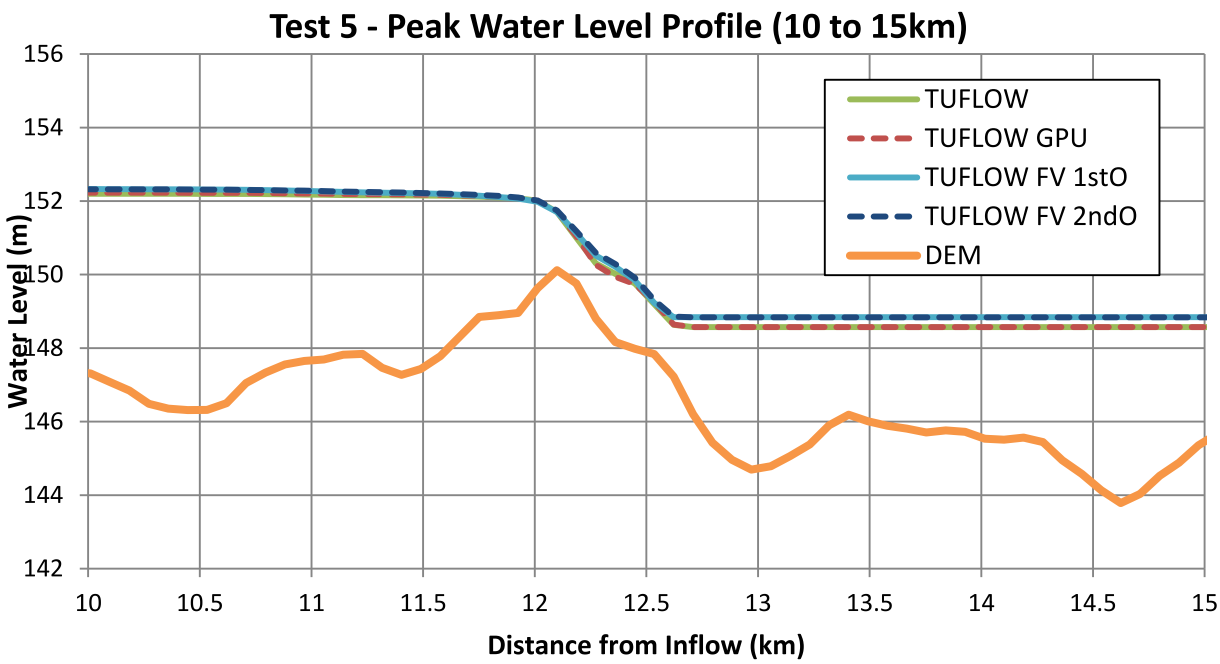


Approximate locations of time series output points along valley centreline:
Point 1 (3.24km)
Point 6 (3.67km)
Point 2 (5.29km)
Point 3 (7.08km)
Point 7 (7.33km)
Point 4 (10.46km).

Cross section of predicted peak levels (5 to 10km) along valley centre line:

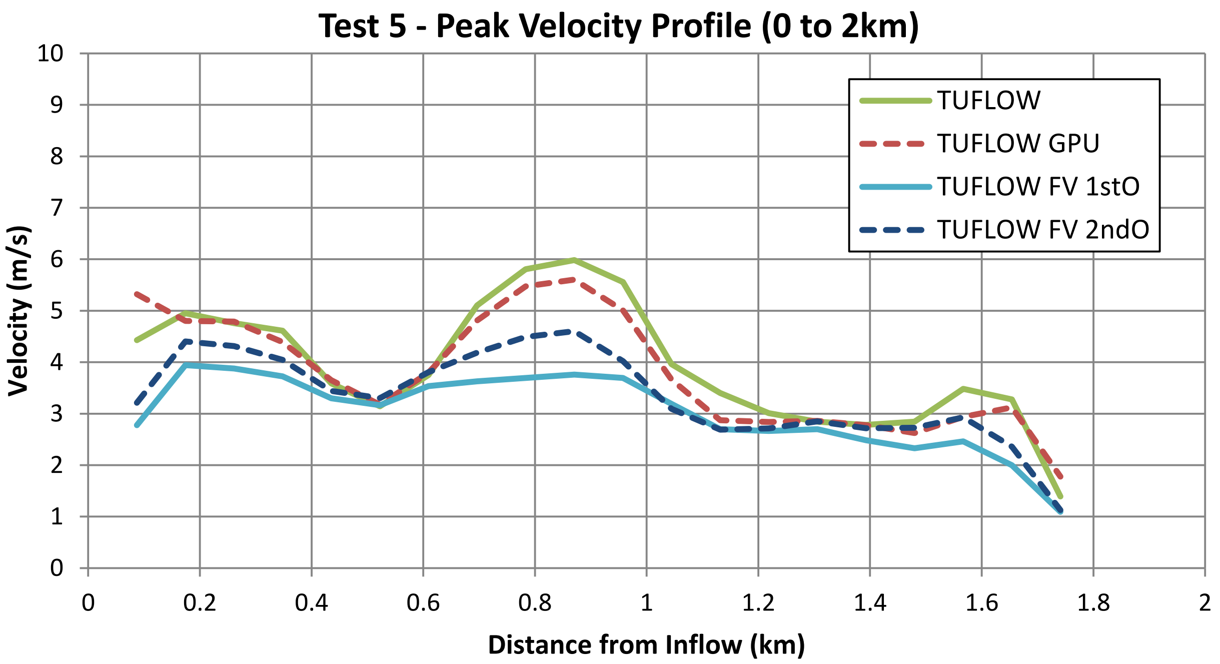


Cross section of predicted peak levels (10 to 15km) along valley centre line:

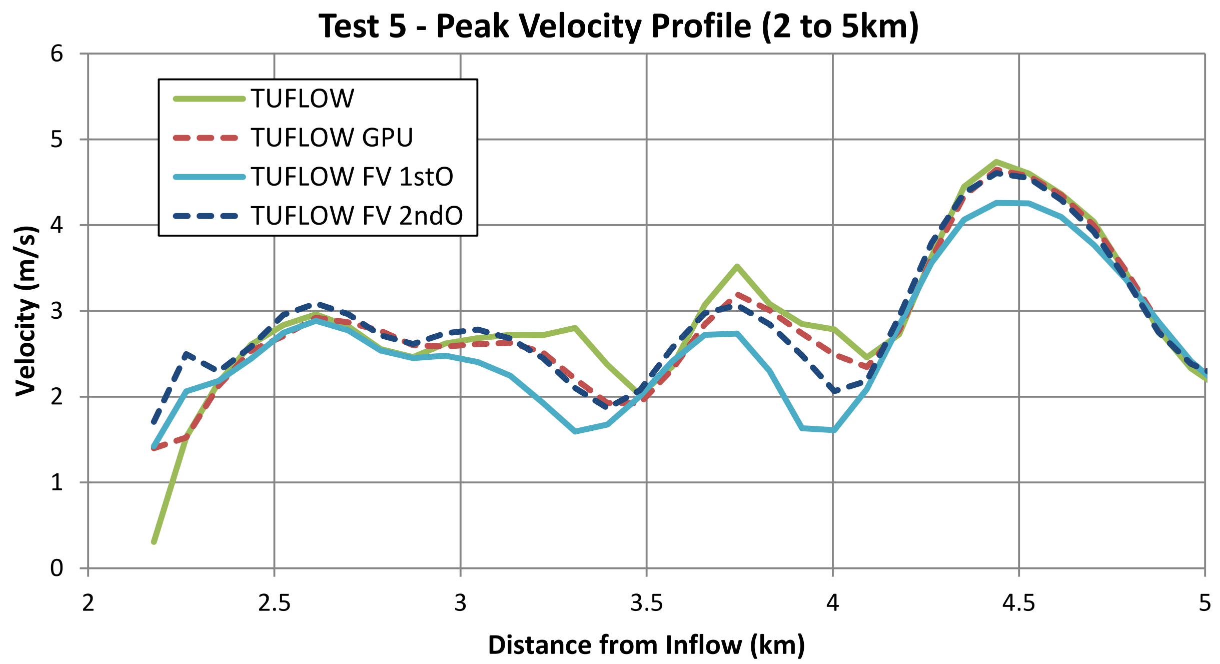


Approximate locations of time series output points along valley centreline:
Point 1 (3.24km)
Point 6 (3.67km)
Point 2 (5.29km)
Point 3 (7.08km)
Point 7 (7.33km)
Point 4 (10.46km).

Cross section of predicted peak velocities (0 to 2km) along valley centre line:

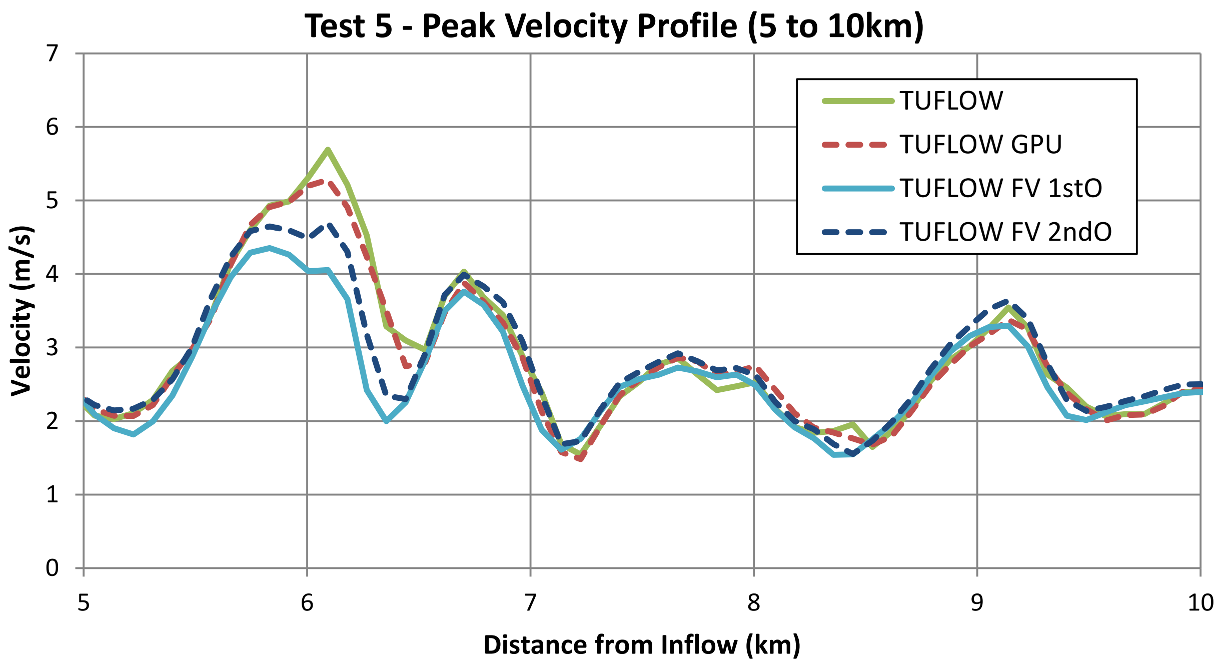


Cross section of predicted peak velocities (2 to 5km) along valley centre line:

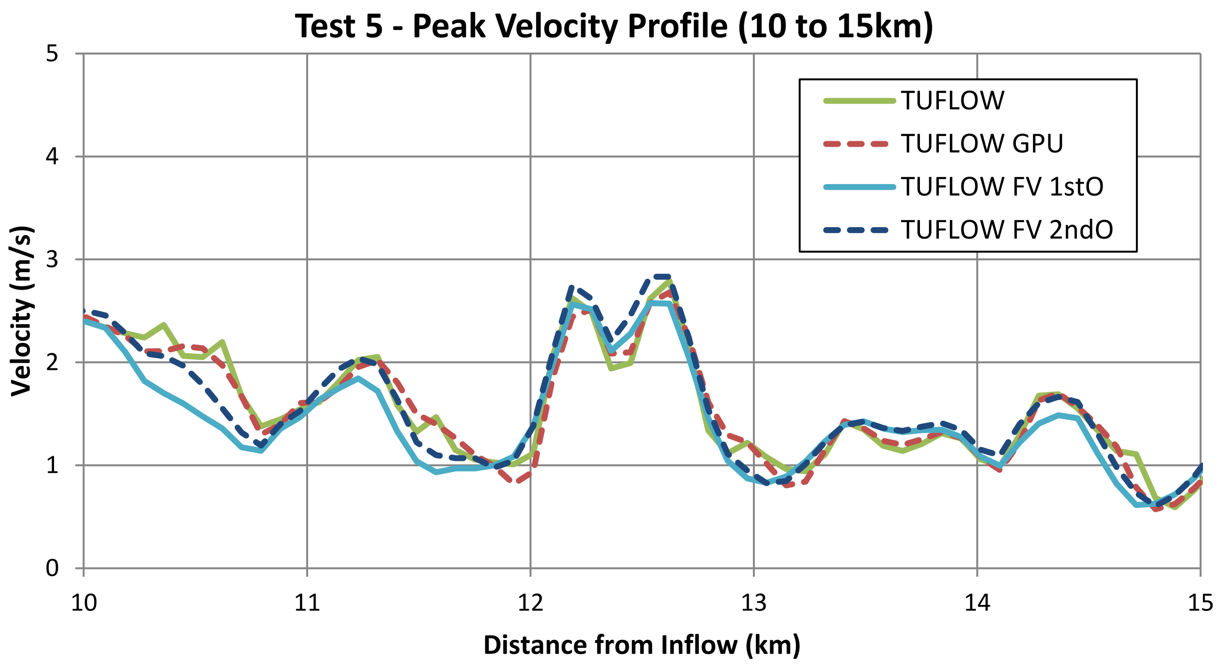


Approximate locations of time series output points along valley centreline:
Point 1 (3.24km)
Point 6 (3.67km)
Point 2 (5.29km)
Point 3 (7.08km)
Point 7 (7.33km)
Point 4 (10.46km)

Cross section of predicted peak velocities (5 to 10km) along valley centre line:



Cross section of predicted peak velocities (10 to 15km) along valley centre line:



Approximate locations of time series output points along valley centreline:
Point 1 (3.24km)
Point 6 (3.67km)
Point 2 (5.29km)
Point 3 (7.08km)
Point 7 (7.33km)
Point 4 (10.46km).

Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.04	0.04	0.04	0.04
Grid	50m	50m	Flexible Mesh 7,424 elements	Flexible Mesh 7,424 elements
Final Volume on Floodplain	9,460,922 (0.12% ME)	9,450,089 (0.00% ME)	9449684 (0.00% ME)	9449988 (0.00% ME)
Time-stepping	Adaptive (5 to 18s)	Adaptive (2.4 to 3.3s)	Adaptive (~1s)	Adaptive (~1s)
Total simulation time (hrs)	0.0072 (26s) 1 CPU Core	0.0086[1] (31s) 448 GPU Cores	0.0187 (67s) 12 CPU Cores	0.0417 (150s) 12 CPU Cores

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: The enhancements in the 2012-05-AA release provide a significant improvement for the TUFLOW results in this test, particularly in terms of peak velocity predictions (for example, the issues highlighted in Figure 12 in the 2010 report no longer occur due to improved representation of steep flows and transitioning between flow regimes). Good results and low mass error are now consistently achieved for dambreak models of this type using the TUFLOW 2012-05-AA release. The "Number Iterations == 4" setting was used for the simulation presented in this report. Using the default of 2 iterations gives near identical results, but with a 1.3% mass error instead of 0.1%.

TUFLOW GPU: Produces results consistent with TUFLOW, TUFLOW FV and other fully dynamic codes presented in the 2010 report.

TUFLOW FV: Results similar to those from the 2010 report and consistent with other full 2D solvers. 1st order solution produces lower peak velocities.

Test 6A and 6B: Dam break

Objective:

This tests the capability of each package to correctly simulate hydraulic jumps and wake zones behind buildings using high-resolution modelling.

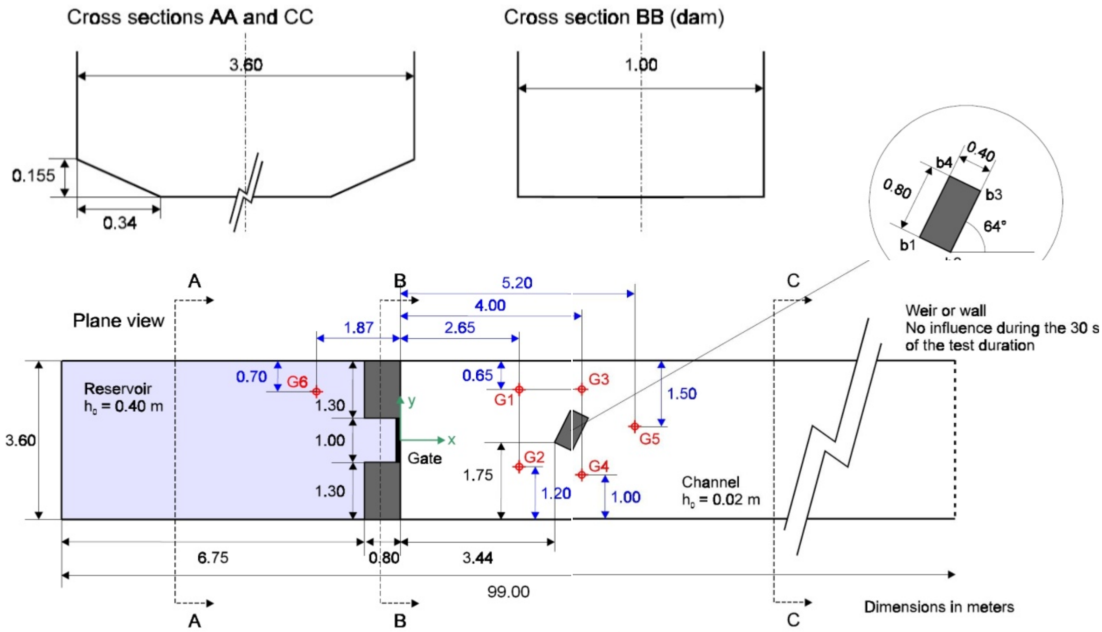
Description:

This dam-break test case has been adapted from an original benchmark test available from the IMPACT project (IMPACT, 2004; Soares-Frazao and Zech, 2002), for which measurements from a physical model at the Civil Engineering Laboratory of the Université Catholique de Louvain (UCL) are available.

Test 6A is the original test is the original test proposed in Soares-Frazao and Zech 2002, where the physical dimensions are those of the laboratory model. The test involves a simple topography, a dam with a 1m wide opening, and an idealised representation of a single building downstream of the dam, see Figure (a). An initial condition is applied, consisting in a uniform depth of 0.4m upstream from the dam, and 0.02m downstream from the dam. The flow is contained by vertical walls at all boundaries of the DEM.

Test 6B is identical to Test 6A although all physical dimensions have been multiplied by 20 to reflect realistic dimensions encountered in practical flood inundation modelling applications.

Figure (a): Set-up for Test 6A (adapted from Soares-Frazao and Zech, 2002).



Boundary and initial conditions:

- No boundary condition specified as the flow is contained by vertical walls.
- Initial condition: in test 6A:
    - depth = 0.4m upstream from the dam (i.e. for X<0);
    - depth = 0.02m downstream from the dam (i.e. for X>0);
- Initial condition: in test 6B:
    - depth = 8m upstream from the dam (i.e. for X<0);
    - depth = 0.4m downstream from the same (i.e. for X>0);

Parameter values:

- No preferred value of eddy viscosity is specified;
- In test 6A:
    - Manning's n: 0.01 (uniform);
    - Model grid resolution: 0.1m or ~36000 nodes in area bounded by vertical scale;
    - Time of end: the model is to be run until time t = 2mins (if an alternative end time is used, run times must be reported for t=2mins)
- In test 6B:
    - Manning's n: 0.05 (uniform);
    - Model grid resolution: 2m or ~36000 nodes in area bounded by vertical scale;

- Time of end: the model is to be run until time t=30mins (if an alternative end time is used, run times must be reported for t=30mins)

Results:

Test 6A: Water level (depth) and velocity time series:

<table>
<tr><th>Water level (depth) time series:</th><th>Velocity time series:</th></tr>
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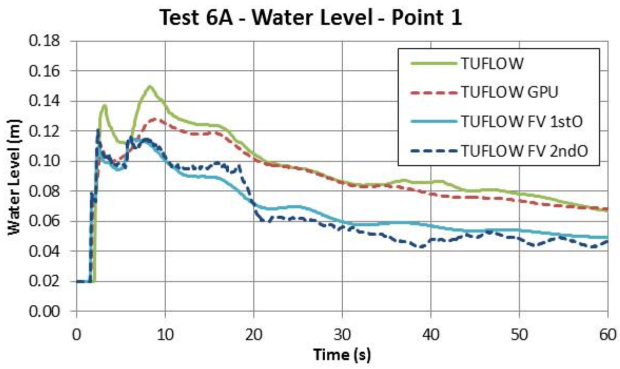
Test 6A, point 1:



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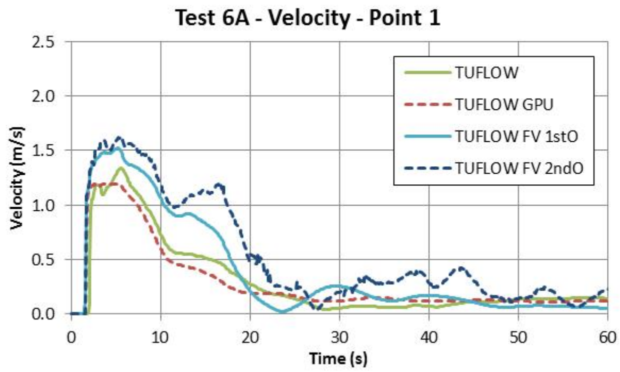
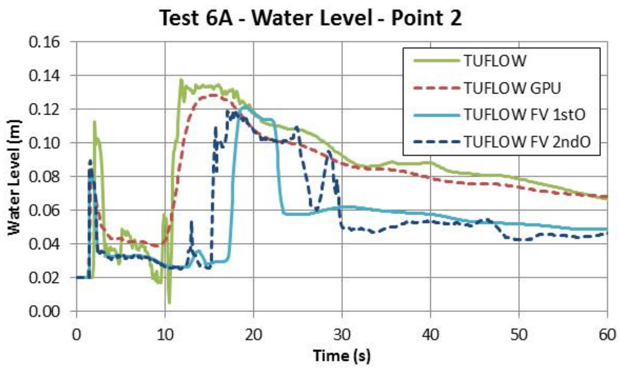
Test 6A, point 1:



</td></tr>
<tr><td>

Test 6A, point 2:



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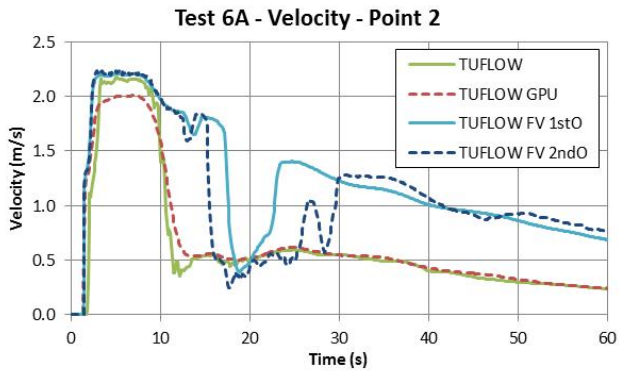
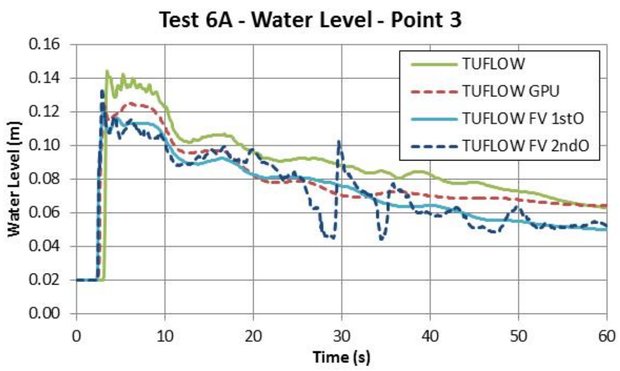
Test 6A, point 2:



</td></tr>
<tr><td>

Test 6A, point 3:



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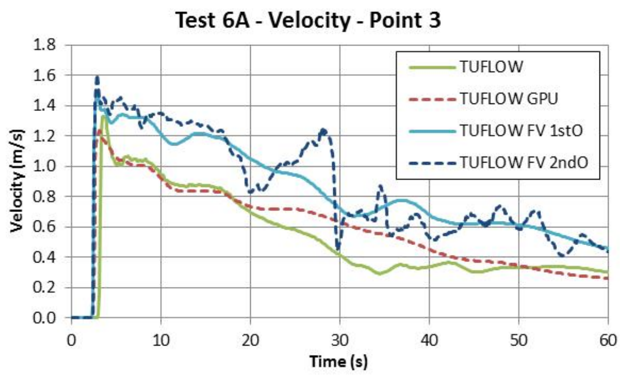
Test 6A, point 3:



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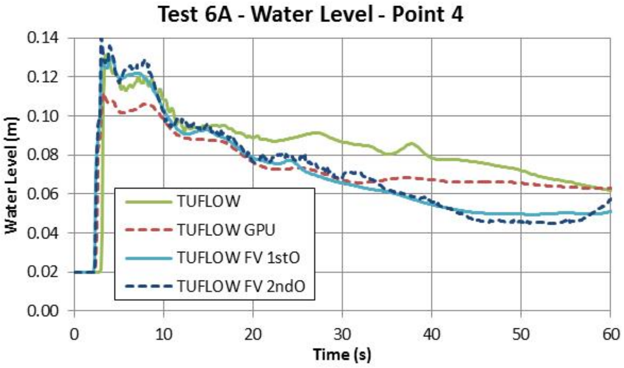
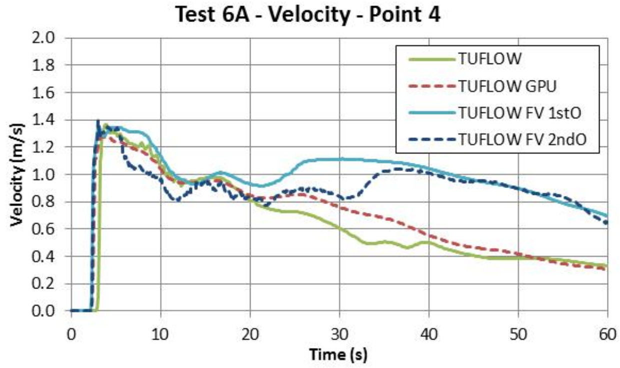
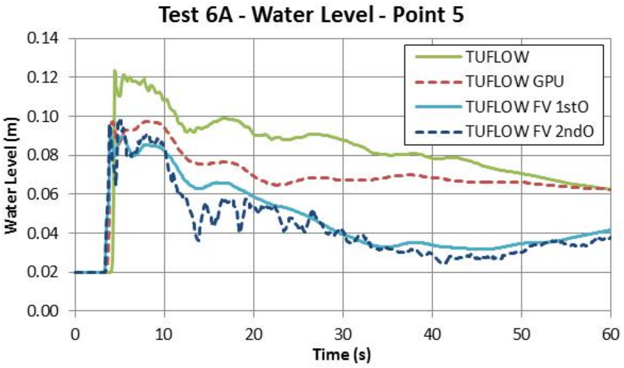
Test 6A, point 4:



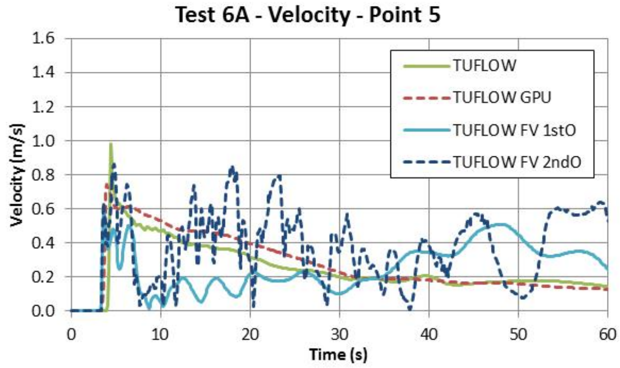
Test 6A, point 4:



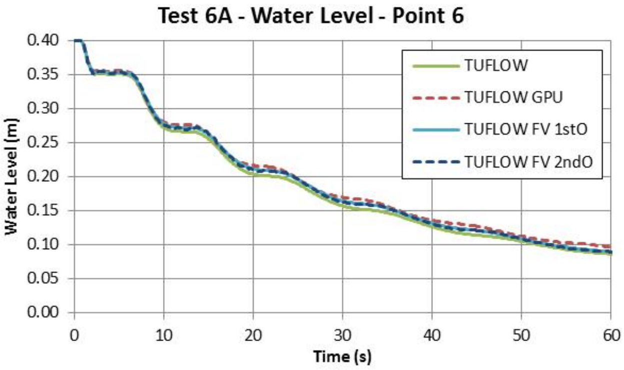
Test 6A, point 5:



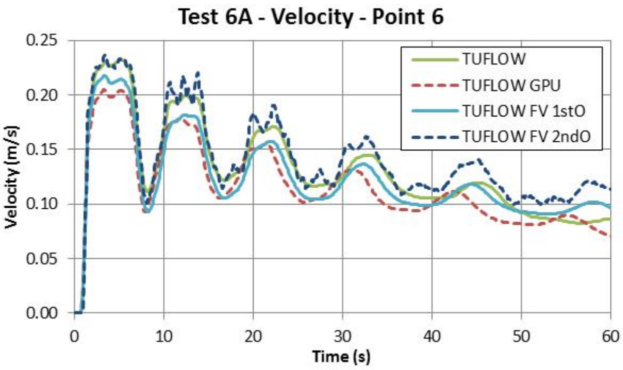
Test 6A, point 5:



Test 6A, point 6:



Test 6A, point 6:



Summary of relevant technical information for the test 6A:

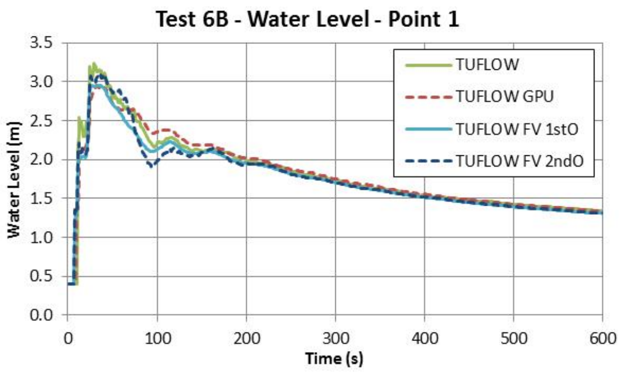
Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.01	0.01	0.01	0.01
Eddy viscosity	Spatially and time varying[1].	Spatially and time varying[1].	Spatially varying using a 0.2 Smagorinsky Coefficient	Spatially varying using a 0.2 Smagorinsky Coefficient
Grid	0.1m	0.1m	Flexible Mesh 31,254 elements	Flexible Mesh 31,254 elements
Time-stepping	Adaptive (0.01 to 0.5s)	Adaptive (0.013 to 0.05s)	Adaptive (~0.005s)	Adaptive (~0.005s)
Total simulation time (hrs)	0.0089 (32s) 1 CPU Core	0.0019[1] (7s) 448 GPU Cores	0.0124 (45s) 12 CPU Cores	0.0241 (87s) 12 CPU Cores
	1. Eddy viscosity recalculated every timestep using the Smagorinsky velocity based formulation with a coefficient of 0.5, plus a constant component of 0.05m^2/s. The majority of the model had peak values of 0.05 to 0.07 m^2/s with localised areas of large velocity gradients experiencing peak values up to 0.09 m^2/s.			

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

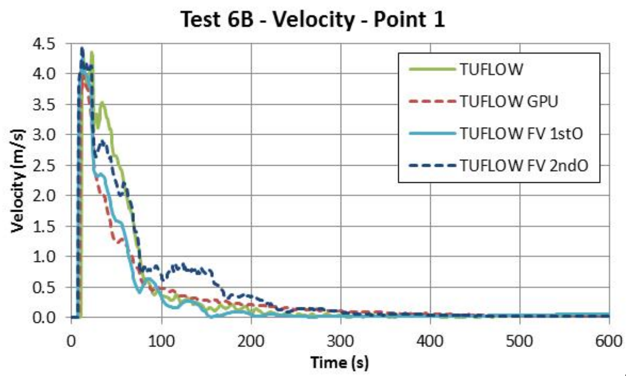
Test 6B: Water level (depth) and velocity time series:

Water level (depth) time series:	Velocity time series:

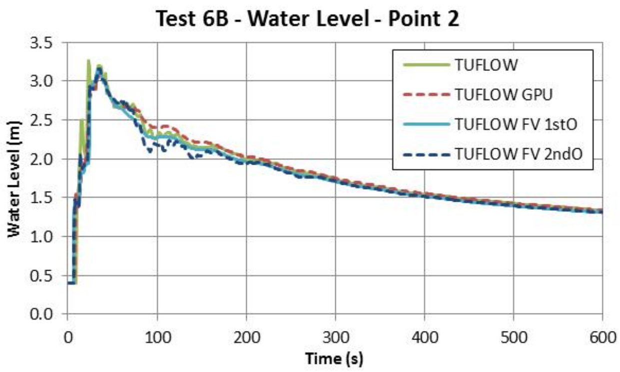
Test 6B, point 1:



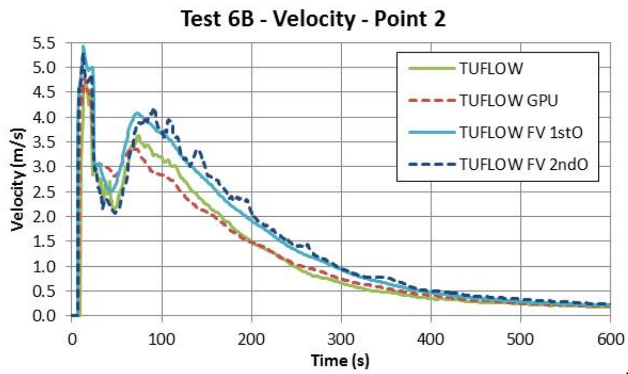
Test 6B, point 1:



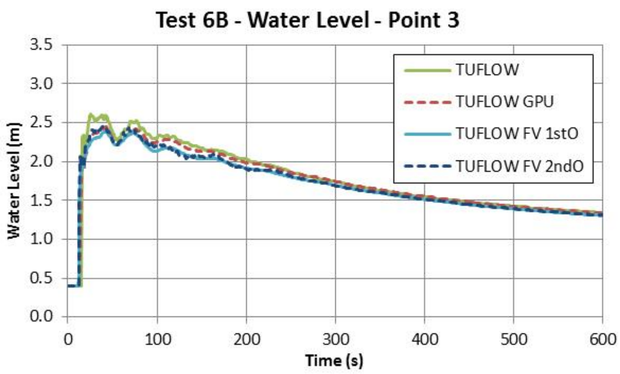
Test 6B, point 2:



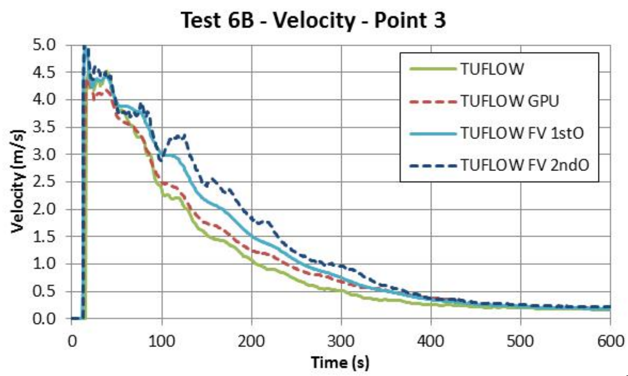
Test 6B, point 2:



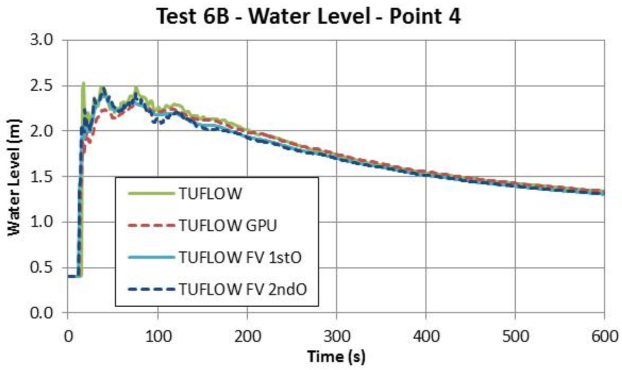
Test 6B, point 3:



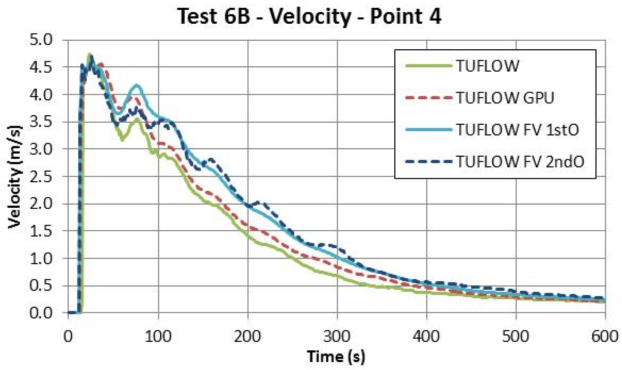
Test 6B, point 3:



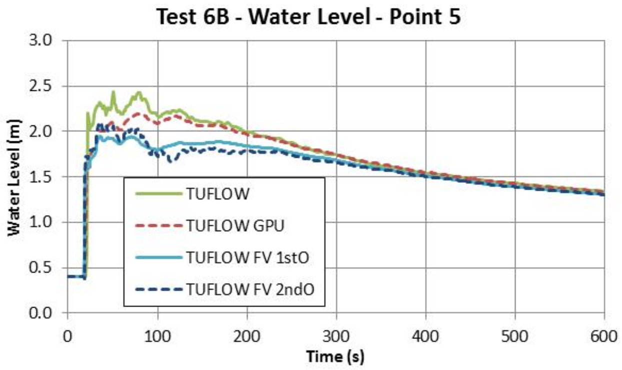
Test 6B, point 4:



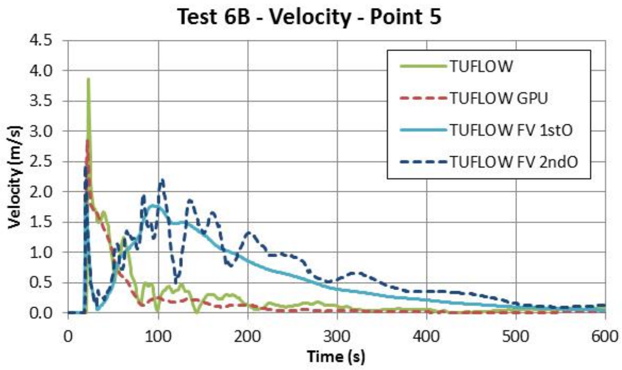
Test 6B, point 4:



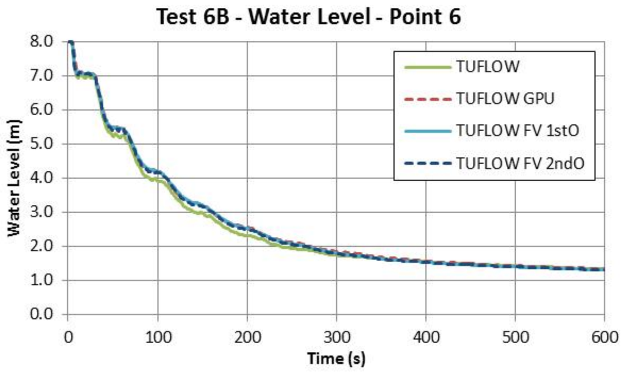
Test 6B, point 5:



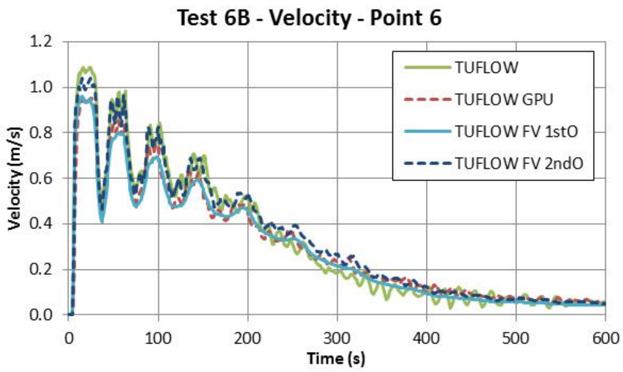
Test 6B, point 5:



Test 6B, point 6:

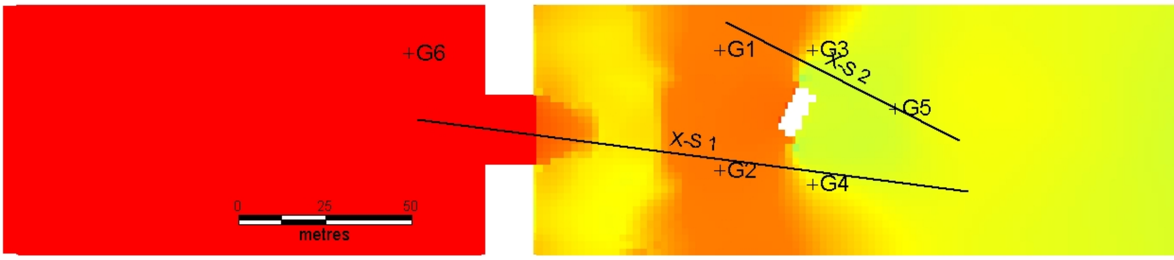


Test 6B, point 6:

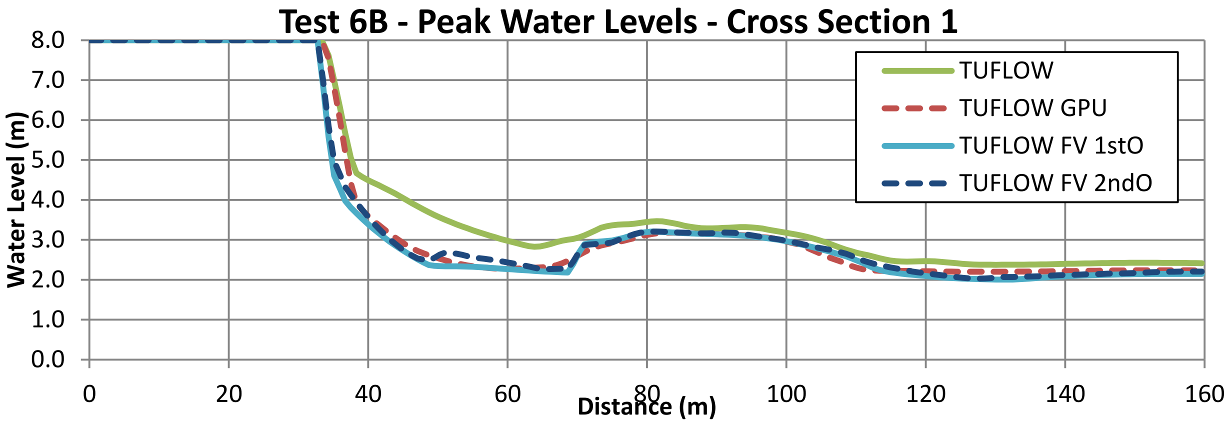


Test 6B: peak levels and velocities for cross sections 1 and 2 (shown in figure (b)):

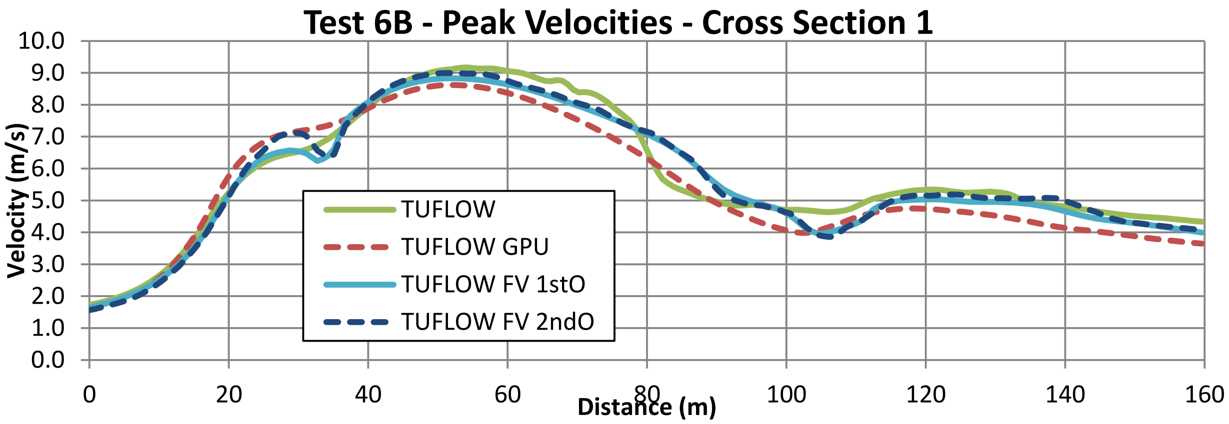
Figure (b): plan view showing the hydraulic jump and locations of the cross sections (from a peak level water grid)



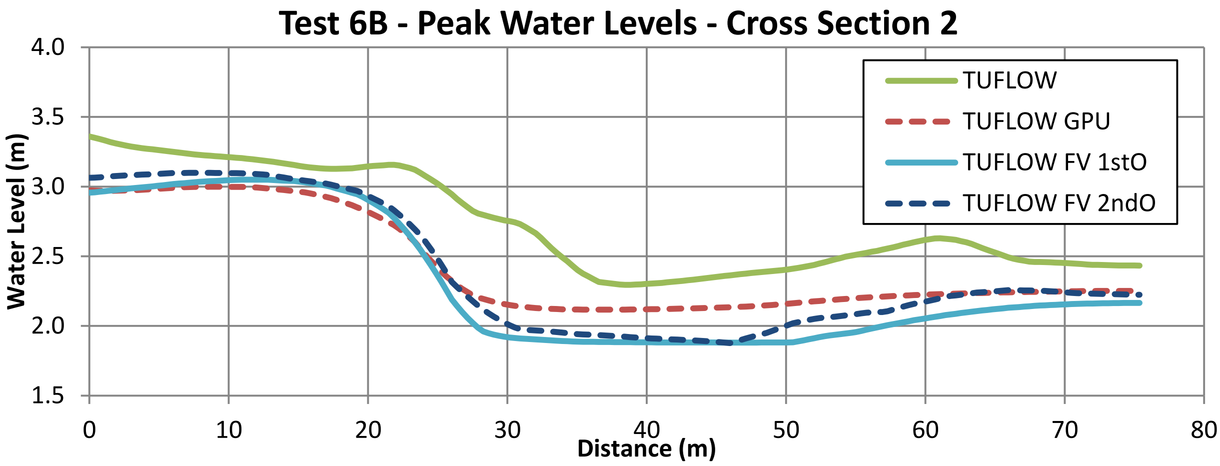
Peak water level elevations along cross-section 1 (figure (b))



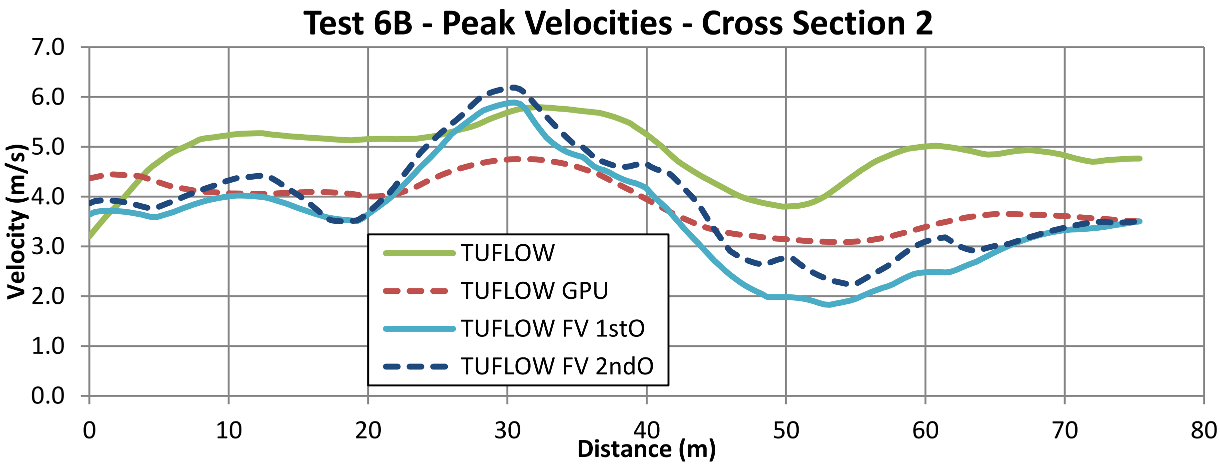
Peak velocities along cross section 1 (figure (b))



Peak water level elevations along cross section 2 (figure (b))



Peak velocities along cross section 2 (figure (b))



Summary of relevant technical information for the test 6B:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.05	0.05	0.05	0.05
Eddy viscosity coefficient used	Spatially and time varying[1].	Spatially and time varying[1].	Spatially varying using a 0.2 Smagorinsky Coefficient	Spatially varying using a 0.2 Smagorinsky Coefficient
Grid	2m	2m	Flexible Mesh 31,254 elements	Flexible Mesh 31,254 elements
Time-stepping	Adaptive (0.1 to 3.3s)	Adaptive (0.06 to 0.25s)	Adaptive (~0.035s)	Adaptive (~0.035s)
Total simulation time (hrs)	0.0106 (38s) 1 CPU Core	0.0033[1] (12s) 448 GPU Cores	0.0303 (109s) 12 CPU Cores	0.0542 (195s) 12 CPU Cores
	1. Eddy viscosity recalculated every timestep using the Smagorinsky velocity based formulation with a coefficient of 0.5, plus a constant component of $0.05 m^2/s$. The majority of the model had peak values of 0.05 to 0.15 m^2/s with localised areas of large velocity gradients experiencing peak values up to 3.5 m^2/s.			

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: Similarly for Test 5, the enhancements in the 2012-05-AA release provide an improvement for the TUFLOW results in these tests. The "Number Iterations == 4" setting was used for the simulation presented in this report. Whilst TUFLOW handles models of this type better than in 2010 and reasonable results are obtained, the shock capturing functionality of finite volume schemes may be more appropriate where the need to analyse hydraulic jumps in detail is required.

TUFLOW GPU: Produces results consistent with TUFLOW, TUFLOW FV and other fully dynamic codes presented in the 2010 report. The finite volume shock capturing is aptly demonstrated with the TUFLOW GPU results. Even better reproduction of the hydraulic jump and comparison with the flume test results in Test 6A are achieved using a 0.05m grid.

TUFLOW FV: Results represent are consistent with those in the 2010 report with an improvement for Test 6A at Gauge 2.

Test 7: River to floodplain linking

Objective:

The objective of the test is to assess the package's ability to simulate fluvial flooding in a relatively large river, with floodplain flooding taking place as the result of river bank overtopping. The following capabilities are also tested: 1) the ability to link a river model component and a 2D floodplain model component, with volume transfer occurring by embankment/bank overtopping and through culverts and other pathways; 2) the ability to build the river component using 1D cross-sections; 3) the ability to process floodplain topography features supplied as 3D breaklines to complement the DEM

Description:

The site to be modelled is approximately 7 km long by 0.75 to 1.75 km wide, see Map 1, and consists of a set of three distinct floodplains (Maps 2, 3, 4) in the vicinity of the English village of Upton-upon-Severn, although the river Severn that flows through the site is modelled for a total distance of ~20km. Boundary conditions are a hypothetical inflow hydrograph for the Severn (a single flood event with a rising and a falling limb, resulting in below bankfull initial and final levels in the river (table provided), and a downstream rating curve (table provided). This poses a relatively challenging test through the need for the model to adequately identify and simulate flooding along separate floodplain flow paths, and predict correct bank/embankment overtopping volumes. The volume exchange takes place over natural river banks and/or embankments along which flood depths are expected to be small.

The site has been subjected to flooding on a number of occasions but it is not the intention to replicate an observed flood for this exercise, hence the boundary conditions have been designed to provide a suitable benchmarking case.

River channel geometry

The channel geometry is provided in the form of a text file with cross-sections labelled M013 to M054 (a separate csv file containing cross-section locations and spacing is provided). A uniform channel roughness value is used. Any head losses due to the plan geometry of the river (meanders) are ignored. Along some sections the channel is adjacent to floodplains on just one or on both sides. 3D "breaklines" are provided which define a) the boundary between the river channel and the area expected to be modelled in 2D, and b) elevations along these boundaries (these are consistent with the DEM elevations). These elevations are to be used in the prediction of bank/embankment overtopping. Wherever no floodplain is modelled along the river channel (more than 50% of the total length of river banks), a "glass wall" approach (or equivalent) should be applied if water levels exceed the bank elevation in the cross-section (i.e. the water level rises above the bank without spilling out of the 1D model).

A bridge at the North end of Upton (between cross-sections M033 and M034), for which no data are provided, is ignored. No other structure is known to affect the flow along the modelled reach of the river.

Floodplains

The extents of the three modelled floodplains are defined as follows (See Maps 2, 3, 4):

- **Floodplain 1:** on West bank of the River, from upstream from Cross-Section M024, to upstream from M030 (floodplain breakline number 2, see below).
- **Floodplain 2:** on East bank of the river, from upstream from Cross-Section M029, to upstream from M036.
- **Floodplain 3:** on West bank of the river, from half-way between cross-sections M031 and M032 to half-way between cross-sections M043 and M044. This includes the "island" on which the village of Upton lies.

The floodplains are otherwise bounded by the river bank breaklines provided, see above in "River channel geometry". Away from the river, for consistency in model extent, it is suggested to draw the boundaries of the 2D models approximately along the 16m contour line.

Floodplain 3 has a physical opening below the 16m altitude along the Pool Brook stream to the North-West of Upton. The model should extent to the edge of the DEM in this location. (however this boundary is to be treated as closed, i.e. no flow)

Note that the narrow strip of floodplain (between FP 1 and FP 3) on the West bank of the river in the vicinity of cross-sections M030 and M031 does not need modelling in 2D. Cross-sections M030 and M031 have been extended as far as the hillside to the West.

A shapefile containing polylines defining the outer boundaries of the floodplains is provided.

A number of features in the floodplains are expected to impact on results significantly and will be modelled. This includes:

- embankments and elevated roads, for which 3D breaklines are provided as part of the dataset. These can be used to adjust nodes elevations in the computational grid. They should be distinguished from the river/floodplain boundary breaklines mentioned in the previous section.
- a set of low bridges of total width ~40m under the elevated causeway (A4104 road) immediately west of Upton. This can be modelled as a single 40m opening through the A4104 causeway (elevations provided as floodplain breakline number 7). A photograph and a datafile containing various parameters (including X Y coordinates and dimensions) are provided as part of the dataset.

The modelled flood is not expected to inundate roads and built-up areas to any significant extent. Therefore a uniform roughness value is applied across the floodplains, with a specified value. The floodplain land use in this reach is predominately pasture with a lesser amount of arable crops. Any effect of buildings are ignored (for example in the town of Upton).

Any feature of the floodplain not mentioned above, including any perceived 'false blockages' should be ignored. 2 'marinas' within floodplain 1 (near North end) and floodplain 2 (near South end) should simply be modelled as ground, with elevations as given by the DEM.

1D-2D volume transfer

No parameter value or modelling approach is specified for the prediction of river/floodplain volume transfer (except the elevations specified by the breaklines).

At the real site volume exchange between the channel and the floodplains also occur through a number of flapped outfalls. These are ignored.

A masonry culvert immediately upstream from the village of Upton ("Pool Brook") is however modelled, see Map 4. It is assumed circular in cross-section. A photograph and a spreadsheet containing various parameters (including XY coordinates and dimensions) are provided as part of the dataset.

An opening in the embankment (floodplain breakline number 2) at location X=384606 Y=242489 (see Map 2) at the southern end of Floodplain 1 (blocked by a sluice in reality) is assumed to remain opened during the duration of the flood. This should be understood as a 10m wide opening (invert level 10m) offering a pathway from Floodplain 1 to the river at cross-section M030.

Misc

The DEM is a 1.0m resolution LIDAR Digital Terrain Model (no vegetation or buildings) provided by the Environment Agency (http://www.geomatics-group.co.uk). Due to the very large size of the 1m DEM file, a coarsened 10m DEM is also provided, but it is emphasised that this is unlikely to provide the right elevations along embankments, river banks and other features, for which 3D breaklines are provided.

Minor processing of the original EA LIDAR DEM was done, consisting in merging tiles and filling small areas of missing data in the modelled floodplains. Areas of missing data (-9999) may remain in the DEM, but only outside the modelled 2D domain described previously.

The model is run until time T = 72 hours to allow the flood to settle in the lower parts of the modelled area.

Boundary and initial conditions:

River channel:

- Upstream: inflow versus time applied at the northernmost cross-section, cross-section M013.
- Downstream: rating curve (flow versus head), applied at the southernmost cross-section, cross-section M054.
- Initial condition: a uniform water level of 9.8m.

Floodplains:

- Linked to the river channel along the river bank breaklines provided, and through the Pool Brook culvert (Floodplain 3) and the opening (sluice) at the South end of Floodplain 1.
- All other boundaries are closed (no flow).
- Initial condition: A uniform water level of 9.8m.

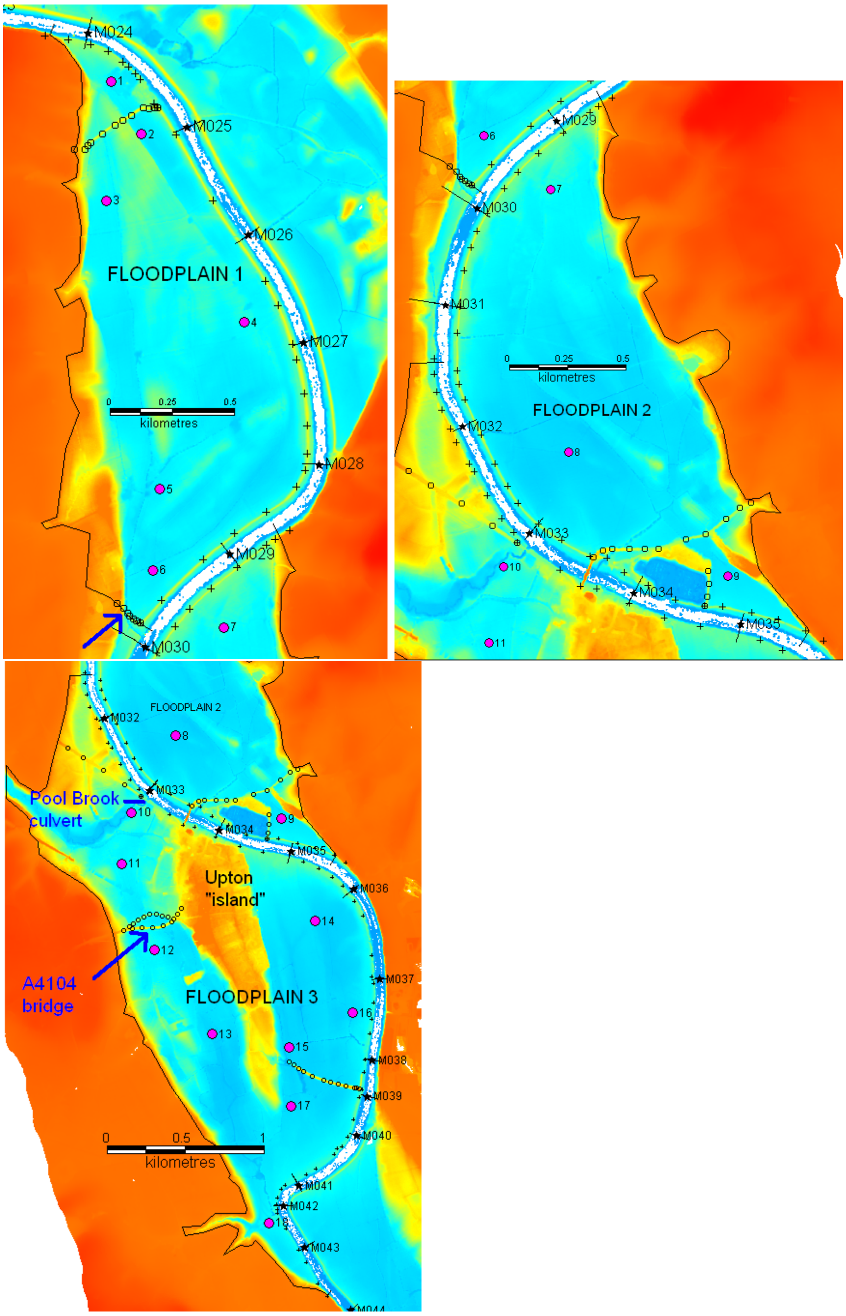
Pool Brook culvert: Initial water level 9.8m.

Parameter values:

- Manning's n: 0.028 uniformly in river, 0.04 uniformly in floodplains

- Model grid resolution: 20m (or ~16700 nodes in the model extent defined in Section 2 under "Floodplains")
- Time of end: the model is to be run until time t = 72 hours (if an alternative end time is used run times must be reported for t=72 hours)

Results:



<table>
<tr><td>Water level (depth) time series:</td><td>Velocity time series:</td></tr>
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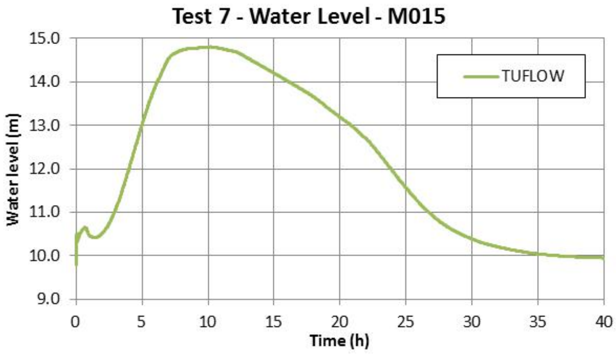
Test 7, cross section M015:



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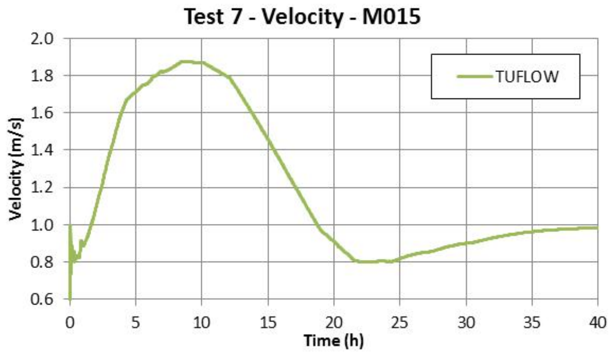
Test 7, cross section M015:



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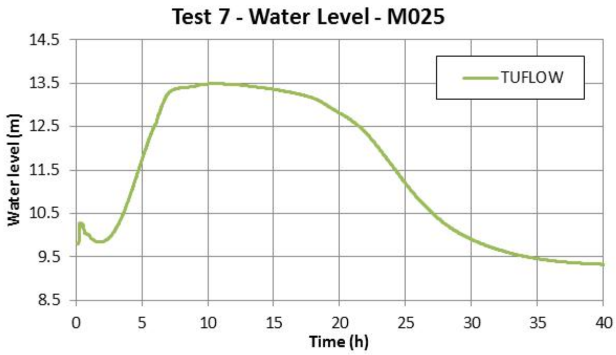
Test 7, cross section M025:



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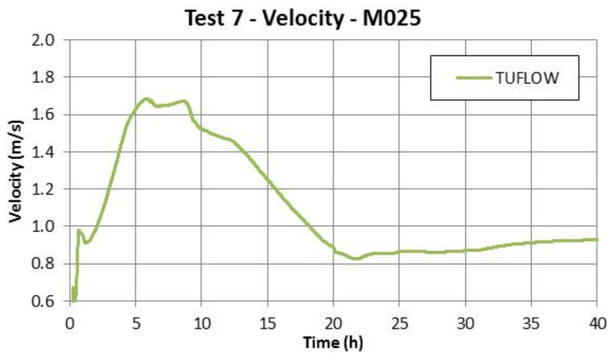
Test 7, cross section M025:



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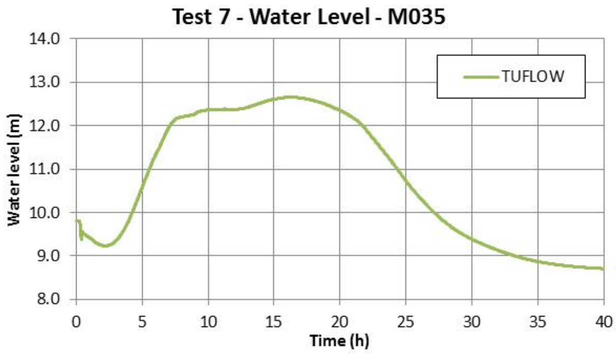
Test 7, cross section M035:



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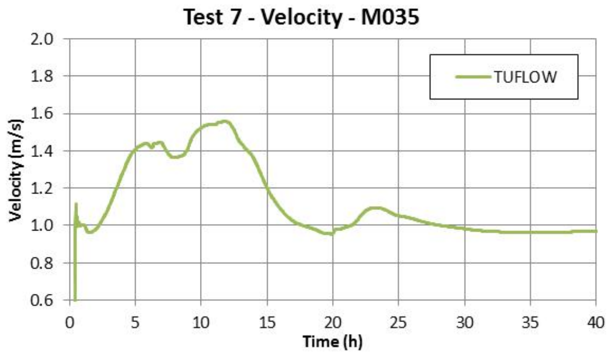

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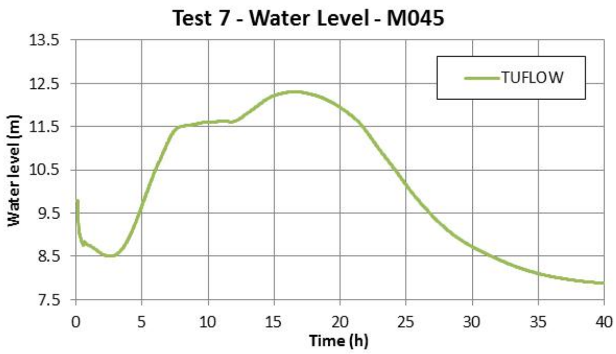
Test 7, cross section M045:



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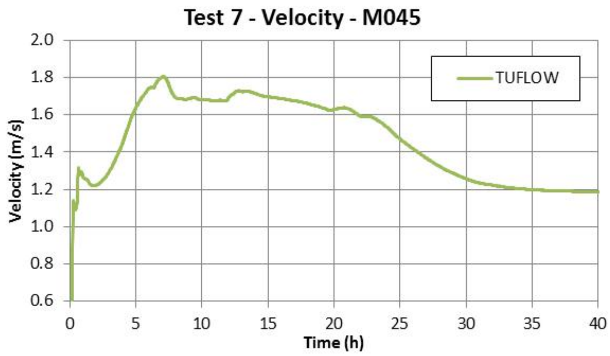
Test 7, cross section M045:



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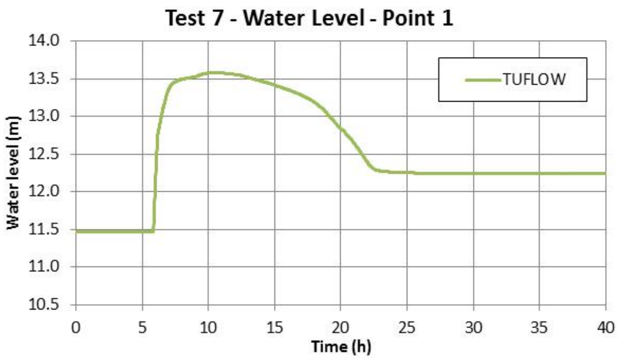
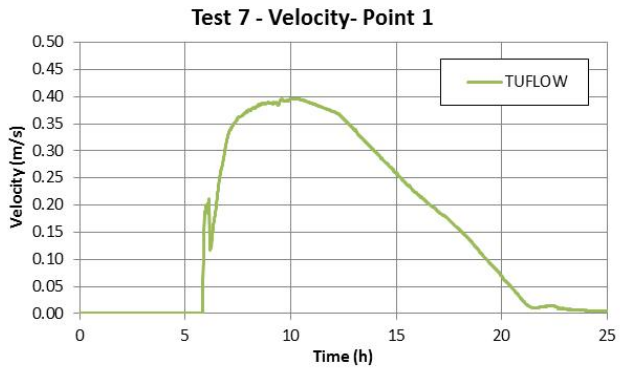
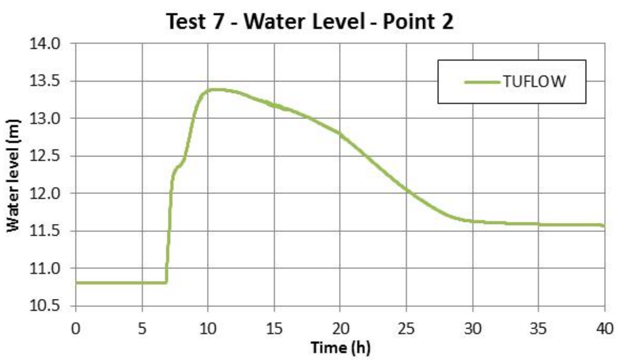
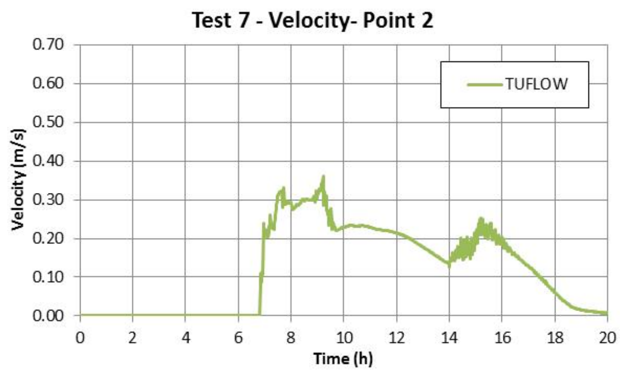
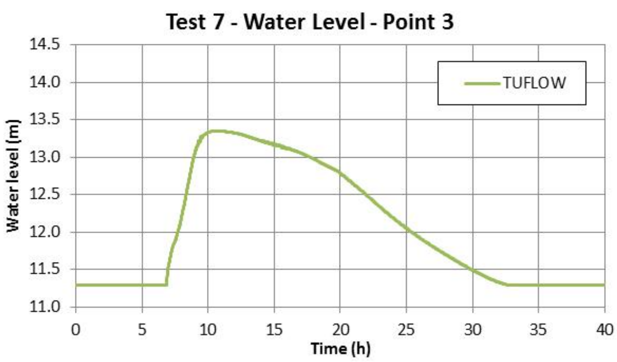
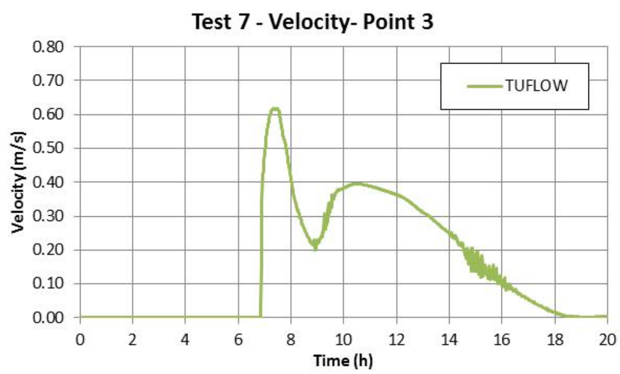
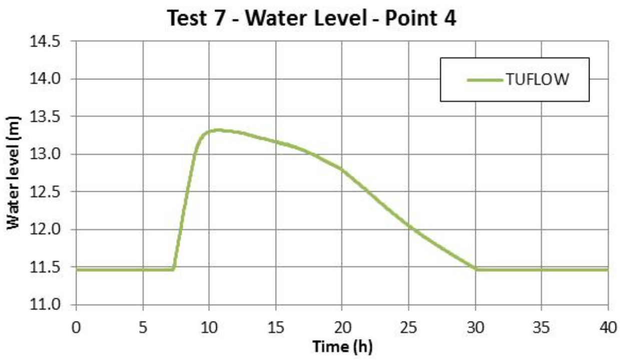
</table>

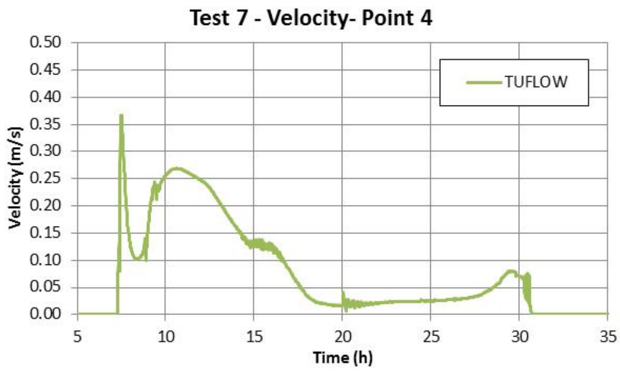
Floodplain 1:

Water level (depth) time series:	Velocity time series:
Test 7, point 1: 	**Test 7, point 1:** 
Test 7, point 2: 	**Test 7, point 2:** 
Test 7, point 3: 	**Test 7, point 3:** 

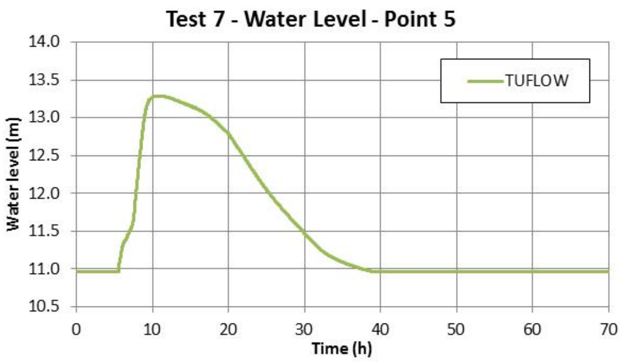
Test 7, point 4:



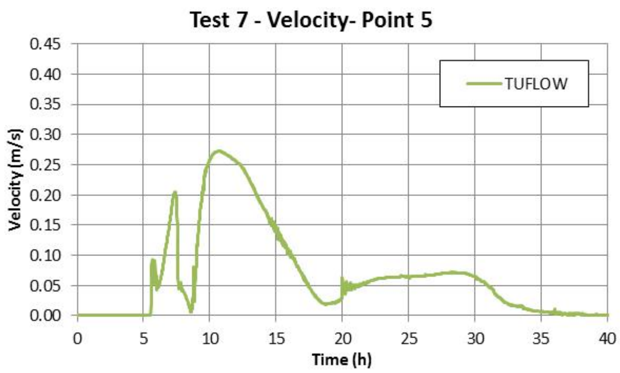
Test 7, point 4:



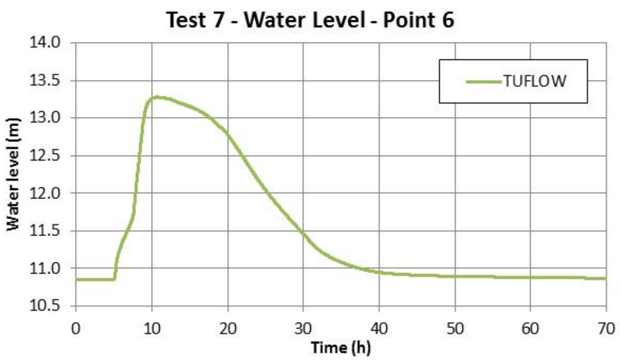
Test 7, point 5:



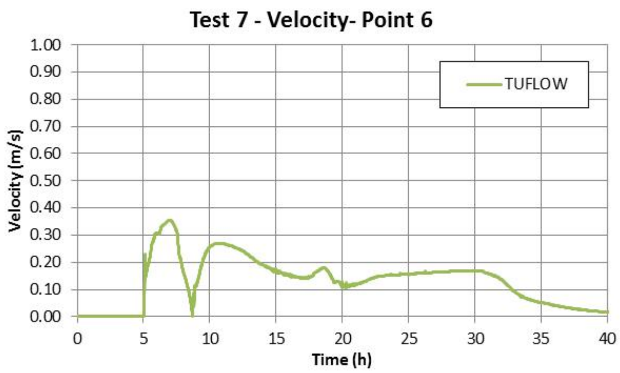
Test 7, point 5:



Test 7, point 6:



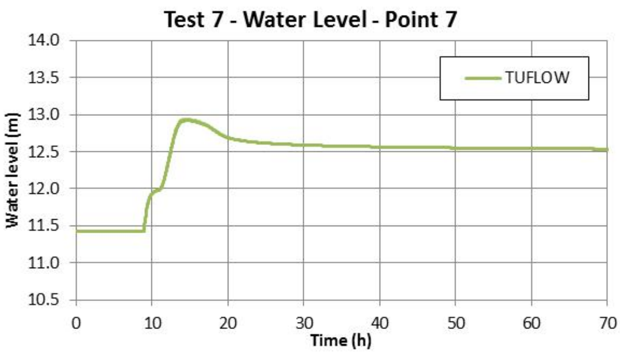
Test 7, point 6:



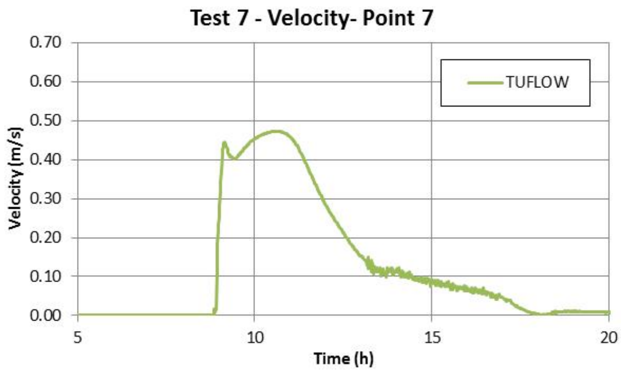
Floodplain 2:

Water level (depth) time series:	**Velocity time series:**

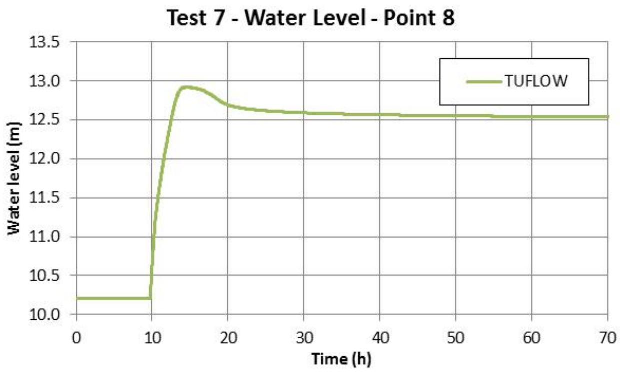
Test 7, point 7:



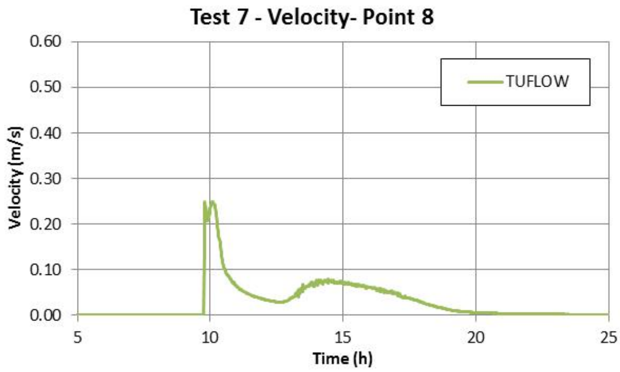
Test 7, point 7:



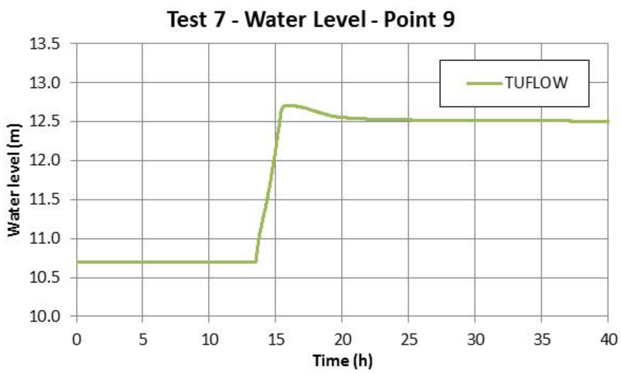
Test 7, point 8:



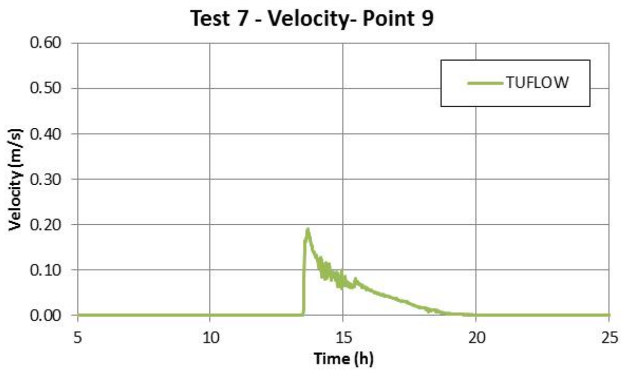
Test 7, point 8:



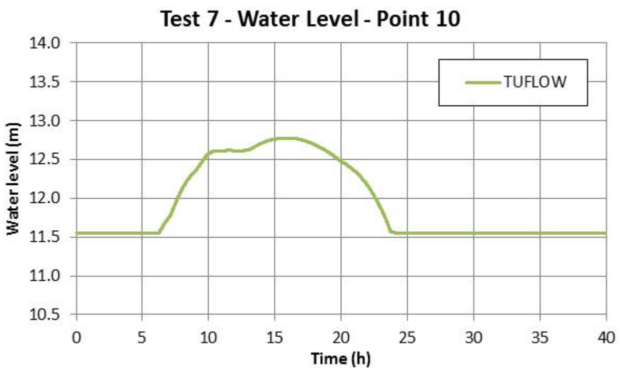
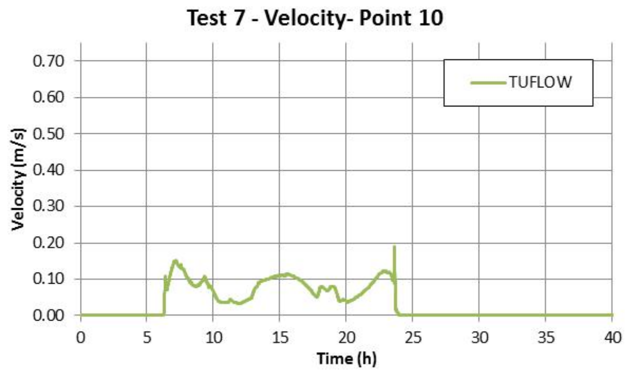
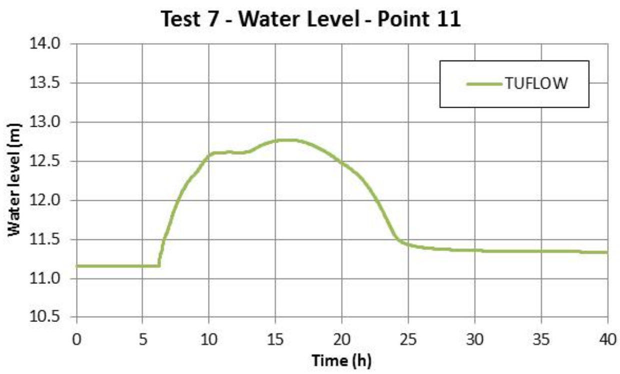
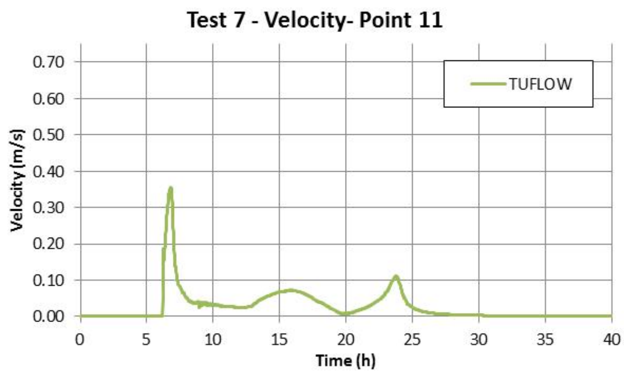
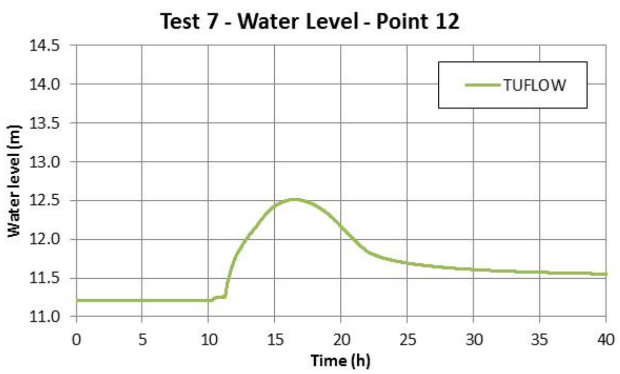
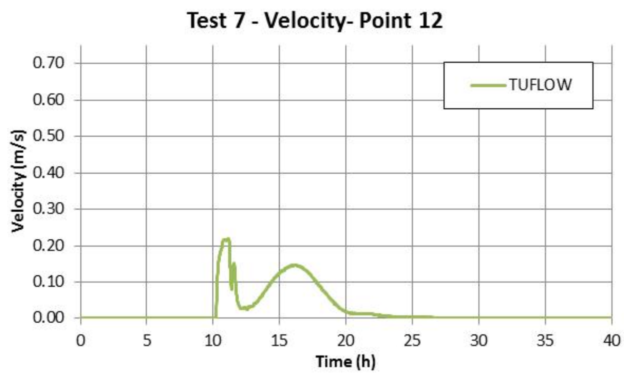
Test 7, point 9:



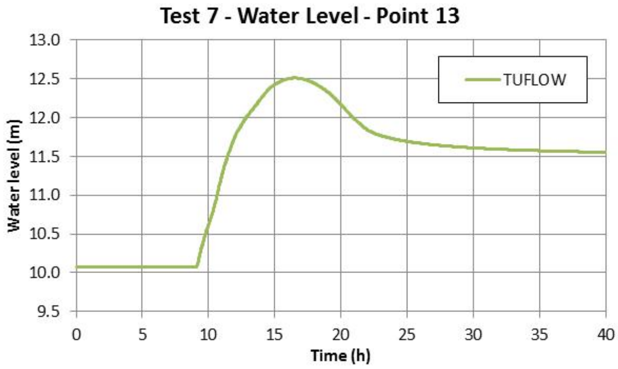
Test 7, point 9:



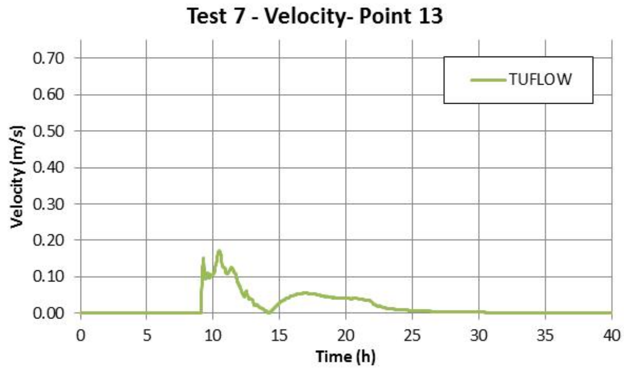
Floodplain 3:

Water level (depth) time series:	**Velocity time series:**
Test 7, point 10: 	**Test 7, point 10:** 
Test 7, point 11: 	**Test 7, point 11:** 
Test 7, point 12: 	**Test 7, point 12:** 

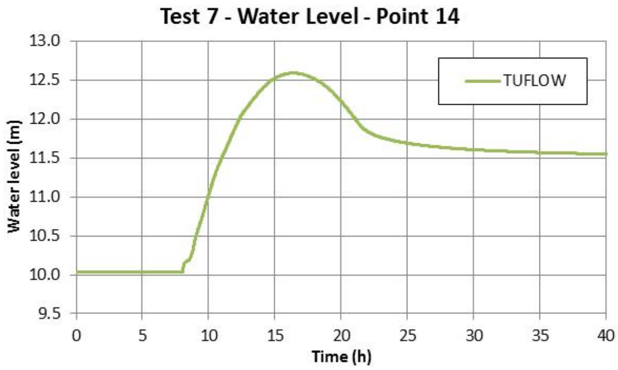
Test 7, point 13:



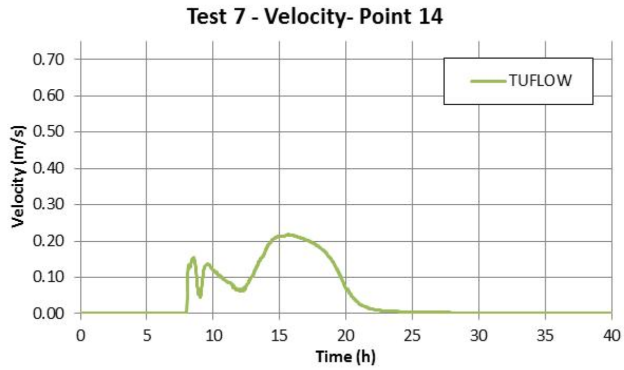
Test 7, point 13:



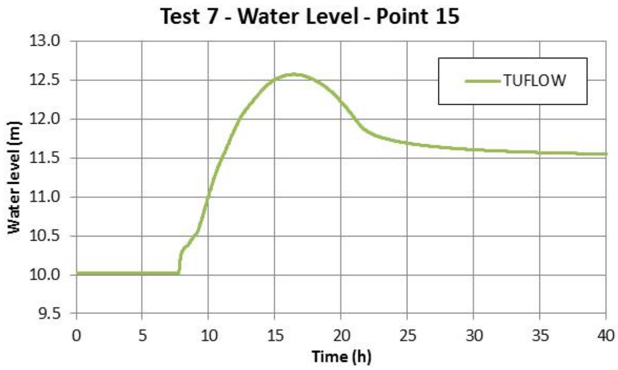
Test 7, point 14:



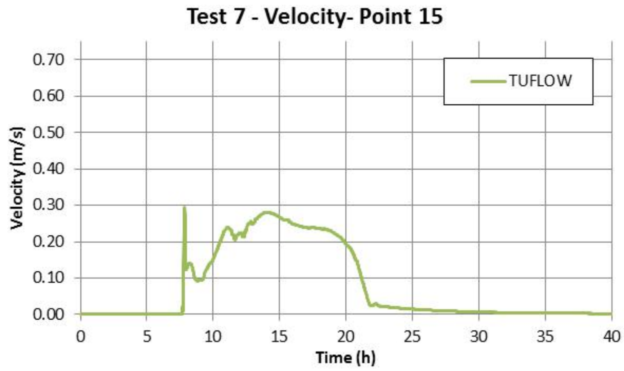
Test 7, point 14:



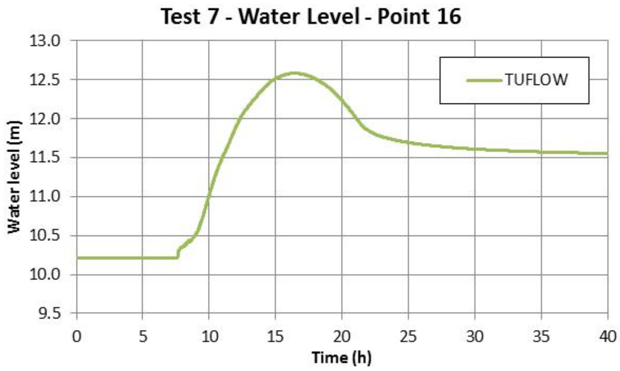
Test 7, point 15:



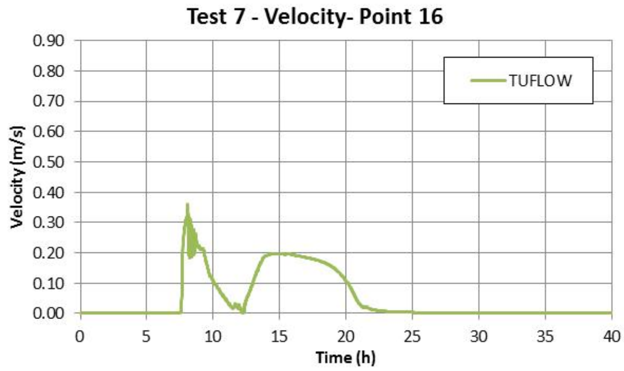
Test 7, point 15:



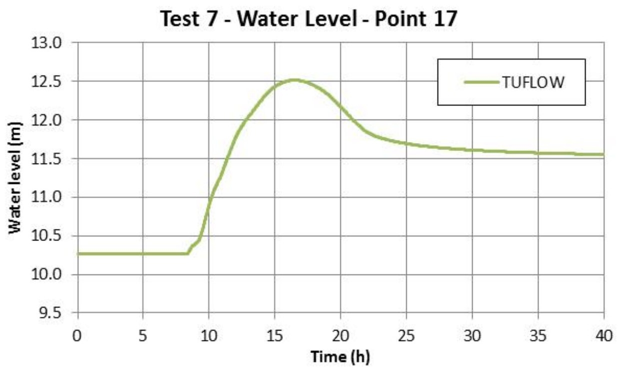
Test 7, point 16:



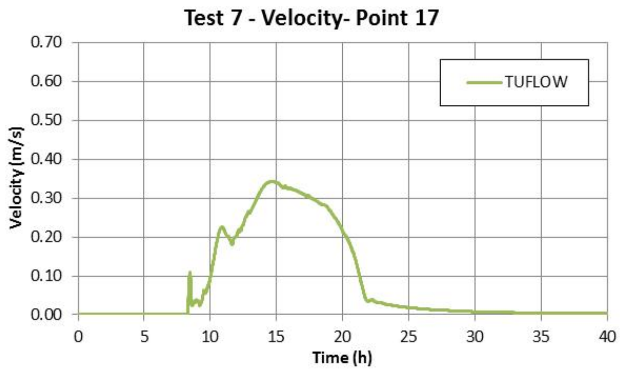
Test 7, point 16:



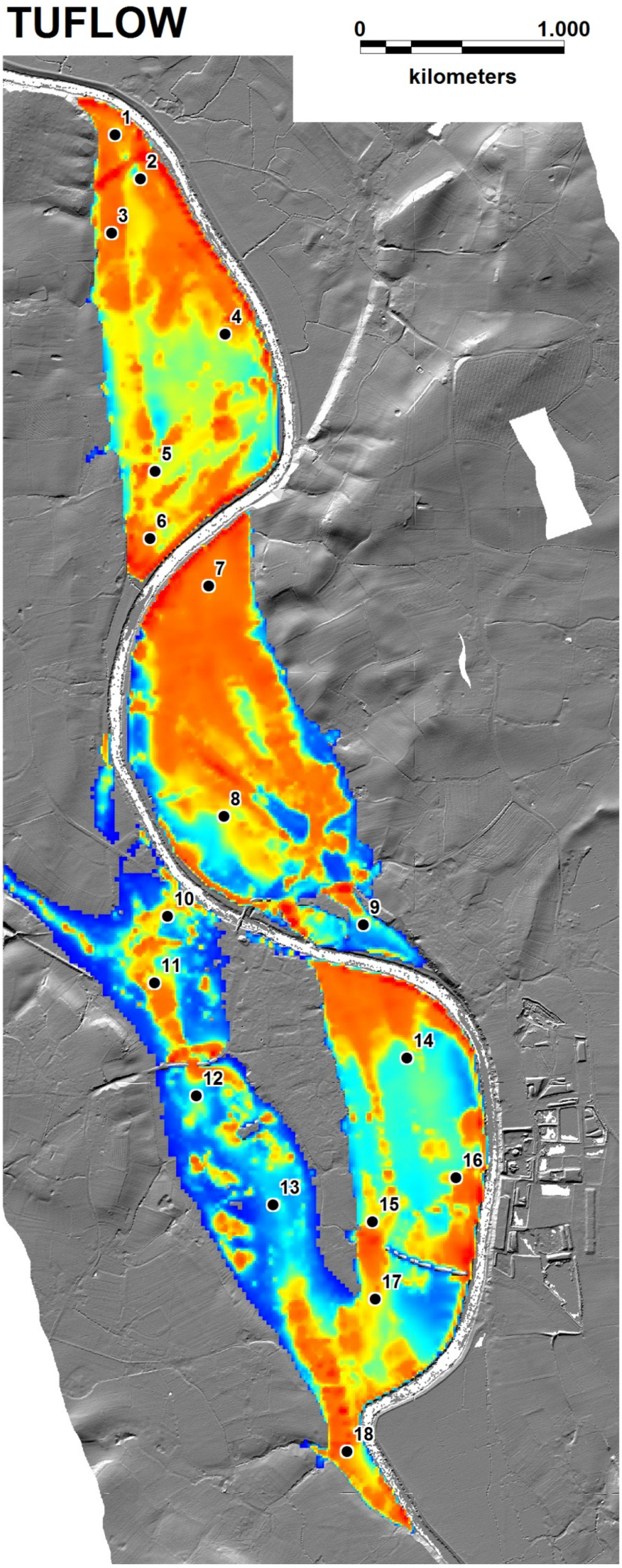
Test 7, point 17:



Test 7, point 17:



Peak velocities in gridded format:



Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Single Precision (SP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	n/a	n/a	n/a
Manning's n used	0.028 river 0.04 floodplain			
Grid	20m			
Time-stepping	2D: 15s 1D: 3s			
Total simulation time (hrs)	0.0556 (200s) 1 CPU Core			

Software developer comments:

TUFLOW: The 1D results are near identical to the 2010 report and the 2D results are very similar. The enhancements made for the 2012-05 release have improved the velocity outputs and have allowed the 2D timestep to be increased from 10s to 15s with improved stability and less mass error (-0.06% 2010/10s timestep vs -0.04% for 2012/15s).

Test 8: Rainfall and sewer surcharge flood in urban areas

Test 8A: Rainfall and point source surface flow in urban areas

Objective:

This tests the package's capability to simulate shallow inundation originating from a point source and from rainfall applied directly to the model grid, at relatively high resolution.

Description:

The modelled area is approximately 0.4 km by 0.96 km and covers entirely the DEM provided and shown in Figure (a). Ground elevations span a range of ~21m to ~37m.

The flood is assumed to arise from two sources:

- a uniformly distributed rainfall event illustrated by the hyetograph in Figure (b). This is applied to the modelled area only (the rest of the catchment is ignored).

- a point source at the location represented in Figure (a), and illustrated by the inflow time series in Figure (c). (This may for example be assumed to arise from a surcharging culvert.)

The DEM is a 0.5m resolution Digital Terrain Model (no vegetation or buildings) created from LiDAR data collected on 13th August 2009 and provided by the Environment Agency (http://www.geomatics-group.co.uk).

Participants are expected to ignore any buildings at the real location (Cockenzie Street and surrounding streets in Glasgow, UK) and to carry out the modelling using the "bare-earth" DEM provided.

A land-cover dependent roughness value is applied, with 2 categories: 1) Roads and pavements; 2) Any other land cover type.

The model is run until time T = 5 hours to allow the flood to settle in the lower parts of the modelled domain.

Figure (a): DEM used, with the location of the point source. Purple lines: outline of roads and pavements. Triangles: output point locations.

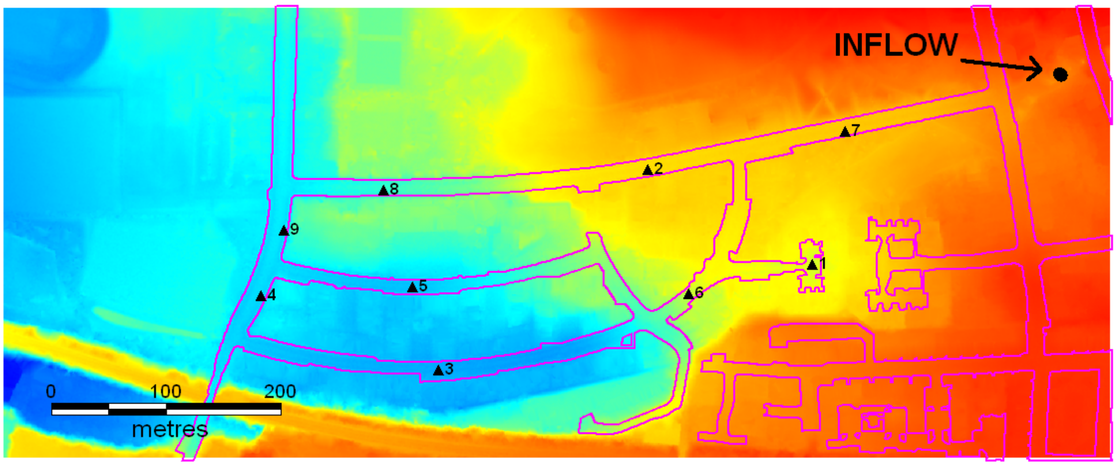


Figure (b): Hyetograph applied in Test 8A.

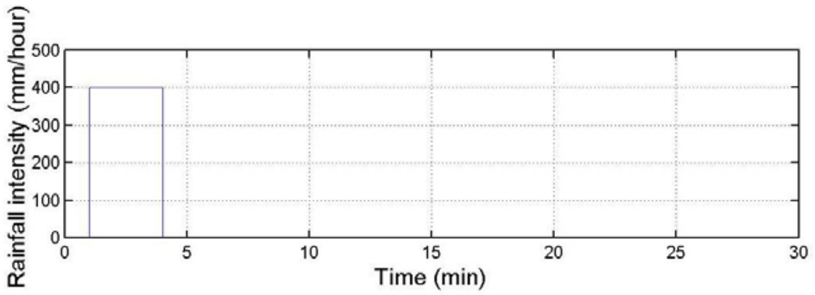
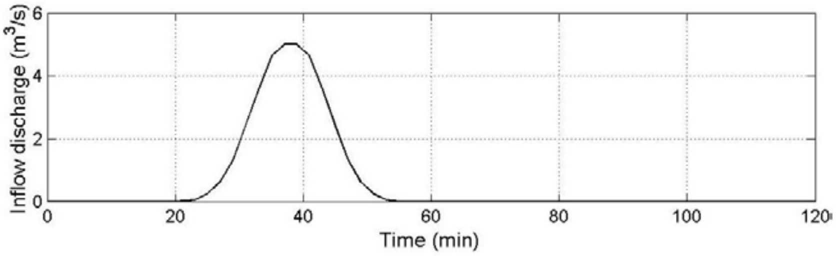


Figure (c): Inflow hydrograph applied in Test 8A at point location shown in Figure (a).



Boundary and initial conditions:

- Rainfall as described above. Hyetograph provided as table in dataset.
- The point source is applied as described above. Coordinates and time series provided as part of dataset.
- All boundaries of the modelled area are closed (no flow).
- Initial condition: Dry bed.

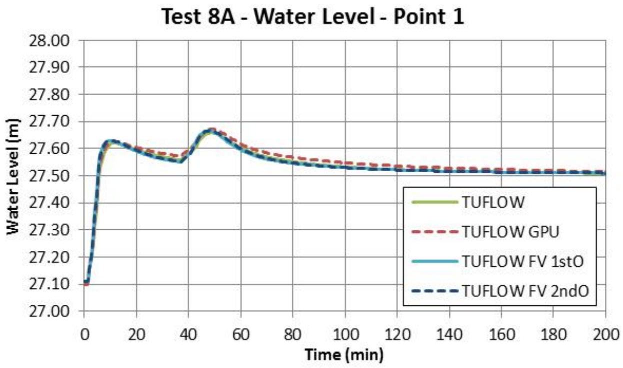
Parameter values:

- Manning's n: 0.02 for roads and pavements, 0.05 everywhere else
- Model grid resolution: 2m (or ~97000 nodes in the 0.388 km^2 area modelled)
- Time of end: the model is to be run until time t = 5 hours (if an alternative end time is used run times must be reported for t=5 hours)

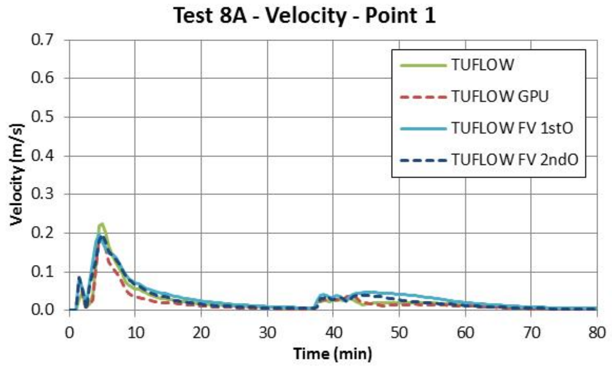
Results:

Water level (depth) time series:	Velocity time series:

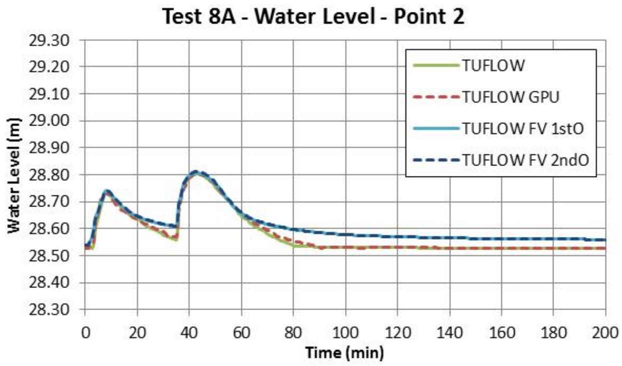
Test 8A, point 1:



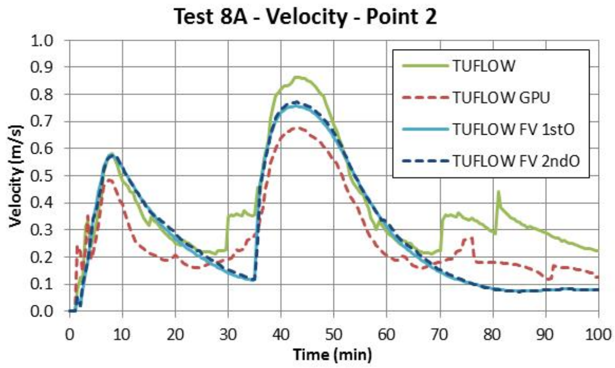
Test 8A, point 1:



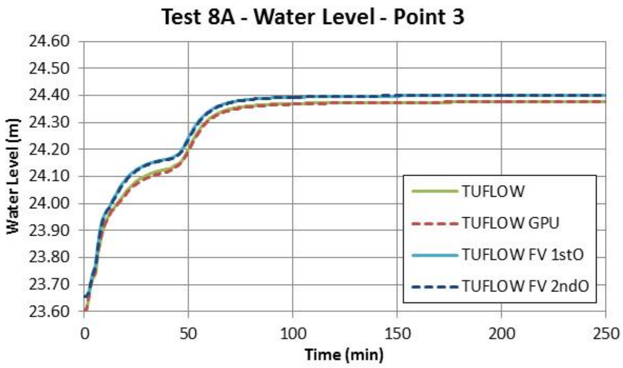
Test 8A, point 2:



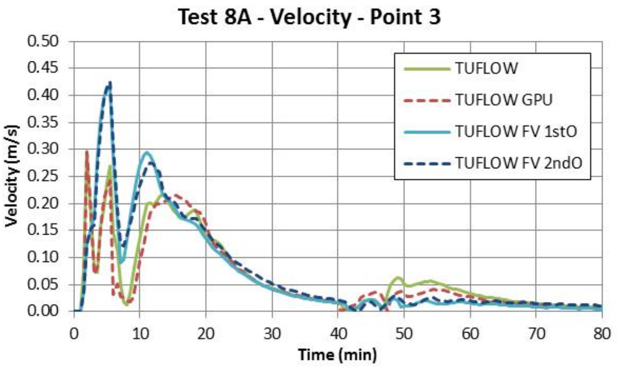
Test 8A, point 2:



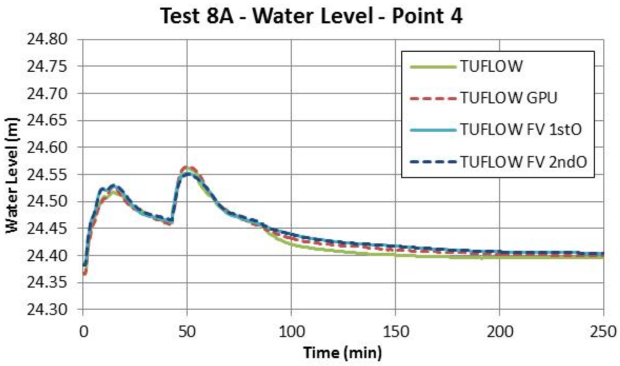
Test 8A, point 3:



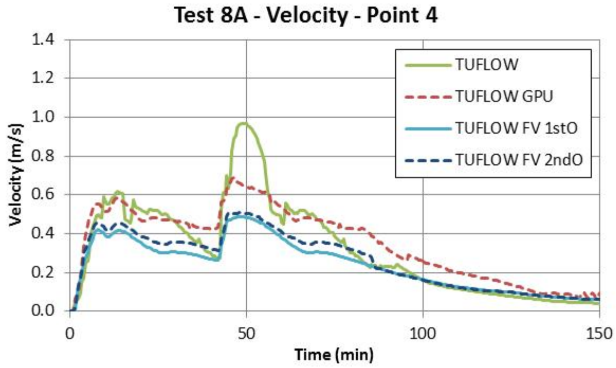
Test 8A, point 3:



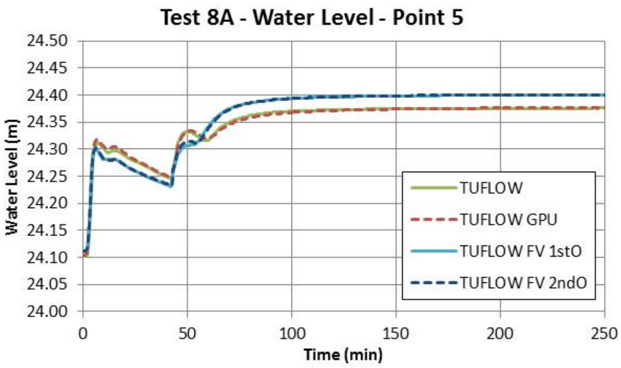
Test 8A, point 4:



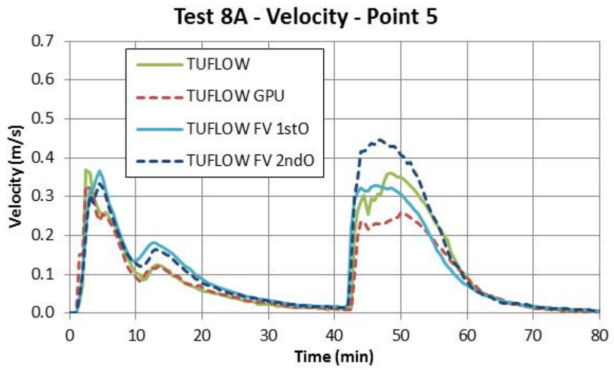
Test 8A, point 4:



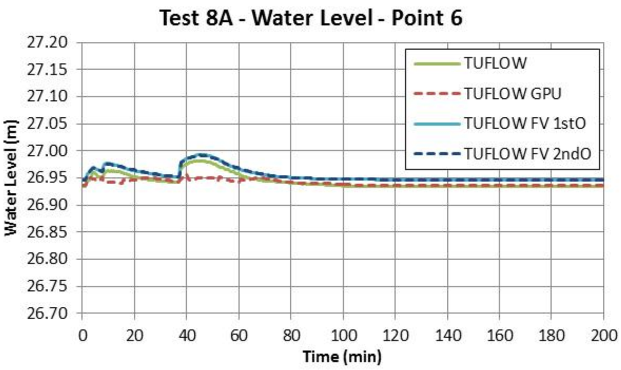
Test 8A, point 5:



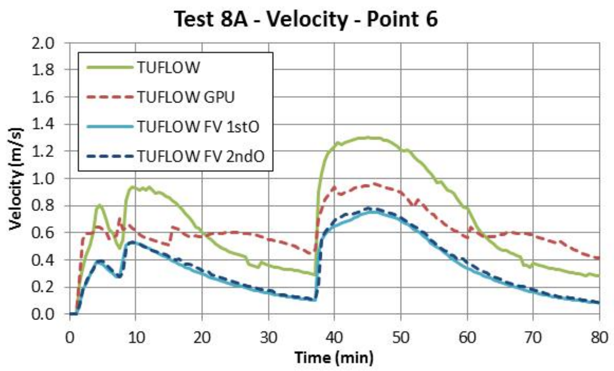
Test 8A, point 5:



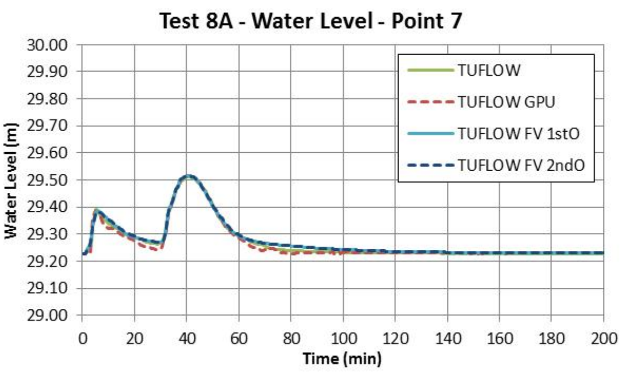
Test 8A, point 6:



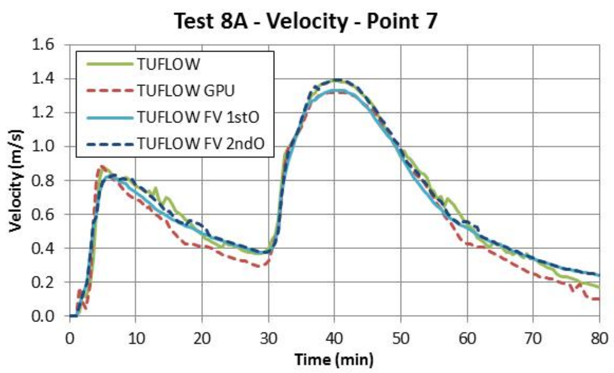
Test 8A, point 6:



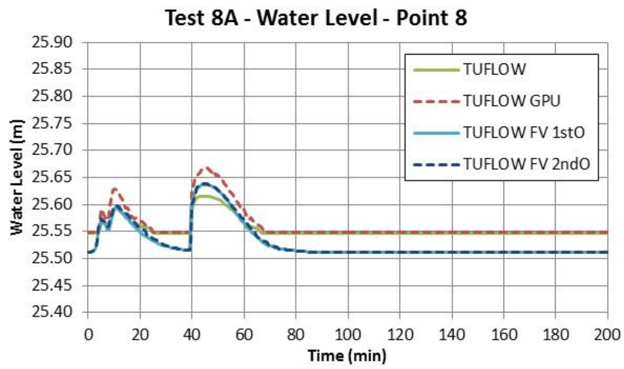
Test 8A, point 7:



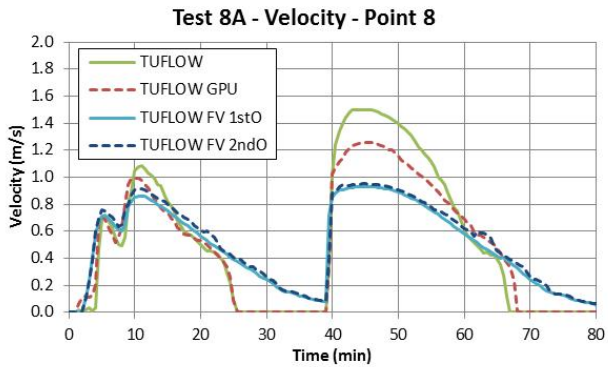
Test 8A, point 7:



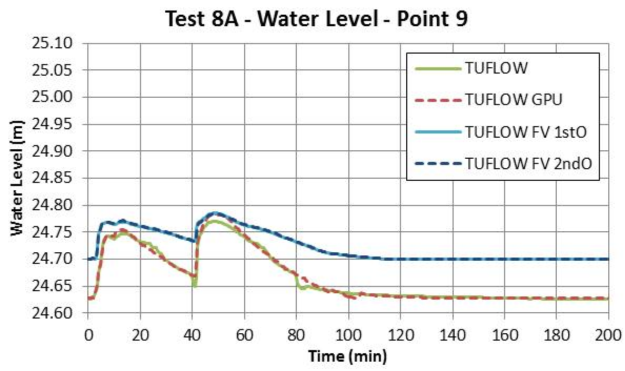
Test 8A, point 8:



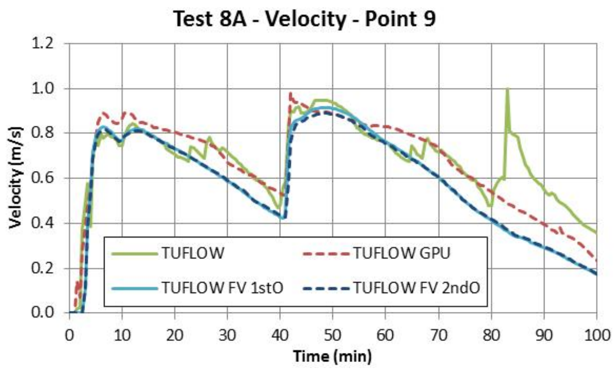
Test 8A, point 8:



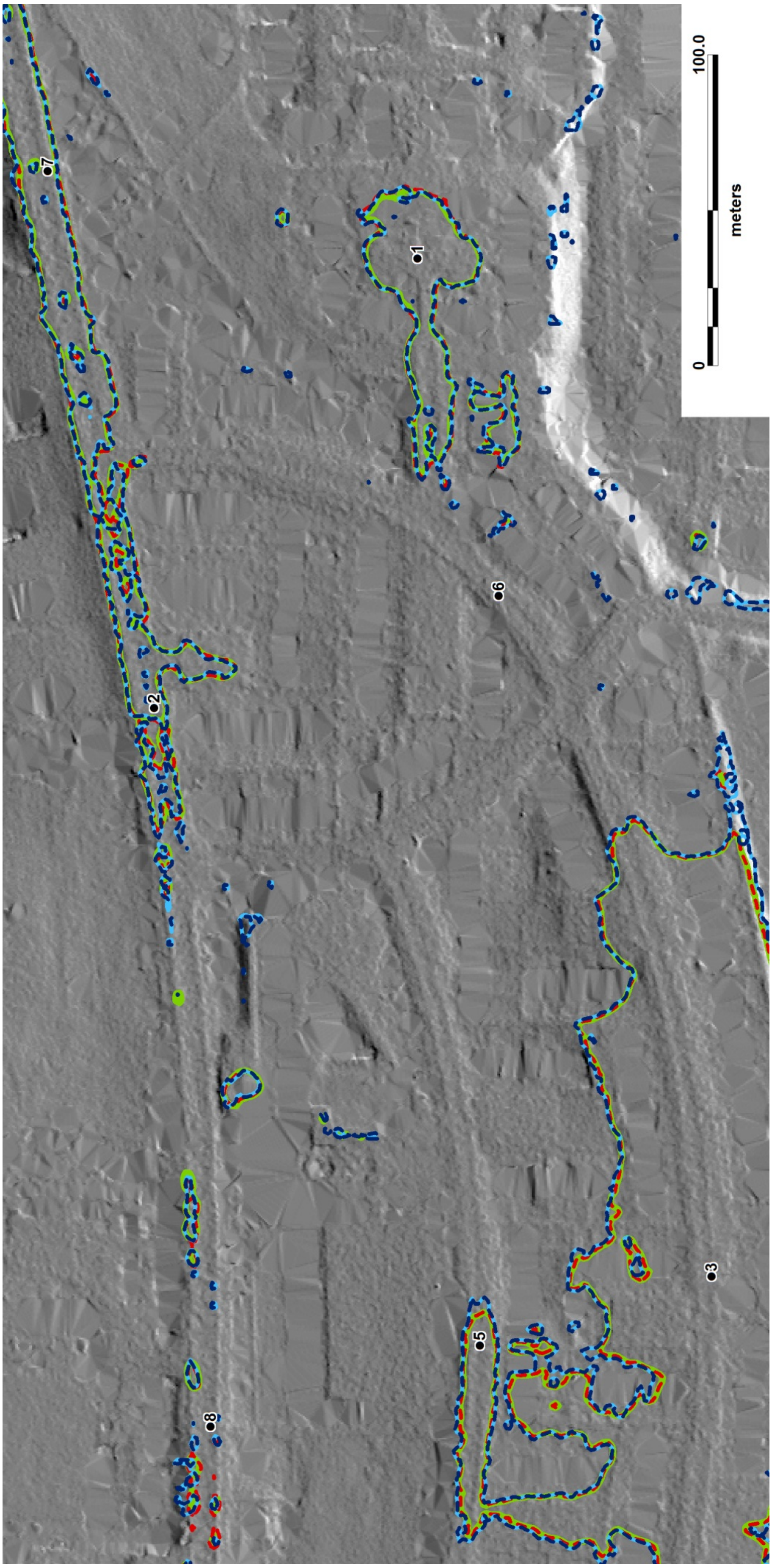
Test 8A, point 9:



Test 8A, point 9:



20cm contours of peak depth. Colours consistent with other figures.



Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Double Precision (DP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	Yes	Yes	Yes
Manning's n used	0.02 roads 0.05 elsewhere	0.02 roads 0.05 elsewhere	0.02 roads 0.05 elsewhere	0.02 roads 0.05 elsewhere
Grid	2m	2m	2m	2m
Time-stepping	1.5s	Adaptive (0.2 to 0.3s)	Adaptive (~0.33s)	Adaptive (~0.33s)
Total simulation time (hrs)	0.1325 (477s) 1 CPU Core	0.0356[1] (128s) 448 GPU Cores	0.1138 (410s) 12 CPU Cores	0.1700 (612s) 12 CPU Cores

1. Refer note on TUFLOW GPU Module run times at end of report in Overall Summary of Performance section.

Software developer comments:

TUFLOW: The enhancements made for the 2012-05 release have improved the velocity outputs and have allowed the 2D timestep to be increased from 1.0s to 1.5s through improved stability.

TUFLOW GPU: Produced very similar water level profiles and similar velocity outputs compared with TUFLOW and TUFLOW FV.

TUFLOW FV: Results similar to those from the 2010 report.

Test 8B: Surface flow from a surcharging sewer in urban areas

Objective:

This tests the package's capability to simulate shallow inundation originating from a surcharging underground pipe, at relatively high resolution. The pipe is modelled in 1D and connected to the 2D grid through a manhole.

Description:

The modelled area is approximately 0.4 km by 0.96 km and covers entirely the DEM provided and shown in Figure (a). Ground elevations span a range of ~21m to ~37m.

A culverted watercourse of circular section, 1400mm in diameter, ~1070m in length, and with invert level uniformly 2m below ground is assumed to run through the modelled area. An inflow boundary condition is applied at the upstream end of the pipe, illustrated in Figure (b). A surcharge is expected to occur at a vertical manhole of 1m2 cross-section located 467m from the top end of the culvert, and at the location shown in Figure (a).

The flow from the above surcharge spreads across the surface of the DEM.

The DEM is a 0.5m resolution Digital Terrain Model (no vegetation or buildings) created from LiDAR data collected on 13th August 2009 and provided by the Environment Agency (http://www.geomatics-group.co.uk).

Participants are expected to take into account the presence of a large number of buildings in the modelled area. Building outlines are provided with the dataset. Roof elevations are not provided (arbitrary elevations to be set by modellers if needed, at least 1m above ground).

A land-cover dependent roughness value is applied, with 2 categories: 1) Roads and pavements; 2) Any other land cover type.

The model is run until time T = 5 hours to allow the flood to settle in the lower parts of the modelled area (or until this has happened according to the model)

Figure (a): DEM used, with the location of the manhole. The course of the underground pipe is indicated, although irrelevant to the modelling. Purple lines: outline of roads and pavements. Black lines: building outlines. Triangles: output point locations.

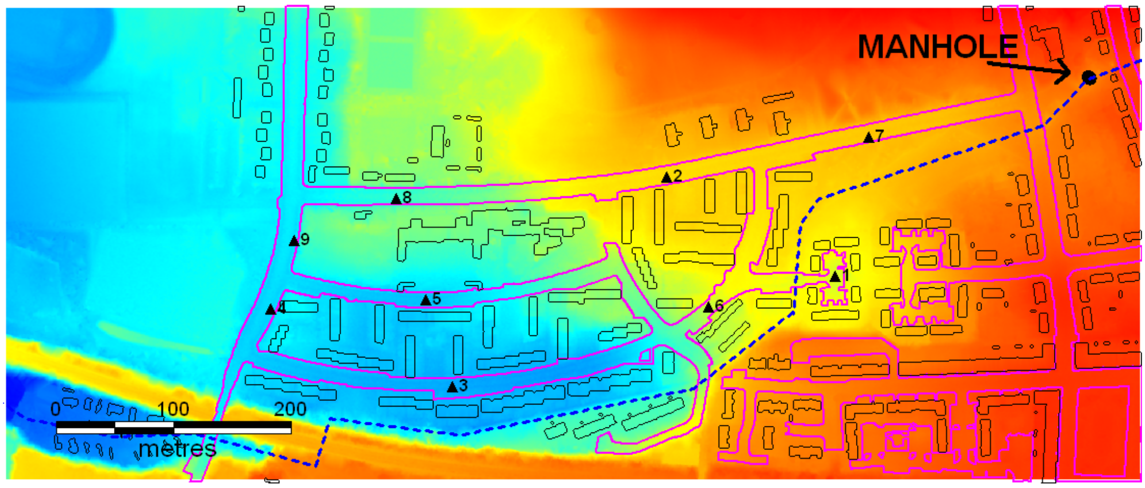
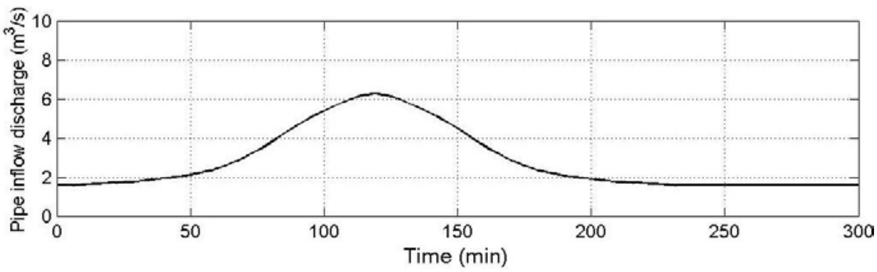


Figure (b): Inflow hydrograph applied in Test 8B at upstream end of culvert.



Boundary and initial conditions:

- Underground pipe
  - Upstream boundary condition: discharge versus time provided as part of dataset
  - Downstream boundary condition: free outfall (critical flow)
  - Baseflow (uniform initial condition): 1.6 m3/s
- 2D domain
  - Manhole connected to 2D grid in one point.
  - All boundaries of the modelled area are closed (no flow).
  - Initial condition: Dry bed.
- Conditions at manhole/2D surface link
  - The surface flow is assumed not to affect the manhole outflow.

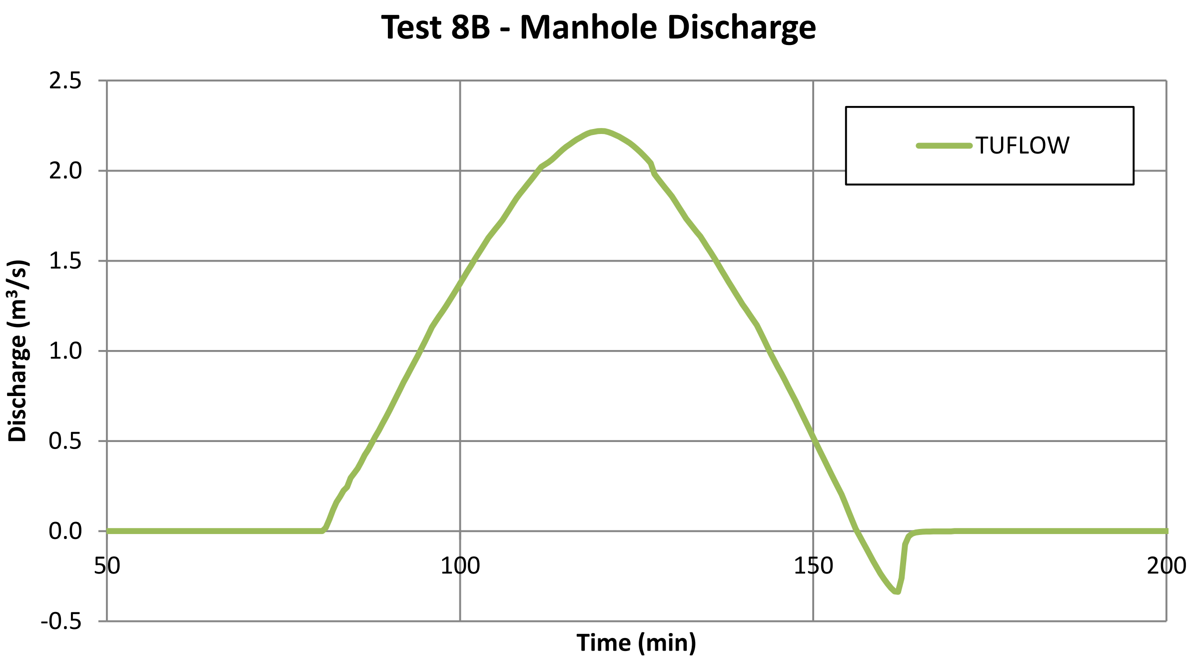
Parameter values:

- Manning's n: 0.02 for roads and pavements, 0.05 everywhere else
- Model grid resolution: 2m (or ~97000 nodes in the 0.388 km^2 area modelled)
- Time of end: the model is to be run until time t = 5 hours (if an alternative end time is used run times must be reported for t = 5 hours)

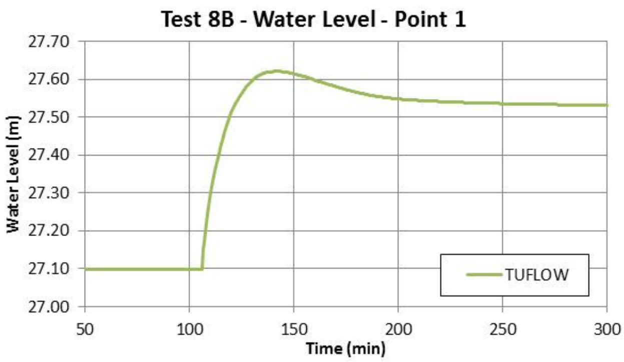
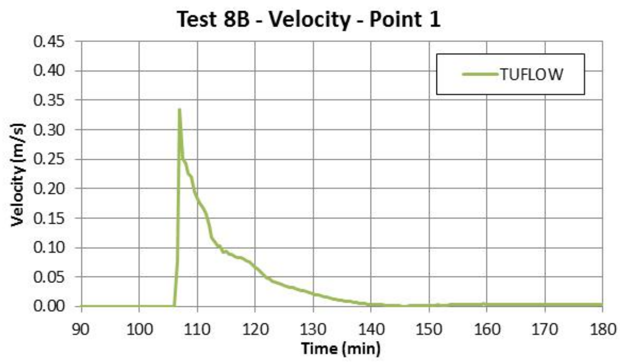
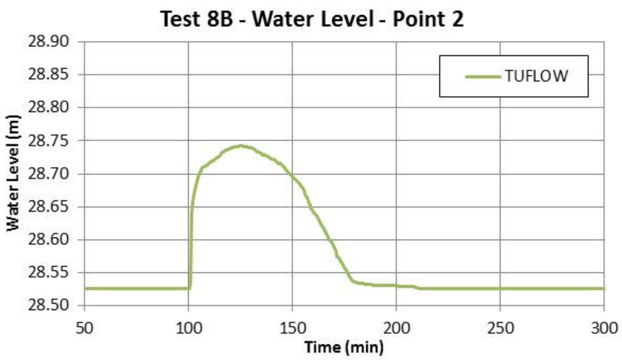
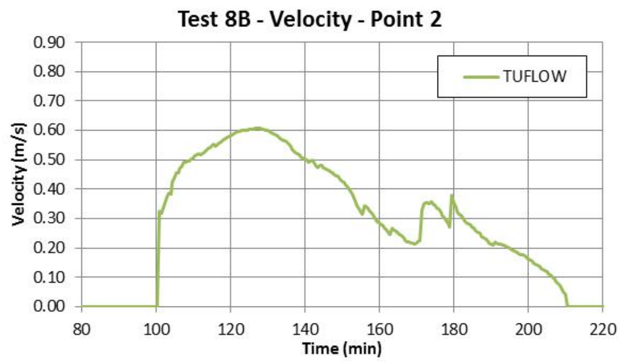
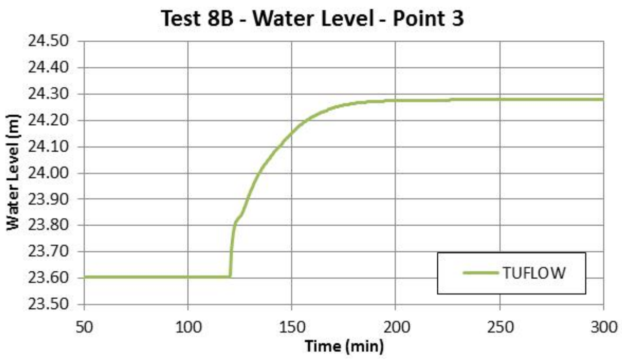
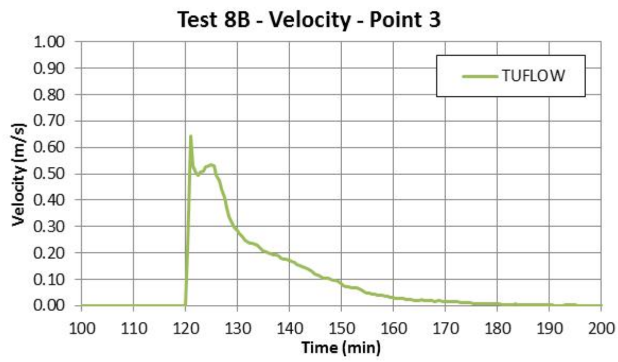
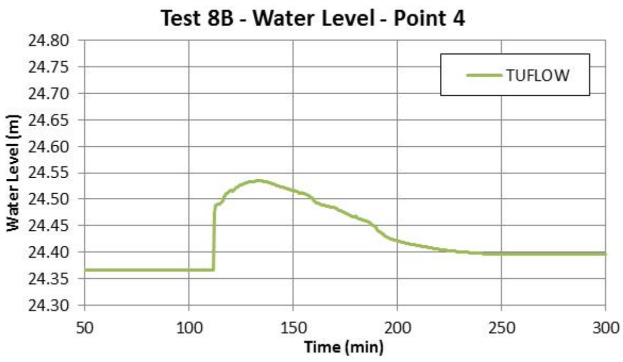
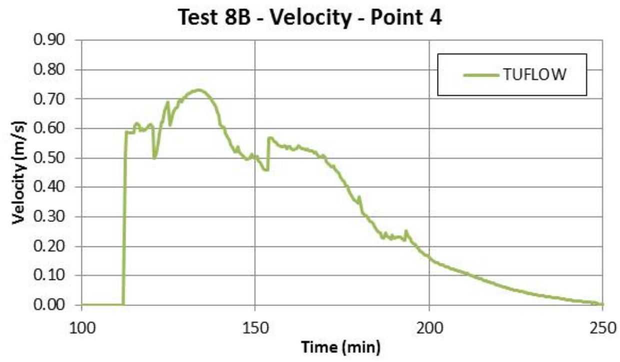
Results:

Manhole discharge:

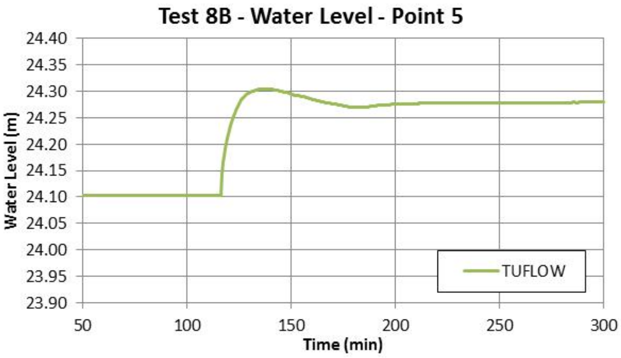
Total volume through manhole: 5,840 m^3



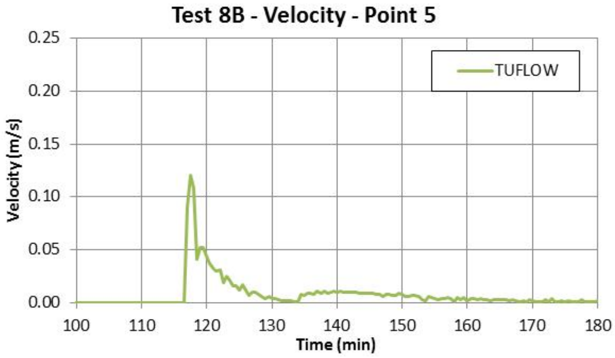
Water levels and velocities:

Water level (depth) time series:	Velocity time series:
Test 8B, point 1: 	**Test 8B, point 1:** 
Test 8B, point 2: 	**Test 8B, point 2:** 
Test 8B, point 3: 	**Test 8B, point 3:** 
Test 8B, point 4: 	**Test 8B, point 4:** 

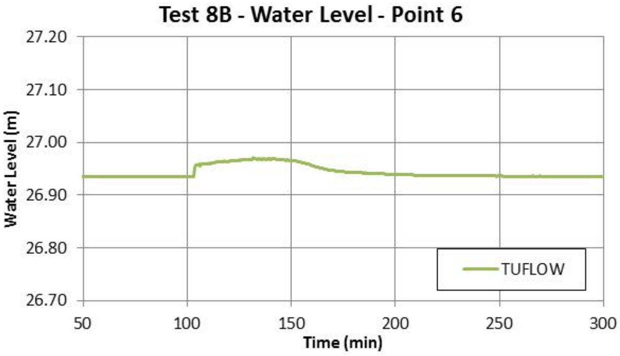
Test 8B, point 5:



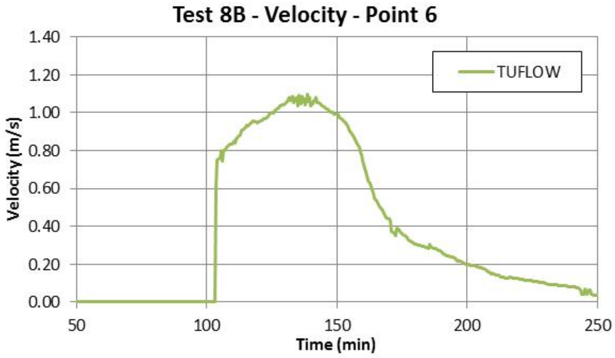
Test 8B, point 5:



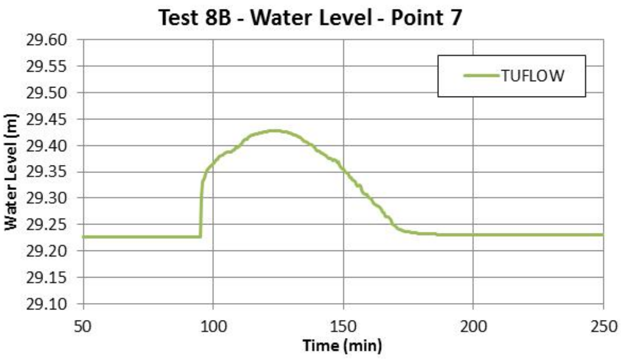
Test 8B, point 6:



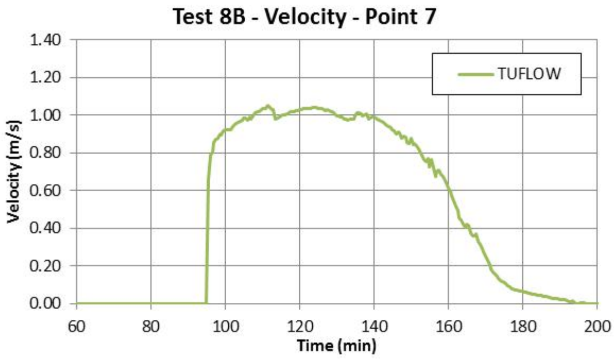
Test 8B, point 6:



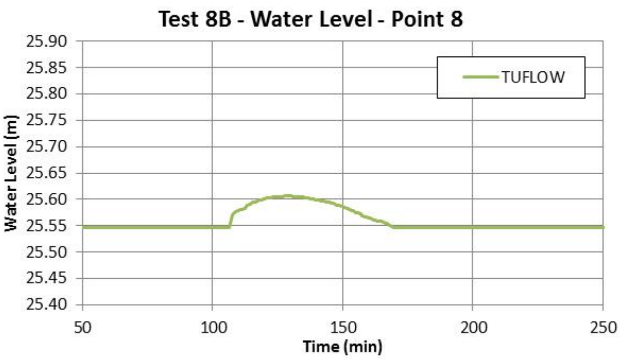
Test 8B, point 7:



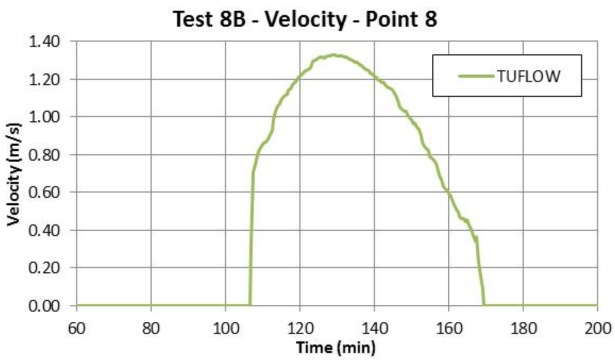
Test 8B, point 7:

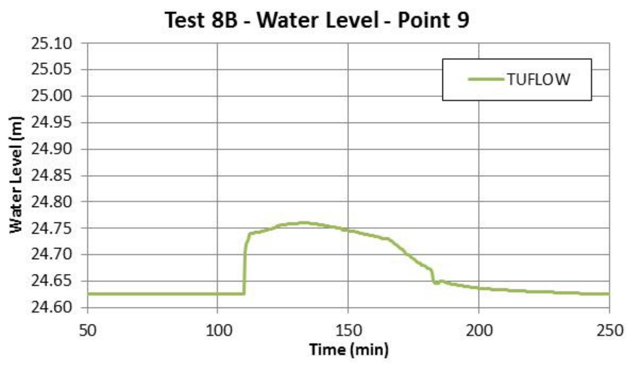
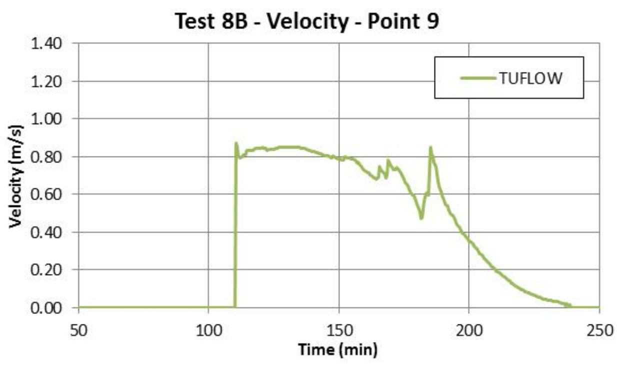


Test 8B, point 8:



Test 8B, point 8:



Test 8B, point 9:	Test 8B, point 9:
	

Summary of relevant technical information for the test:

Version number (and numeric scheme)	Refer to table at start of report. Double Precision (DP) build was used for TUFLOW.			
Hardware used to undertake the simulation	Refer to table at start of report.			
Minimum recommended hardware specification for a simulation of this type	Refer to table at start of report.			
	TUFLOW	**TUFLOW GPU**	**TUFLOW FV 1st Order**	**TUFLOW FV 2nd Order**
Multi-processing	No	n/a	n/a	n/a
Manning's n used	0.02 roads 0.05 elsewhere			
Grid	2m			
Time-stepping	1.5s			
Total simulation time (hrs)	0.0489 (176s) 1 CPU Core			

Software developer comments:

TUFLOW: The 1D results through the manhole and culvert are near identical to the 2010 report and the 2D results are very similar. The enhancements made for the 2012-05 release have improved the velocity outputs and have allowed the 2D timestep to be increased from 1.0s to 1.5s through improved stability.

Overall summary of performance

	Predictions	Suitable?	Software developer comments
Situations the software package is suitable for use	inundation extent	Yes	TUFLOW, TUFLOW GPU Module and TUFLOW FV are all suitable for all of these categories. They have demonstrated consistent results between each other, and their results are consistent with the other fully dynamic schemes presented in the 2010 report. Enhancements to TUFLOW have significantly improved the prediction of peak velocities for dambreak modelling. TUFLOW is also more stable and able to run on larger timesteps compared with the version used for the 2010 report. The issues raised in the 2010 report have been rectified through improvements to the 2D solution.
	maximum depth	Yes	
	maximum velocity	Yes	
	temporal variation in inundation extent	Yes	
	temporal variation in depth	Yes	
	temporal variation in velocity	Yes	
Other comments on performance of software	1. The simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models. For short simulation models, the time transferring memory into/out of the GPU can be a considerable portion of the run time. For large models (>1,000,000 cells), TUFLOW GPU is typically 10 to 100 times faster than TUFLOW "Classic" depending on the GPU specifications and the type of model.		

The table below shows common Environment Agency applications and the predictions required to produce these applications. It shows which benchmark tests can be used to prove the predictions required can be achieved. It should be used with the table above to decide whether the software package reported can achieve the outcomes required by the modelling project being undertaken.

Application	Predictions required	Relevant benchmark test
Large Scale Flood Risk Mapping	inundation extent	1 & 2
Catchment Flood Management Plan	inundation extent maximum depth	1, 2 & 7
Flood Risk Assessment and detailed flood mapping	inundation extent maximum depth	1, 2, 3 and 7
Strategic Flood Risk Assessment	inundation extent maximum depth maximum velocity	1, 2, 3, 4 7, and 8.
Flood Hazard Mapping	inundation extent maximum depth maximum velocity	1, 2 3, 4, 7 and 8
Contingency Planning for Real Time Flood Risk Management	temporal variation in inundation extent temporal variation in depth temporal variation in velocity	1, 2 3, 4, 5, 7 and 8
Reservoir Inundation Mapping	temporal variation in inundation extent temporal variation in depth temporal variation in velocity	1, 2, 3, 4, 5, and 6.