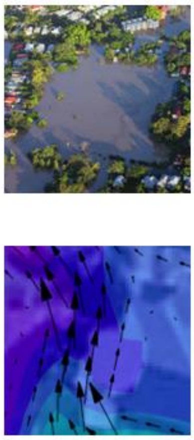
UK Environment Agency
2D Hydraulic Model Benchmark Tests



2019.01 TUFLOW FV
Release Update

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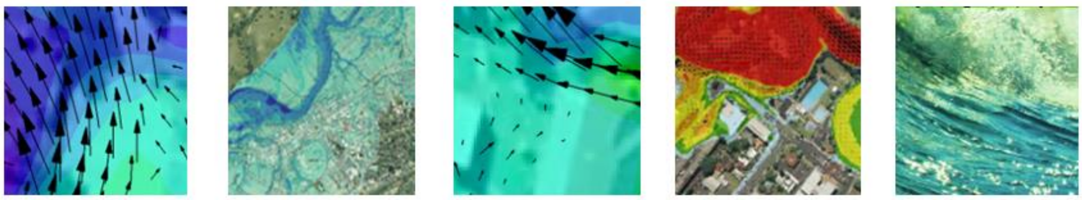

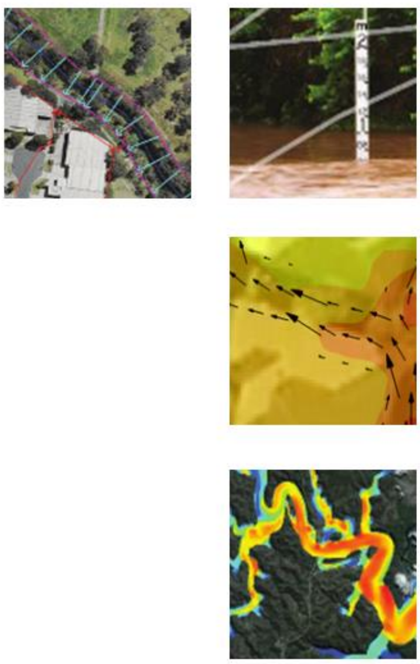

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This report summarises how the TUFLOW 2017-09 release and TUFLOW FV 2019.01 release performed in the benchmark tests developed during the Joint UK Defra / Environment Agency (EA) research programme. The report from the research project was originally published in 2010 and repeated in 2012. This document updates the performance of the 2019.01 (Build ID 2019.01.008) TUFLOW FV release.

REVISION/CHECKING HISTORY

Revision Number	Date	Checked by		Issued by	
2019.02	21/03/2019	WJS		SG	

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1 Introduction

1.1 Background

This report presents the performance of the TUFLOW 2017-09 release and TUFLOW FV 2019.01 Release against the benchmark tests developed during the Joint UK Defra / Environment Agency (EA) research programme into assessing 2D hydraulic modelling software. The UK EA released their original report in 2010 and again in 2012 to accommodate new developments and software since 2010. There has been no update of the 2012 report as of 2017. The UK EA reports can be downloaded from:

https://www.gov.uk/government/publications/benchmarking-the-latest-generation-of-2d-hydraulic-flood-modelling-packages

The 2017 report presented the results using the 2017-09 release version of TUFLOW, including results for TUFLOW HPC (Heavily Parallelised Compute), a new high accuracy, high speed product first commercially released with the 2017-09 TUFLOW release in September 2017. In this report, the results using the 2019.01 Release version of TUFLOW FV has been updated.

The EA benchmarks include 8 Tests, listed in Table 1.

Table 1 EA Benchmark Test Objectives

Test Case	Test Objective
Test 1: Flooding a Disconnected Water Body	Assess basic capabilities such as handling disconnected water bodies and wetting and drying of floodplains.
Test 2 – Filling of Floodplain Depressions	Assess basic capabilities such as handling disconnected water bodies and wetting and drying of floodplains.
Test 3: Momentum Conservation over a	Assess the capability to exhibit inertial effects to push water over a sill.
Test 4: Speed and Symmetry of Flood Propagation	Compare different scheme's abilities to simulate flood wave celerity (propagation speed), maintain symmetry as a water propagates from a point source over a flat terrain, 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.
Test 5: Dambreak Valley Flooding	Assess a package's capability to simulate flood inundation and hazard arising from a dam failure (peak levels, velocities, travel times).
Test 6A and 6B: Flume Dam Break	Benchmark against flume test results to simulate dam failure, a moving hydraulic jump in front of a building, and wake zones behind the building. An very rigorous test with extremely complex flow patterns.

Test Case	Test Objective
Test 7: Real-World 1D-2D River / Floodplain Linking	Compare and demonstrate software’s ability to simulate a real-world case of fluvial flooding along a river with man-made levees using a 1D river, 2D floodplain modelling approach. Key aspects were the ability to handle levee overtopping across the 1D/2D interface, preservation of the levee crest as the controlling spill height, and the inclusion of gated culverts and other pathways through the levees.
Test 8A: Rainfall and Sewer Surcharge in Urban Areas **Test 8B: Urban Surface Flow from a Surcharging Sewer**	Simulate real-world urban inundation originating from rainfall applied directly to the 2D model’s ground surface in combination with a point source from a surcharging sewer (Test 8A), and solely from the point source but with the inclusion of 1D pipe network elements to represent the underground flows (Test 8B).

The EA benchmarks models have been used to test all of the available TUFLOW hydraulic modelling solvers, including

- TUFLOW Classic 2017-09 Release
- TUFLOW HPC 2017-09 Release
- TUFLOW GPU (Pre HPC) 2016-03 Release
- TUFLOW FV 2019.01 (Build ID 2019.01.008) Release

Table 2 lists the tests each solver completed, and if not completed the reason why. For further information about the software versions used, refer to Table 3. Table 4 lists the computer hardware used for this benchmark study and the minimum hardware requirements for each of the above mentioned solvers.

Table 2 Benchmark Tests Completed

Test Case	Regular Grid Solvers			Flexible Mesh Solver
	TUFLOW Classic	TUFLOW HPC	TUFLOW GPU	TUFLOW FV
Test 1: Flooding a Disconnected Water Body	Yes	Yes	Yes	Yes
Test 2 – Filling of Floodplain Depressions	Yes	Yes	Yes	Yes
Test 3: Momentum Conservation over a	Yes	Yes	Yes	Yes
Test 4: Speed and Symmetry of Flood Propagation	Yes	Yes	Yes	Yes
Test 5: Dambreak Valley Flooding	Yes	Yes	Yes	Yes
Test 6A and 6B: Flume Dam Break	Yes	Yes	Yes	Yes
Test 7: Real-World 1D-2D River / Floodplain Linking	Yes	Yes	No Test 7 includes 1D open channel features that TUFLOW GPU cannot model.	No Test 7 includes 1D open channel features that TUFLOW FV currently cannot model.
Test 8A: Rainfall and Sewer Surcharge in Urban Areas **Test 8B: Urban Surface Flow from a Surcharging Sewer**	Yes 8A and 8B	Yes 8A and 8B	8A only. 8B was not assessed. It includes 1D pipe and manhole features that TUFLOW GPU cannot model.	8A only. 8B was not assessed. It includes 1D pipe and manhole features that TUFLOW FV currently cannot model.

1.2 Testing Software

Table 3 Benchmark Test Software

Software	Regular Grid Solvers			Flexible Mesh Solver
	TUFLOW Classic	TUFLOW HPC	TUFLOW GPU	TUFLOW FV
Version of software	2017-09-AC	2017-09-AC	2017-09-AC (uses TUFLOW GPU engine from 2016-03 release)	2019.01
Software developer	BMT	BMT	BMT	BMT
2D Numerical scheme	2^{nd} order finite difference alternating direction implicit scheme over a regular grid of square elements. Solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity.	Finite volume scheme over a regular grid of square elements. 1^{st} and 2^{nd} order spatial available, 4^{th} order time. Solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity.	Finite volume scheme over a regular grid of square elements. 1^{st} order spatial, 4^{th} order time. Solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity.	Finite volume 1^{st} and 2^{nd} order schemes over a flexible mesh of triangular and/or quadrilateral elements. Solves all terms of the 2D Shallow Water Equations including inertia and eddy viscosity.
1D Numerical scheme	Finite difference Runge-Kutta explicit scheme. Solves all terms of the St Venant equations.		N/A	1D structure flow equations for weirs, culverts, etc.
Shock capturing scheme	1D and 2D schemes automatically switch between upstream and downstream controlled flow regimes to represent shocks.	2D finite volume shock capturing capability used. 1D scheme automatically switches between upstream and downstream controlled flow regimes to represent shocks.	2D finite volume shock capturing capability used.	2D finite volume shock capturing capability used.

	Regular Grid Solvers		Flexible Mesh Solver
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 (e.g. weir or supercritical flow). • 2D sink/source suited to linking drains/gully traps/pits/manholes and small culverts under embankments.	1D linkages not available for TUFLOW GPU. Available on GPU hardware using TUFLOW HPC. See TUFLOW HPC.	Embedding of 1D stage discharge relationships and weir/culvert equations to model structures available. More advanced 1D/2D linking similar to TUFLOW “Classic” under development.
	For any queries or additional information on TUFLOW Classic, TUFLOW HPC or TUFLOW FV, please email support@tuflow.com.		

1.3 Testing Hardware

Table 4 Benchmark Test Hardware

Minimum recommended hardware specification	**Make**	Any Windows based or compatible PC.			
	Model	No restrictions.			
	Type	No restrictions.			
	Cores	No minimum requirements. TUFLOW Classic is not parallelised, so each simulation consumes one CPU core. TUFLOW HPC runs parallelised on CPU or Nvidia GPU cores. Supports multiple Nvidia GPU devices. TUFLOW GPU runs parallelised on Nvidia GPU cores. Supports multiple Nvidia GPU devices. TUFLOW FV runs parallelised on CPU cores.			
	RAM	2GB			
	Operating system	All TUFLOW products can run on any Windows O/S, though only later ones are recommended (Windows 2000 onwards). TUFLOW FV is also available on Linux.			
	CPU	64-bit (32-bit versions were discontinued as of 2017)			
	Graphics card	Not needed for TUFLOW Classic and TUFLOW FV. TUFLOW HPC runs on CPU only or on Nvidia GPU devices. TUFLOW GPU only runs on Nvidia GPU devices.			
Hardware specification used to carry out tests	**Software**	**TUFLOW Classic**	**TUFLOW HPC**	**TUFLOW GPU**	**TUFLOW FV**
	Make	Dell	Dell	Dell	Custom Build
	Model	Intel ® Core™ i7-7700K CPU @ 4.2GHz	Intel ® Core™ i7-7700K CPU @ 4.2GHz	Intel ® Core™ i7-7700K CPU @ 4.2GHz	AMD Ryzen Threadripper 2990WX 32-Core Processor
	Type	Desktop	Desktop	Desktop	Desktop
	CPU Cores (Cores Used)	4 (1[1])	4 (see footnote[2])	4 (see footnote[2])	32 (16)
	RAM	64GB	64GB	64GB	128GB
	Operating system	Windows 10	Windows 10	Windows 10	Windows 10
	CPU processing	64-bit	64-bit	64-bit	64-bit
	Graphics card	N/A	Nvidia GeoForce GTX1080ti	Nvidia GeoForce GTX1080ti	N/A

[1] TUFLOW Classic only uses a single CPU core per simulation.

[2] For this testing TUFLOW HPC and TUFLOW GPU were run on the GPU card, noting that at least one CPU core is used intermittently to communicate between CPU and GPU. TUFLOW HPC can alternatively run on multiple CPU cores when run in CPU mode.

2 Test 1: Flooding a Disconnected Water Body

2.1 Objective

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

2.2 Description

This test consists of a sloping topography with a depression, as illustrated in Figure 1. The modelled domain is a 700m x 100m rectangle. The varying water level boundary condition shown in Figure 2 is applied 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.

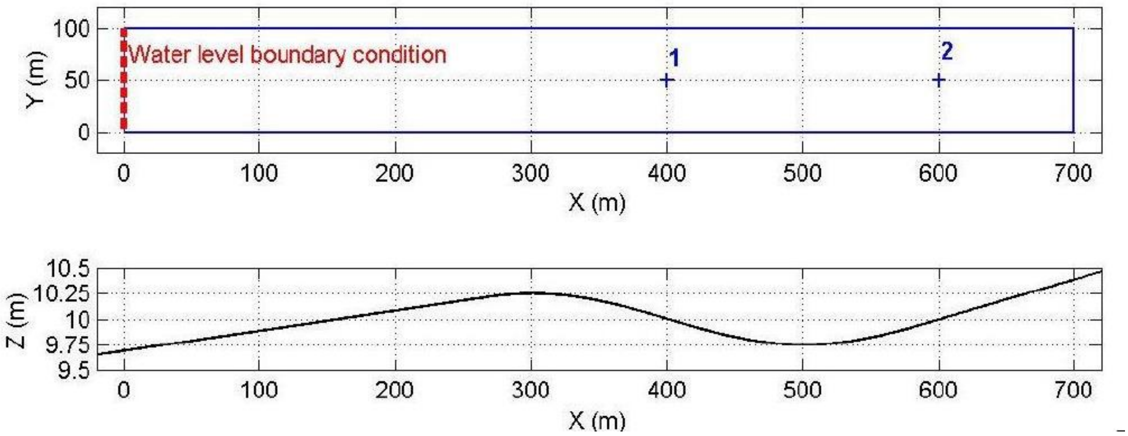


Figure 1 Model Plan and DEM Profile

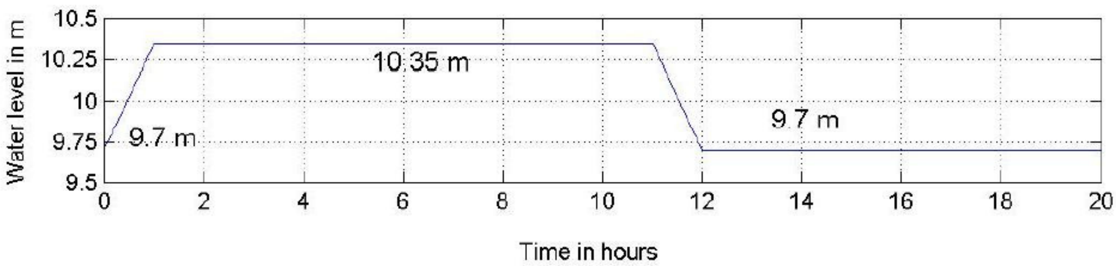


Figure 2 Test 1 Water Level Hydrograph

Initial and Boundary Conditions

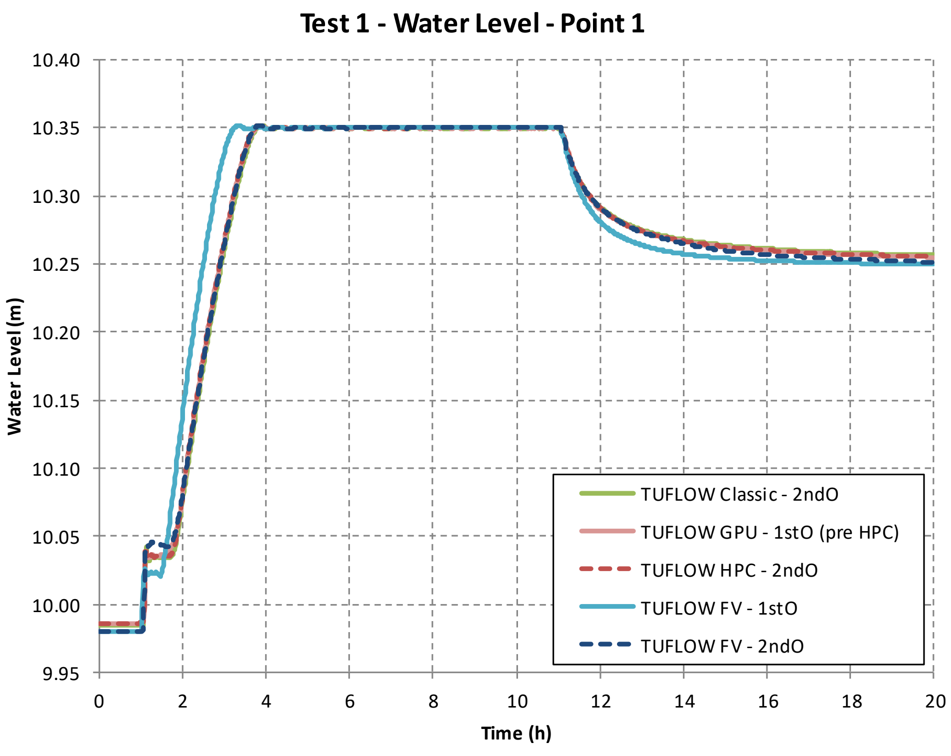
- Initial condition water elevation = 9.7m.
- Varying water level boundary (Figure 2) applied along the dashed red line shown in Figure 1.
- All other boundaries closed.

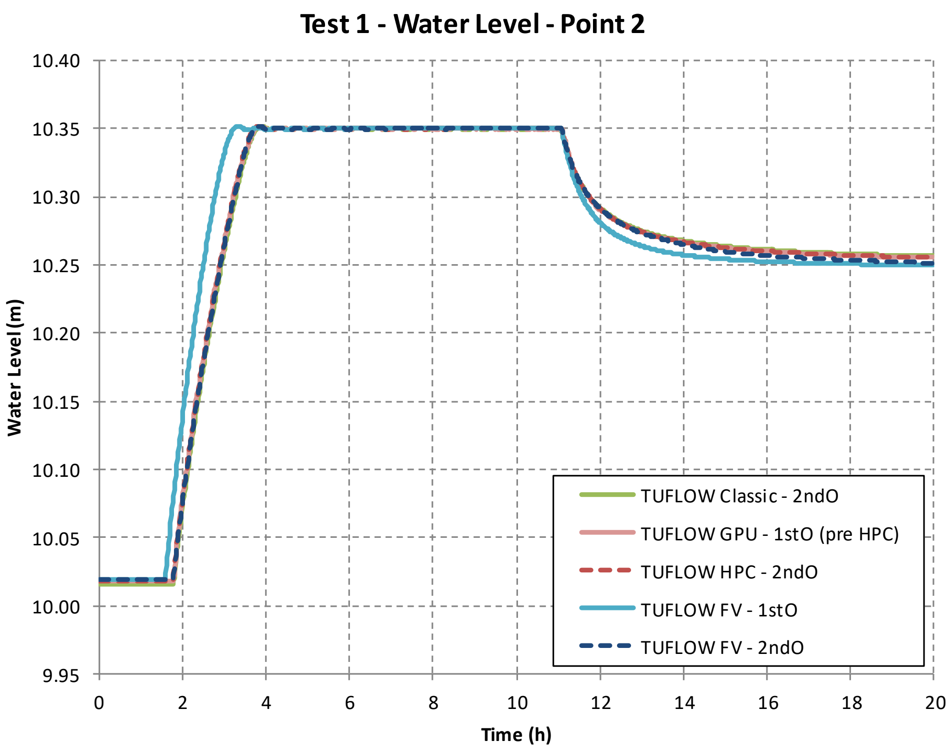
Model Parameter Values

- Manning's n = 0.03 (uniform).
- Model grid resolution = 10m.
- Simulation start time = 0 hours.
- Simulation end time = 20 hours.

2.3 Hydraulic Results

Table 5 Test 1 Results

Reporting Location	Model Result
Refer to Figure 1	

Reporting Location	Model Result
Refer to Figure 1	

2.4 Simulation Summary Table

Table 6 Test 1 Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.03	0.03	0.03	0.03	0.03
Grid resolution	10m	10m	10m	10m	10m
Time-stepping	Adaptive (15s to 60s)	Adaptive (~3.8s)	Adaptive (~1.8s)	Adaptive (~0.9s)	Adaptive (~0.9s)
Total simulation time (hrs)	0.0002 (<1s)	0.0038[1] (13s)	0.0051[1] (18s)	0.013 (46.6s)	0.0225 (81.0s)
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

3 Test 2 – Filling of Floodplain Depressions

3.1 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.

3.2 Description

The area modelled, shown in Figure 3, is a 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 created by multiplying sinusoids in the north to south and west to east directions. 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 ~2 m 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, highlighted in red within Figure 3. A flood hydrograph with a peak flow of 20 m^3/s and time base of ~85 minutes is used, as shown in Figure 4. The model was run for 2 days (48 hours) to allow the inundation to settle to its final state.

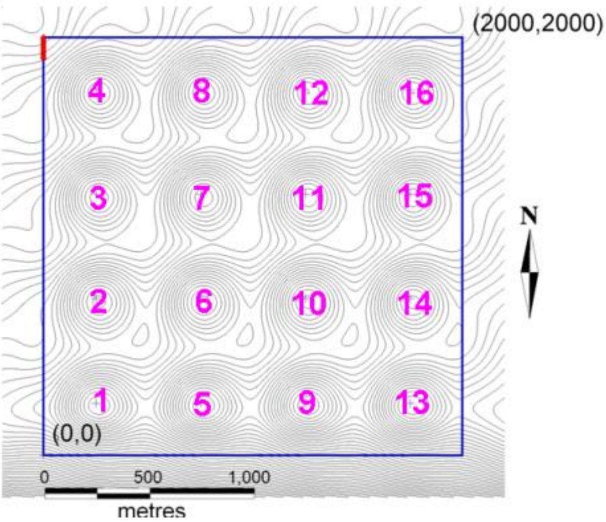


Figure 3 Test 2 Model Plan, DEM Profile and Result Output Locations

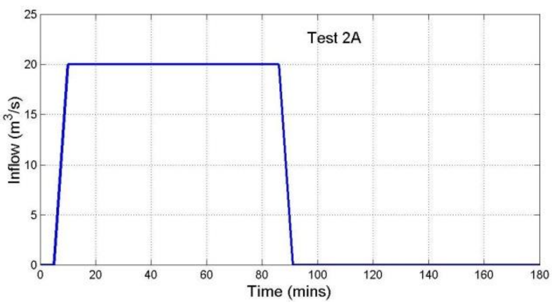


Figure 4 Test 2 Inflow Hydrograph

Initial and Boundary Conditions

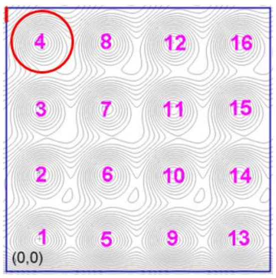
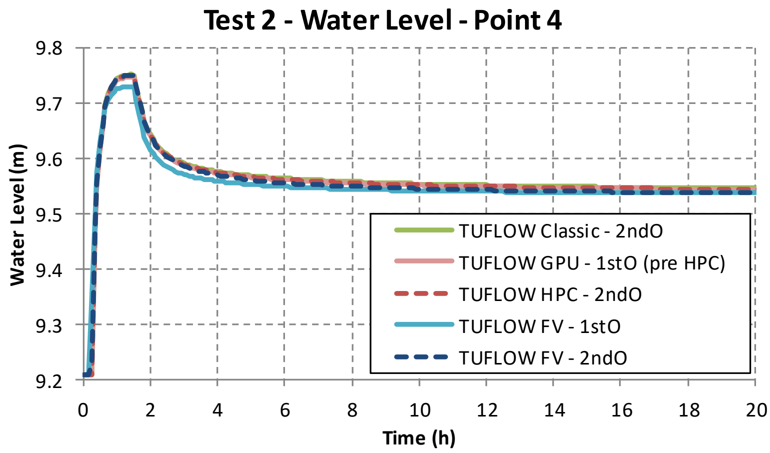
- Initial condition water elevation = dry bed.
- Varying flow boundary (Figure 4) along the dashed red line shown in Figure 3.
- All other boundaries closed.

Model Parameter Values

- Manning's n = 0.03 (uniform).
- Model grid resolution = 20m.
- Simulation start time = 0 hours.
- Simulation end time = 48 hours.

3.3 Hydraulic Results

Table 7 Test 2 Results

<table>
<tr><th>Reporting Location</th><th>Model Result</th></tr>
<tr><td>
</td><td>
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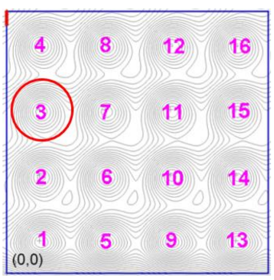
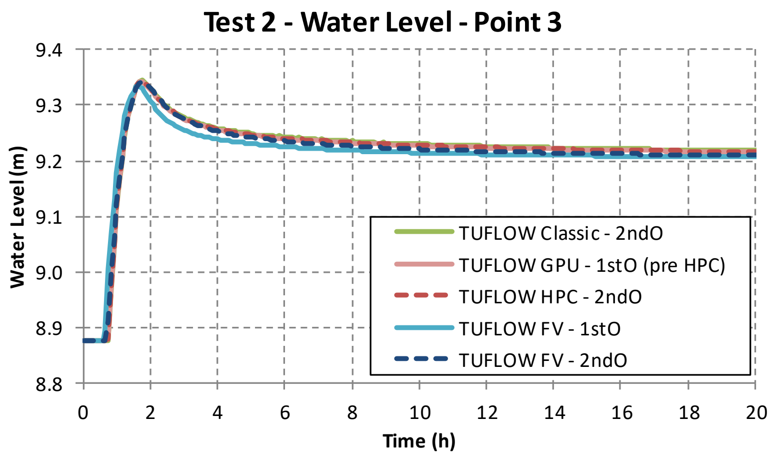
<tr><td>
</td><td>
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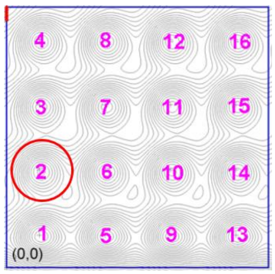
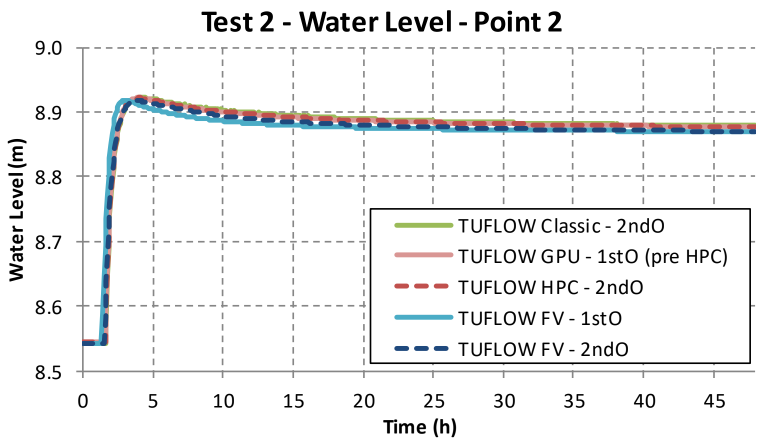
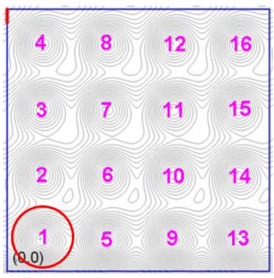
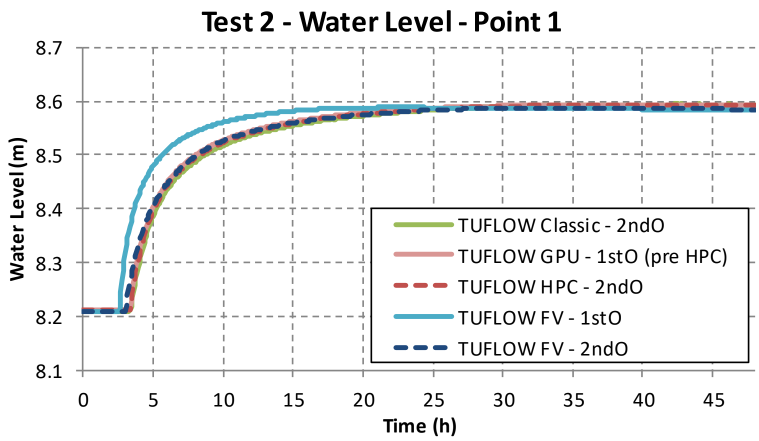
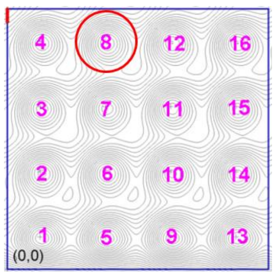
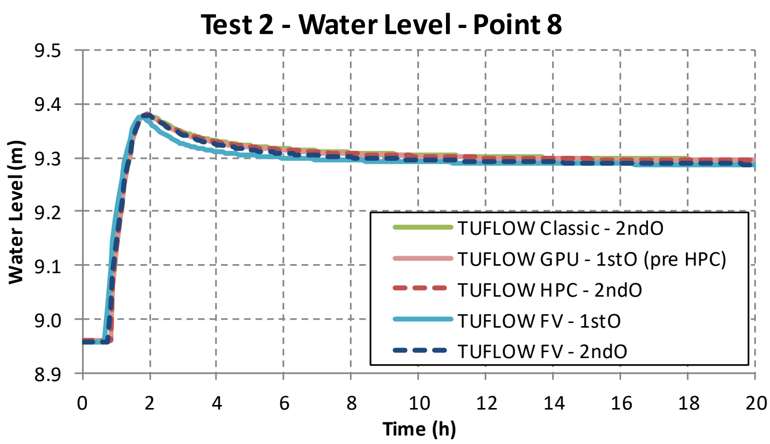
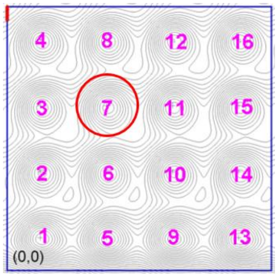
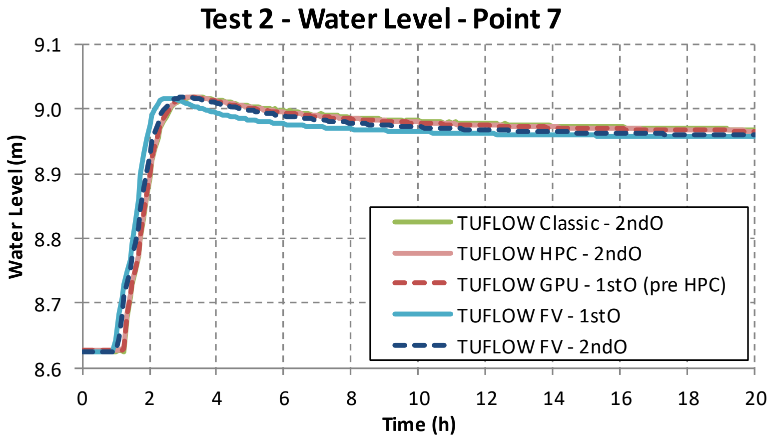
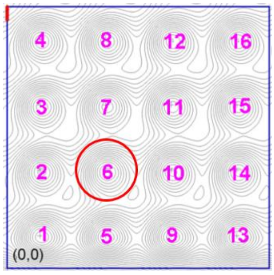
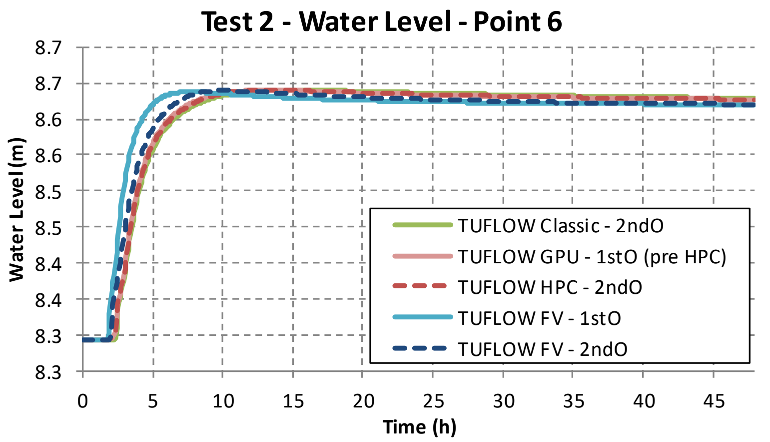
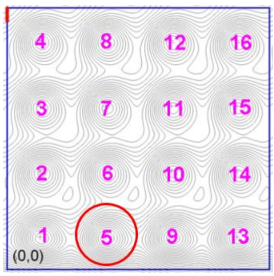
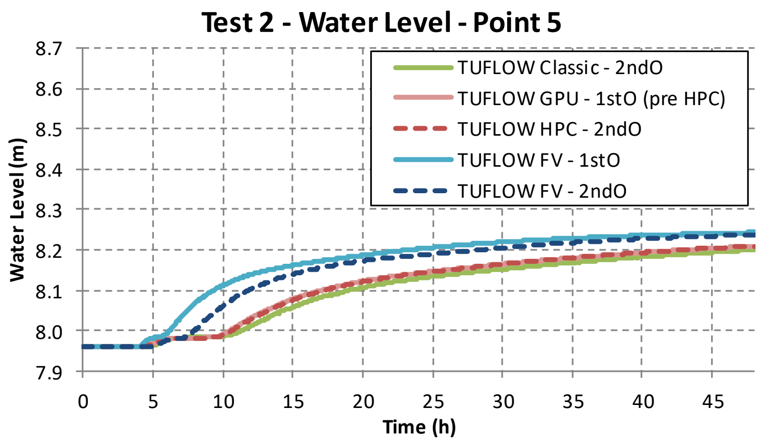
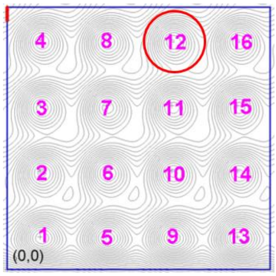
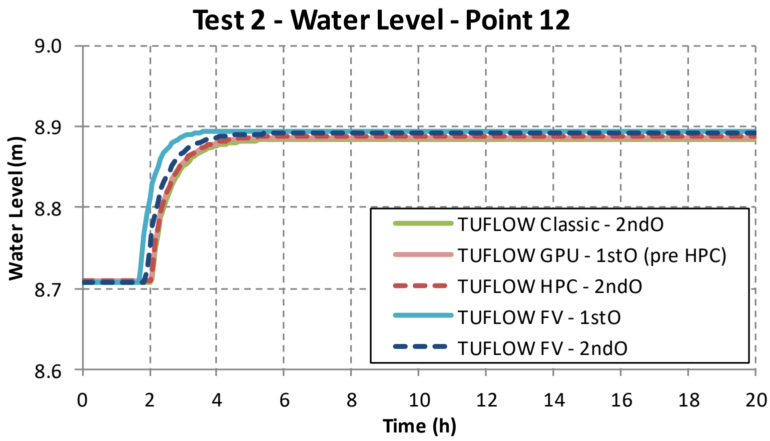
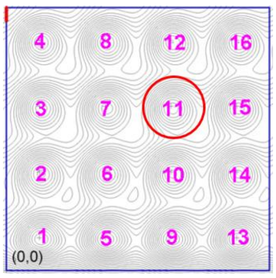
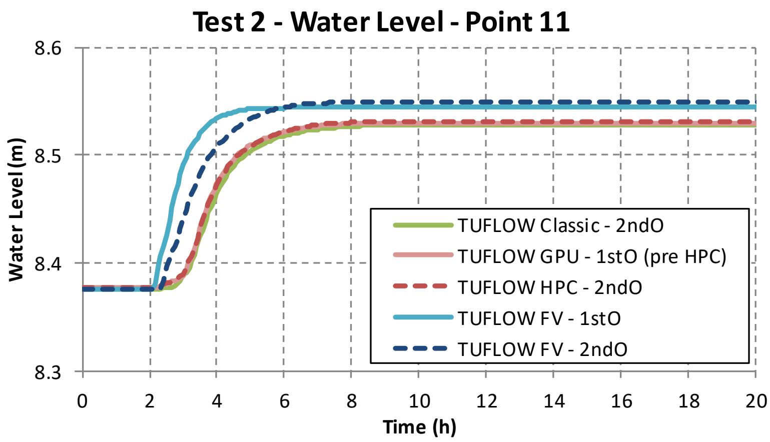
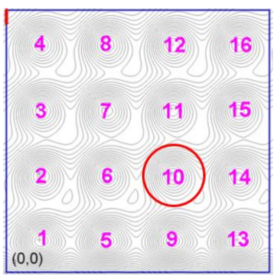
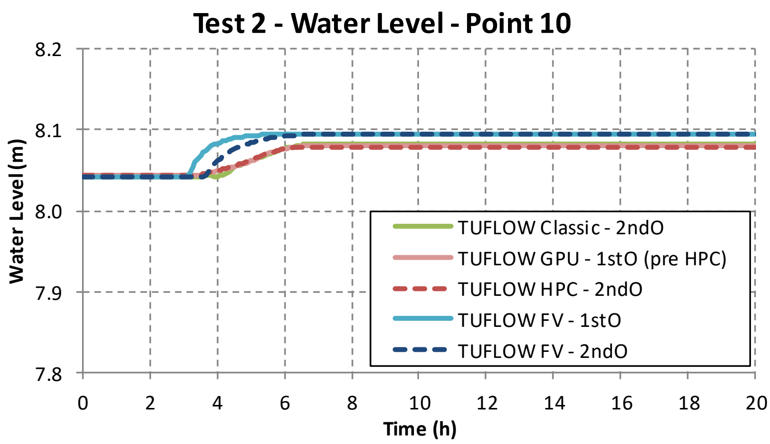
Test 2 – Filling of Floodplain Depressions

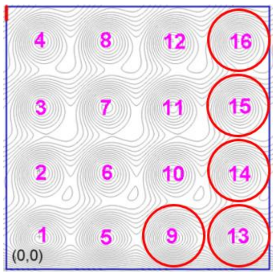
Reporting Location	Model Result
	
	
	

Test 2 – Filling of Floodplain Depressions

Reporting Location	Model Result
	
	
	

Test 2 – Filling of Floodplain Depressions

Reporting Location	Model Result
	
	
	

Reporting Location	Model Result
	No inundation. Reporting location 9, 13, 14, 15 and 16 remain dry in all simulations.

3.4 Simulation Summary Table

Table 8 Test 2 Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.03	0.03	0.03	0.03	0.03
Grid resolution	20m	20m	20m	20m	20m
Volume % error at the end of the simulation	0.0%	0.0%	0.0%	0.0%	0.0%
Time-stepping	Adaptive (5s to 120s)	Adaptive (~10s)	Adaptive (~5s)	Adaptive (~5s)	Adaptive (~5s)
Total simulation time (hrs)	0.001 (4s)	0.0042[1] (15s)	0.0055[1] (20s)	0.010 (36.8s)	0.014 (49.7s)
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

4 Test 3: Momentum Conservation over a Sill

4.1 Objective

The objective of this test is to assess the package's ability to demonstrate momentum or inertial effects by pushing water over an obstruction (sill) in the topography. The barrier to the flow is designed to differentiate the performance of software with and without the inertia terms. The test is designed so that if inertia is being modelled, some of the floodwater should pass over the sill into the right-hand depression in Figure 5. If inertia is not being modelled, no water should enter the right-hand basin.

4.2 Description

This test consists of a sloping topography with two depressions separated by a sill, as shown in Figure 5. The dimensions of the domain are 300m longitudinally (X) and 100m transversally (Y). A varying inflow (shown in Figure 6) 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 sill because of momentum conservation and settle in the depression on the right-hand side at x=250m. The model was run for 900 seconds (15 minutes) to allow the water to settle.

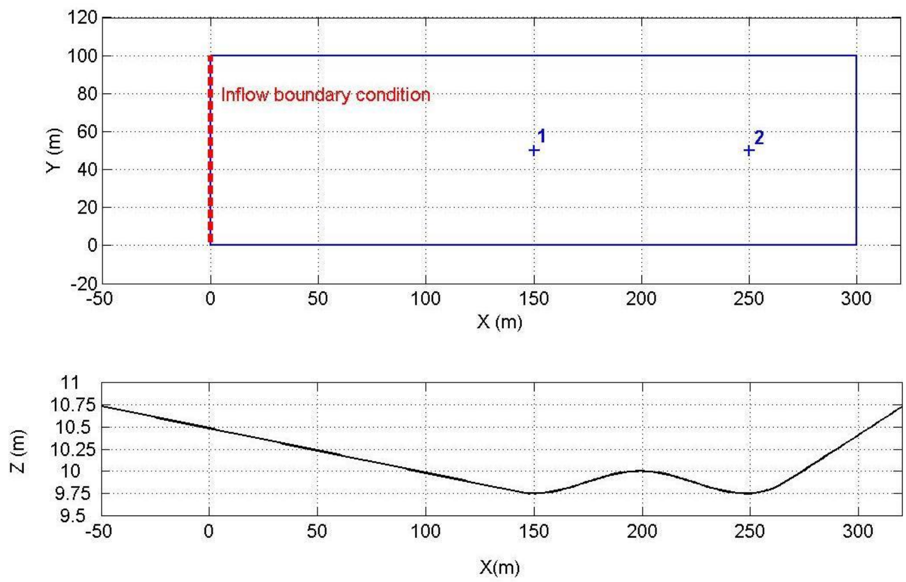


Figure 5 Test 3 Model Plan, DEM Profile and Result Output Locations

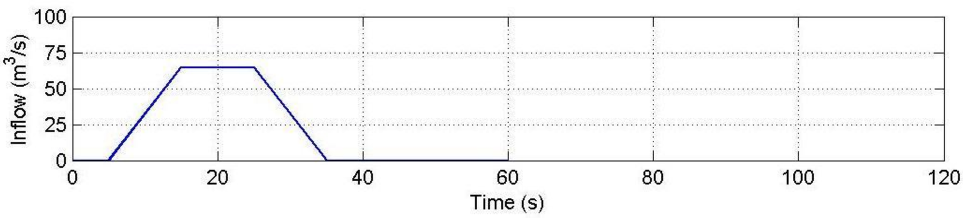


Figure 6 Test 3 Inflow Hydrograph

Initial and Boundary Conditions

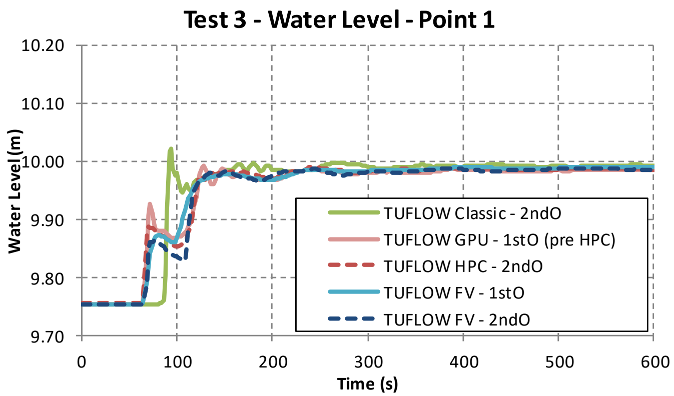
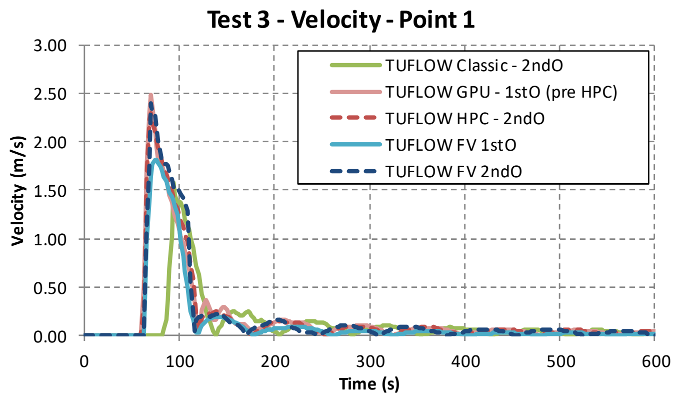
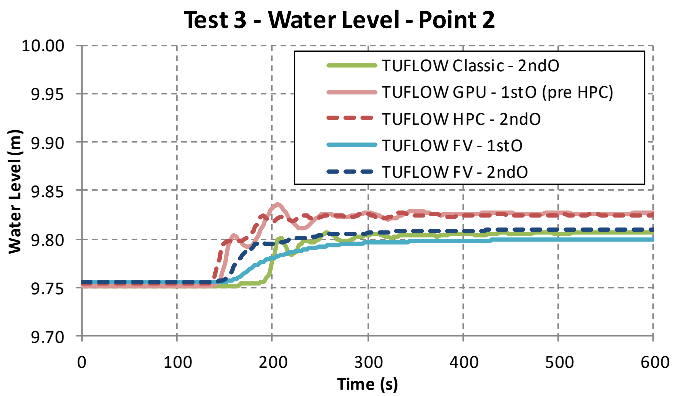
- Initial condition water elevation = dry bed.
- Varying flow along the dashed red line shown in Figure 6.
- All other boundaries closed.

Model Parameter Values

- Manning's n = 0.01 (uniform).
- Model grid resolution = 5m.
- Simulation start time = 0 hours.
- Simulation end time = 900 seconds (15 minutes).

4.4 Hydraulic Results

Table 9 Test 3 Results

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 5</td><td>
</td><td>
</td></tr>
<tr><td>Refer to Figure 5</td><td>
</td><td>Not requested by UK Environment Agency</td></tr>
</table>

4.5 Simulation Summary Table

Table 10 Test 3 Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.01	0.01	0.01	0.01	0.01
Grid Resolution	5m	5m	5m	5m	5m
Time-stepping	2s	Adaptive (~2s)	Adaptive (~1s)	Adaptive (~0.2s)	Adaptive (~0.2s)
Total simulation time (hrs)	0.0001 (<1s)	0.0003[1] (1s)	0.0003[1] (1s)	0.0020 (7.1s)	0.0022 (7.8s)
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

5 Test 4: Speed and Symmetry of Flood Propagation

5.1 Objective

The objective of this test is to assess the package's ability to simulate flood wave celerity (propagation speed), preserve symmetry over a flat bed, 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.

5.2 Description

The test is designed to simulate the rate of flood wave propagation over a 1000 m x 2000 m floodplain following a defence failure. The floodplain surface is horizontal, with a constant elevation of 0 m RL. One inflow boundary condition is used in the test, simulating the failure of an embankment by breaching or overtopping, with a peak flow of 20 m^3/s and time base of 6 hours. The boundary condition is applied along a 20m line in the middle of the western side of the flat floodplain (Location 0, 1000 in Figure 7).

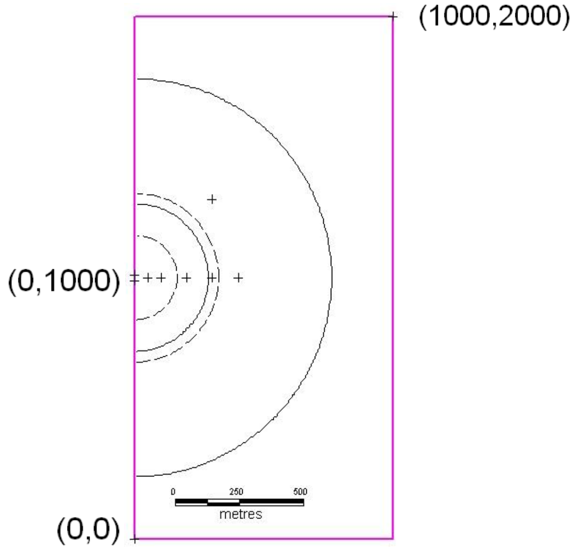


Figure 7 Test 4 Model Plan

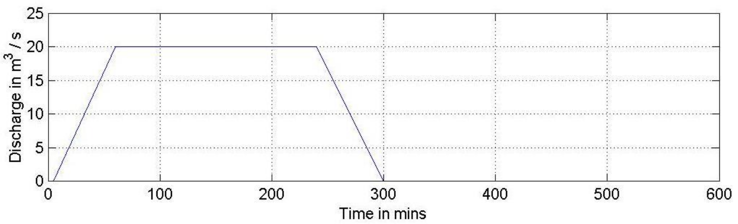


Figure 8 Test 4 Inflow Hydrograph

Initial and Boundary Conditions

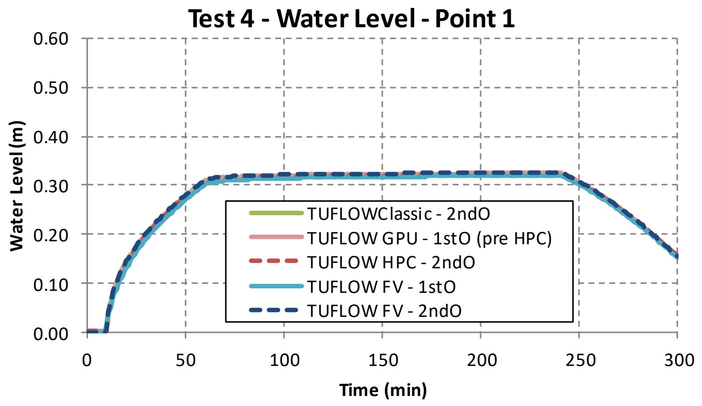
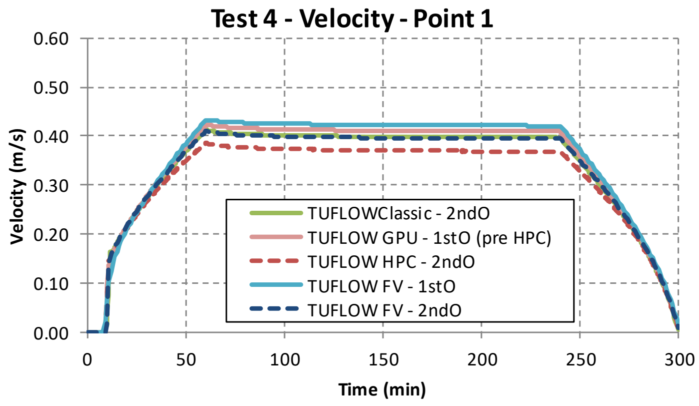
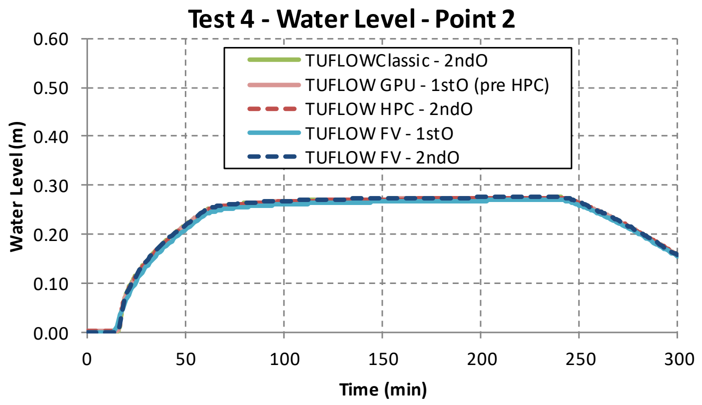
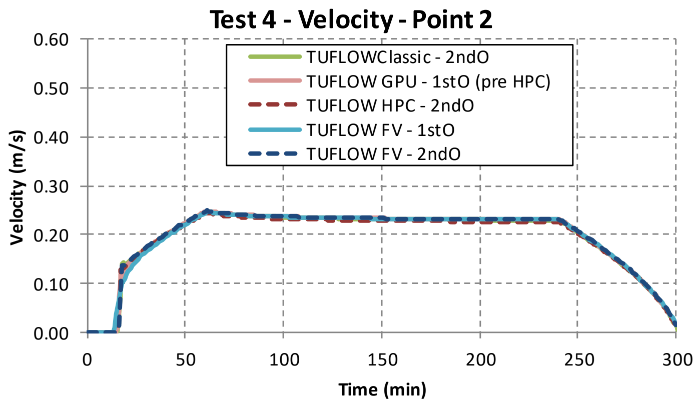
- Initial condition water elevation = dry bed.
- Varying flow along the dashed red line shown in Figure 8.
- All other boundaries closed.

Model Parameter Values

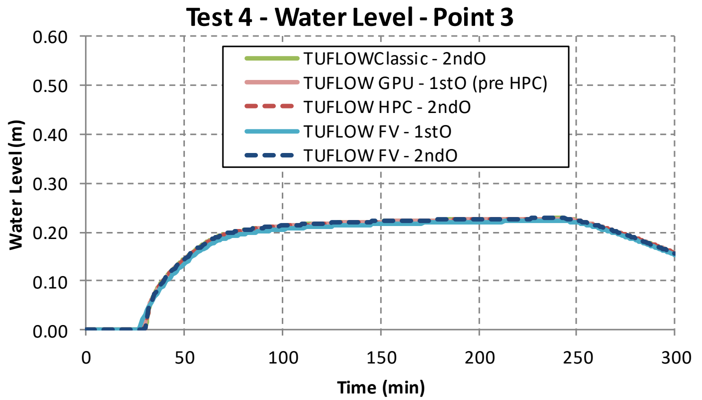
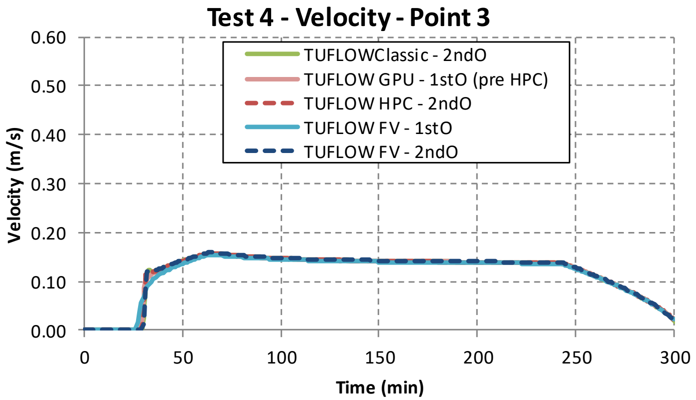
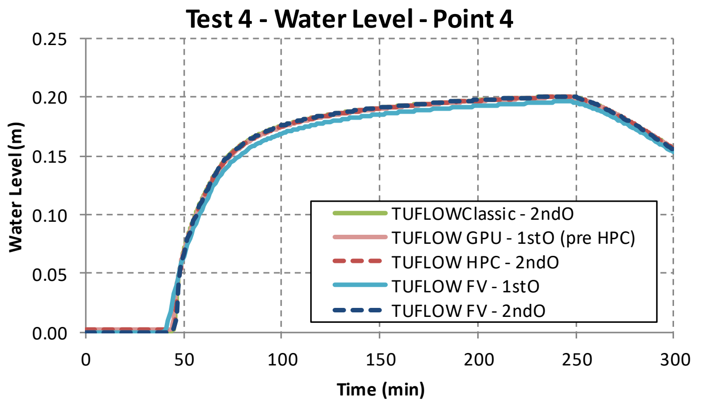
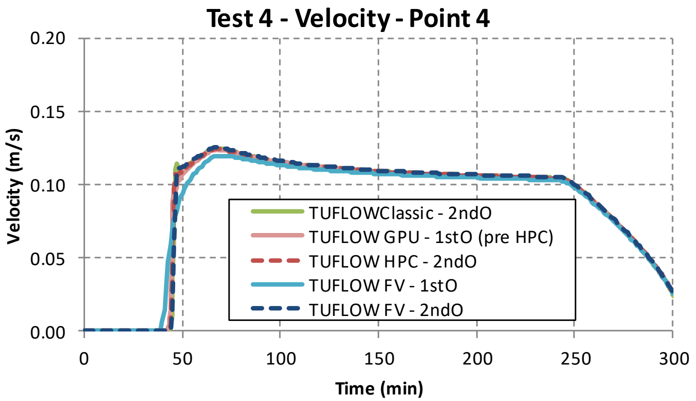
- Manning’s n = 0.05 (uniform).
- Model grid resolution = 5m.
- Simulation start time = 0 hours.
- Simulation end time = 5 hours.

5.3 Hydraulic Results

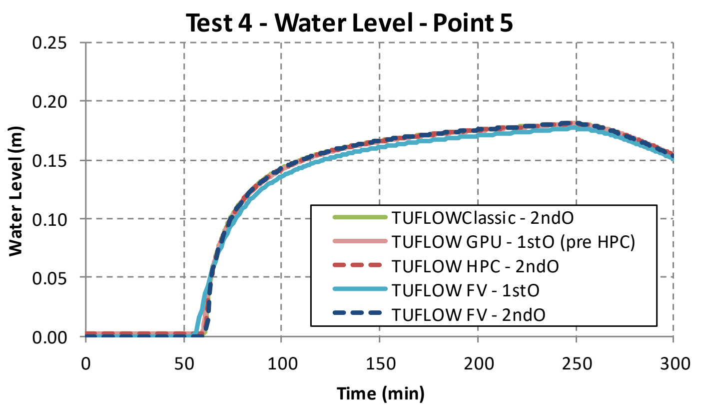
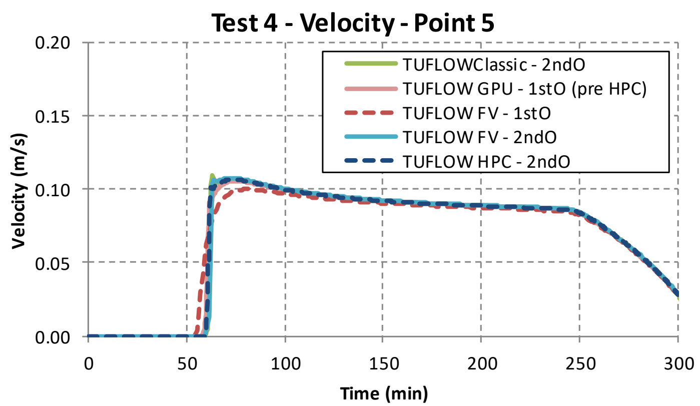
Table 11 Test 4 Point Location Results

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 9		
Refer to Figure 9		

Test 4: Speed and Symmetry of Flood Propagation

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 9</td><td>
</td><td>
</td></tr>
<tr><td>Refer to Figure 9</td><td>
</td><td>
</td></tr>
</table>

Test 4: Speed and Symmetry of Flood Propagation

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 9</td><td>
</td><td>
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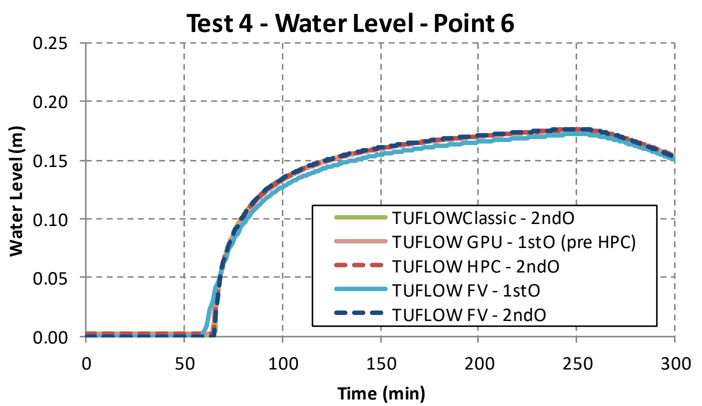
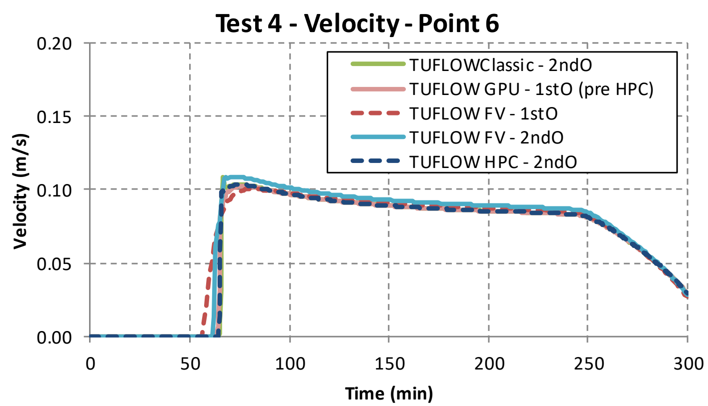
<tr><td>Refer to Figure 9</td><td>
</td><td>
</td></tr>
</table>

Test 4: Speed and Symmetry of Flood Propagation

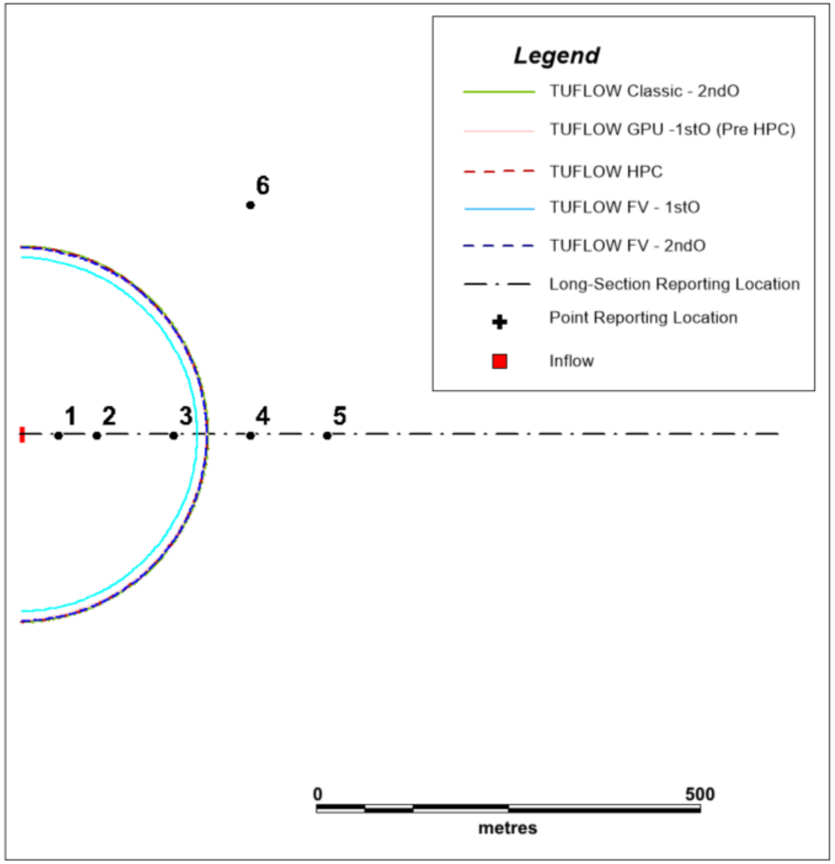


Figure 9 Test 4 0.15m Depth Contour (Time = 1 hour)

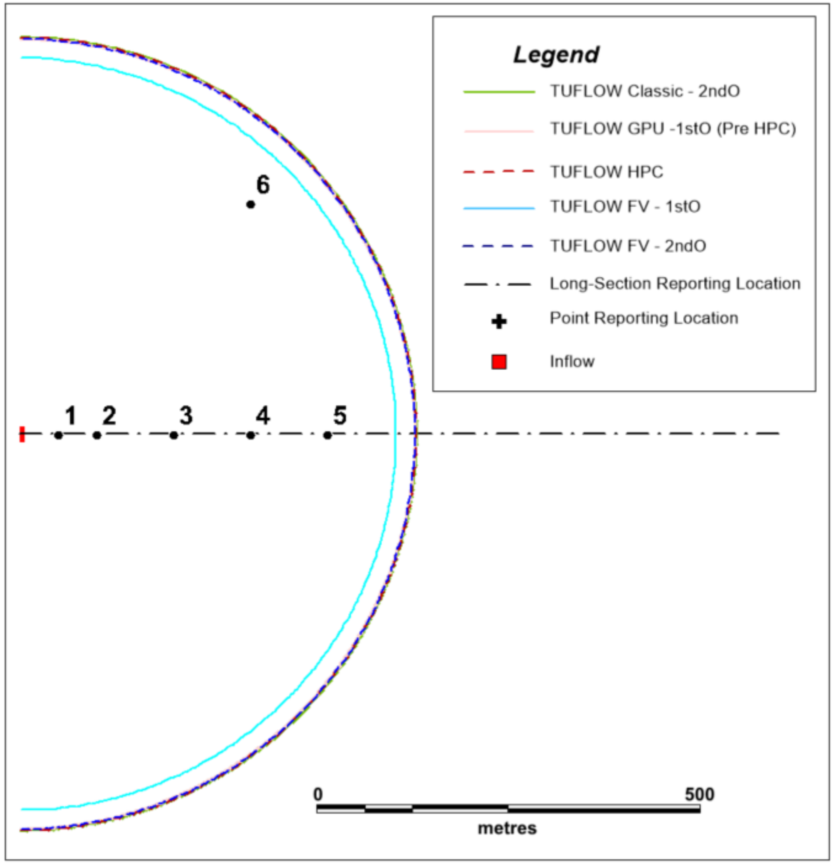
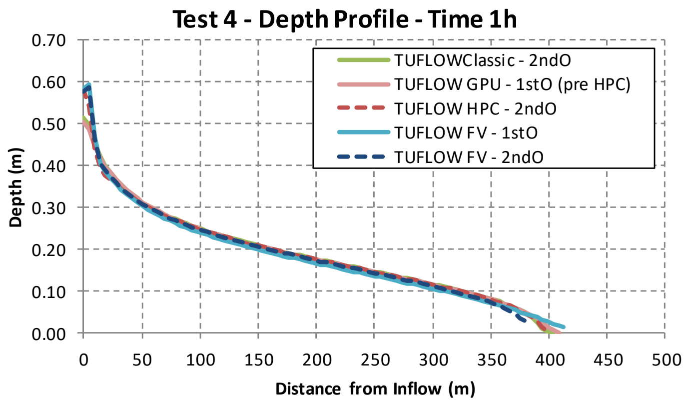
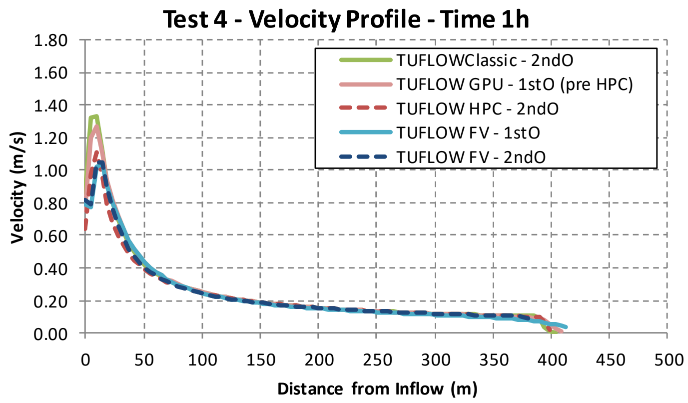


Figure 10 Test 4 0.15m Depth Contour (Time = 3 hour)

Table 12 Test 4 Long-section Results

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 9</td><td>
</td><td>
</td></tr>
</table>

5.4 Simulation Summary Table

Table 13 Test 4 Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.05	0.05	0.05	0.05	0.05
Grid resolution	5m	5m	5m	5m	5m
Time-stepping	Adaptive (18 to 30s)	Adaptive (1.6 to 3.3s)	Adaptive (1 to1.8s)	Adaptive (0.7 to 1.0s)	Adaptive (0.4 to 1.0s)
Total simulation time (hrs)	0.008 (28s)	0.0036[1] (12s)	0.0036[1] (12s)	0.026 (94s)	0.087 (314s)
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

6 Test 5: Dambreak Valley Flooding

6.1 Objective

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

6.2 Description

This test is designed to simulate flood wave propagation down a river valley following the failure of a dam. The valley DEM (Figure 11) is ~0.8 km by ~17 km 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 shown in Figure 12 is applied as a boundary condition along a ~260 m long line at the upstream end of the valley. It 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.

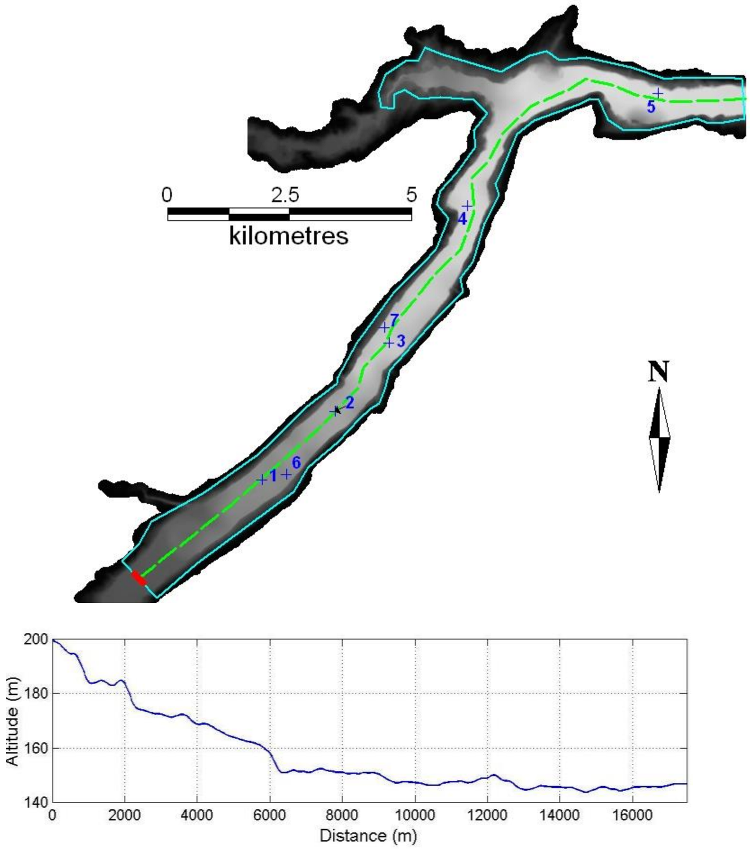


Figure 11 Test 5 Model Plan, DEM Profile and Result Output Locations

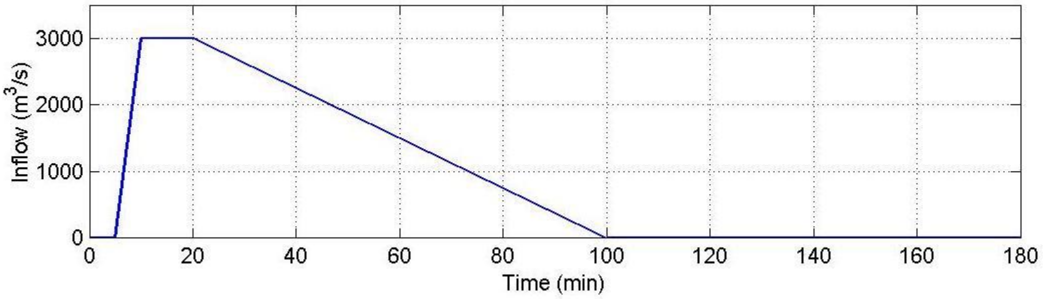


Figure 12 Test 5 Inflow Hydrograph

Initial and Boundary Conditions:

- Initial condition water elevation = dry bed.
- Varying flow along the red line shown in Figure 11.
- All other boundaries closed.

Model Parameter Values:

- Manning's n = 0.04 (uniform).
- Model grid resolution = 50m.
- Simulation start time = 0 hours.
- Simulation end time = 30 hours.

6.3 Hydraulic Results

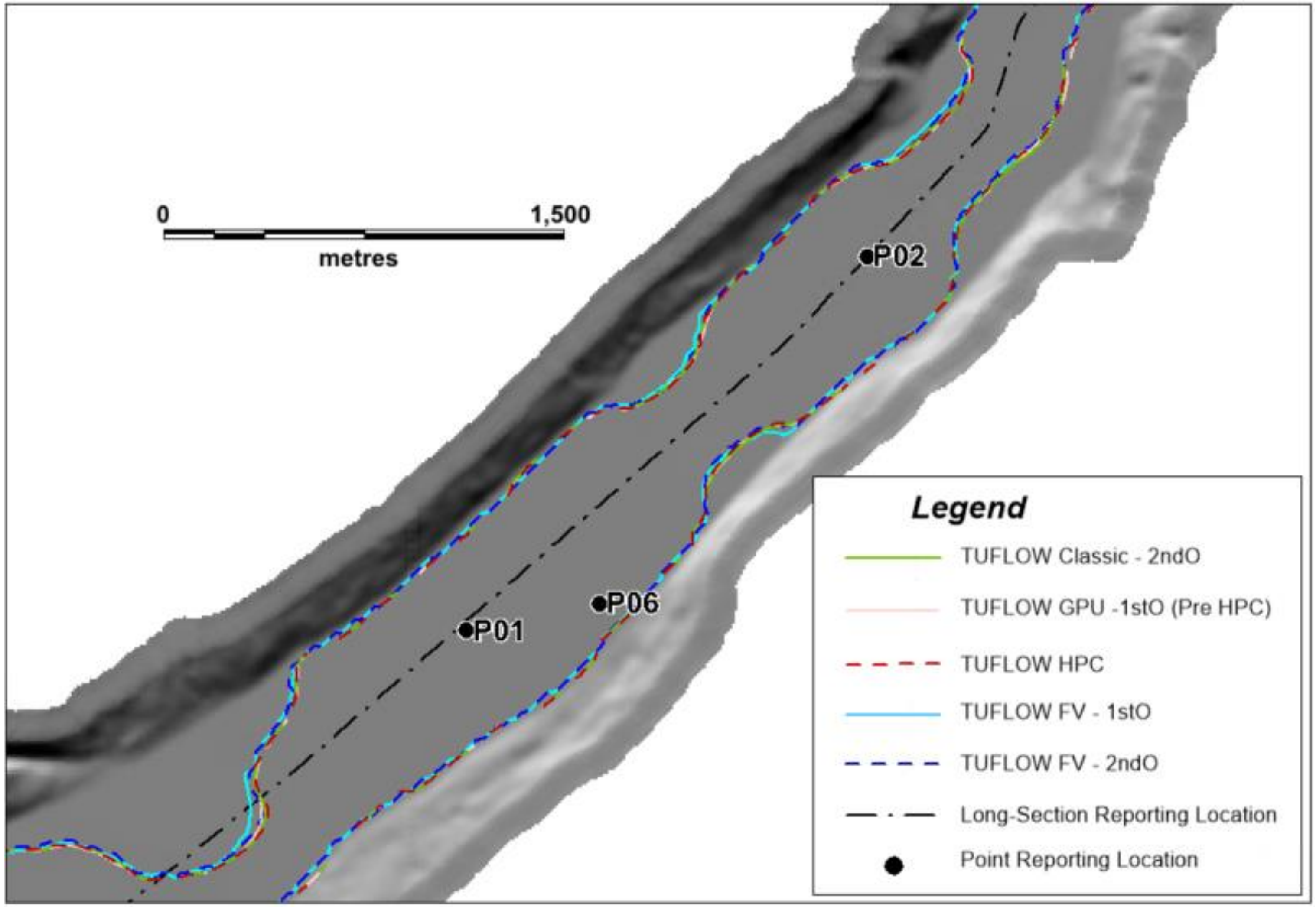


Figure 13 Test 5 Peak Depth 0.5 m Contour Lines

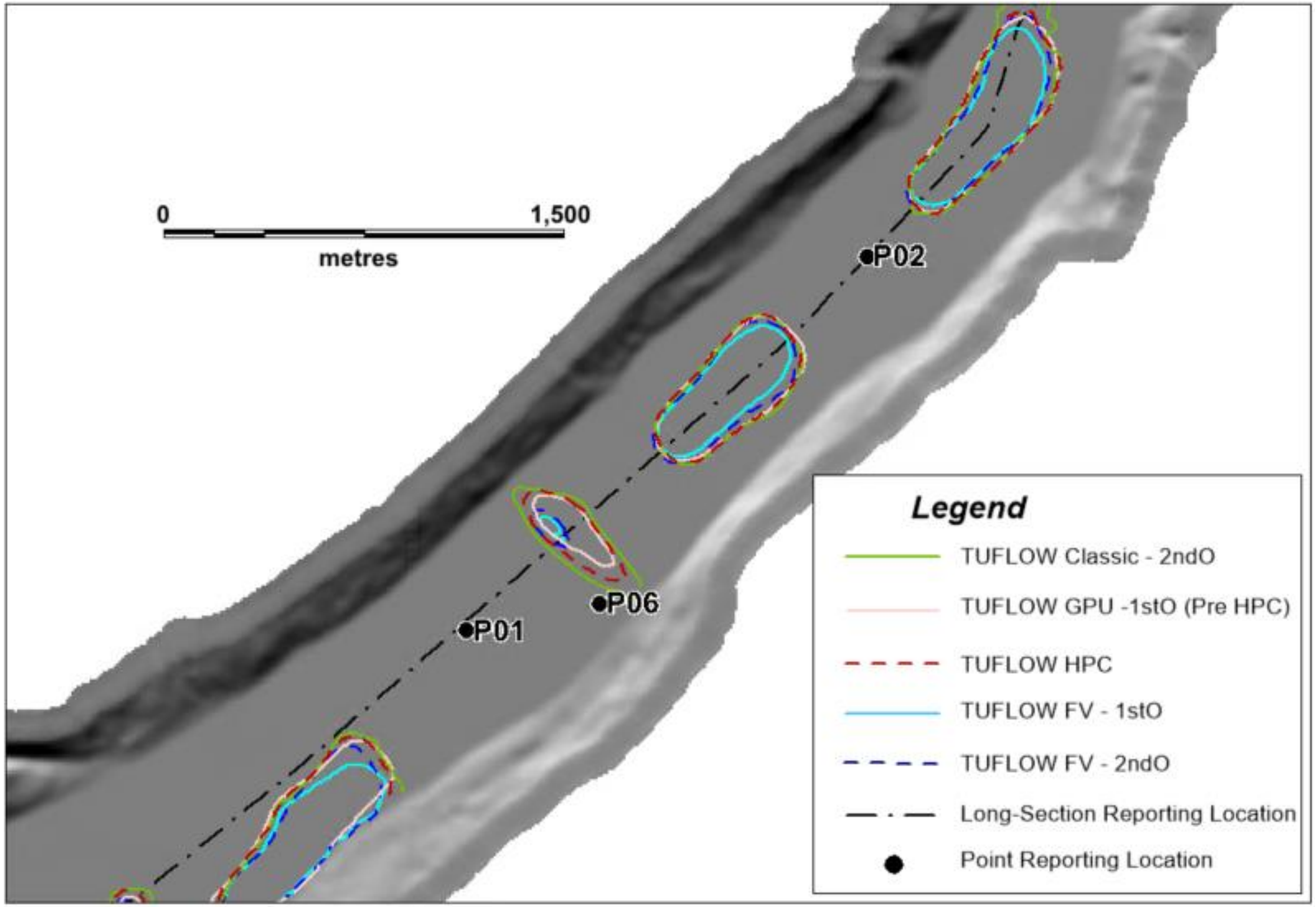
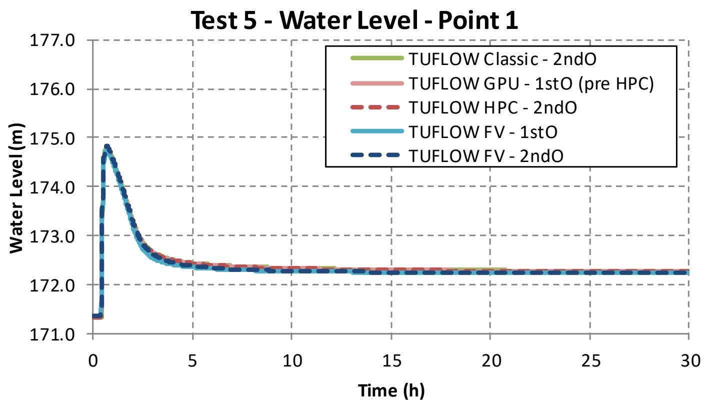
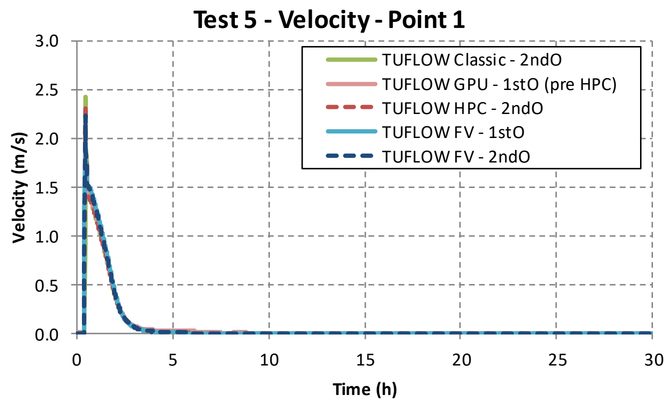
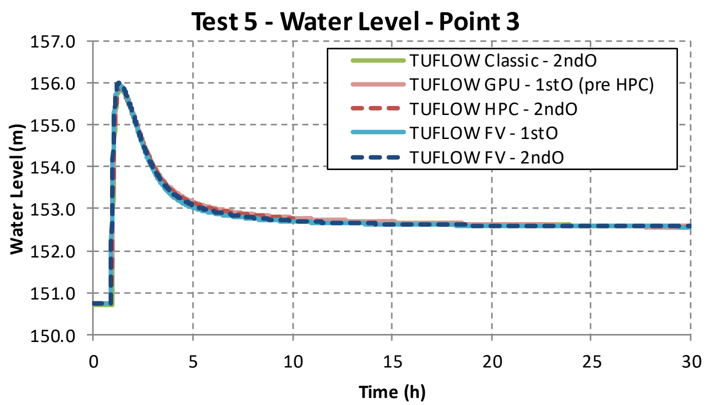
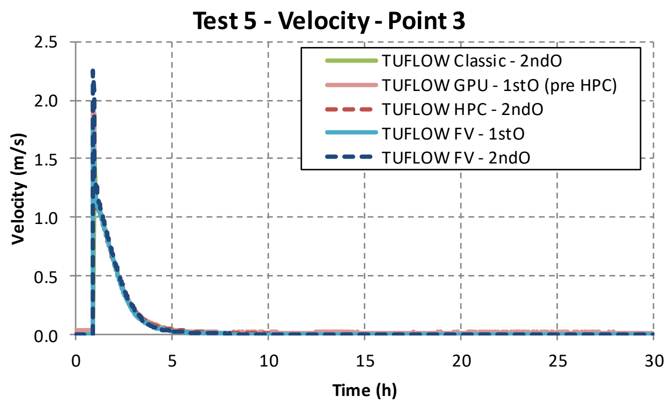


Figure 14 Test 5 Peak Velocity 3 m/s Contour Lines

Test 5: Dambreak Valley Flooding

Table 14 Test 5 Point Location Results

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Point 1 in Figure 11		
Refer to Point 3 in Figure 11		

Test 5: Dambreak Valley Flooding

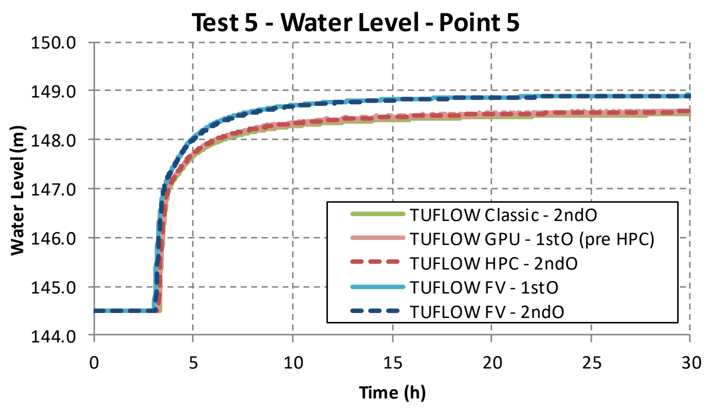
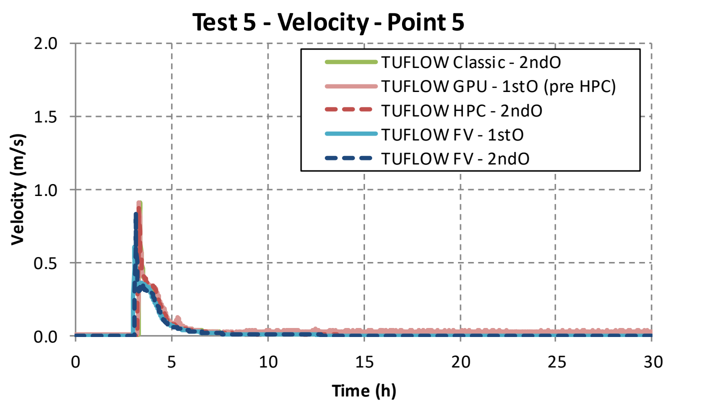
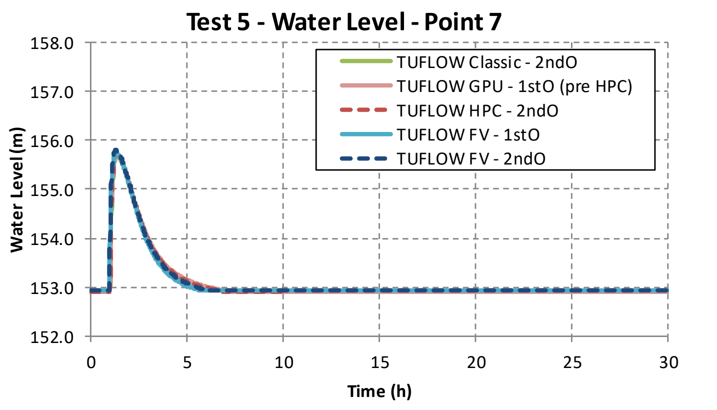
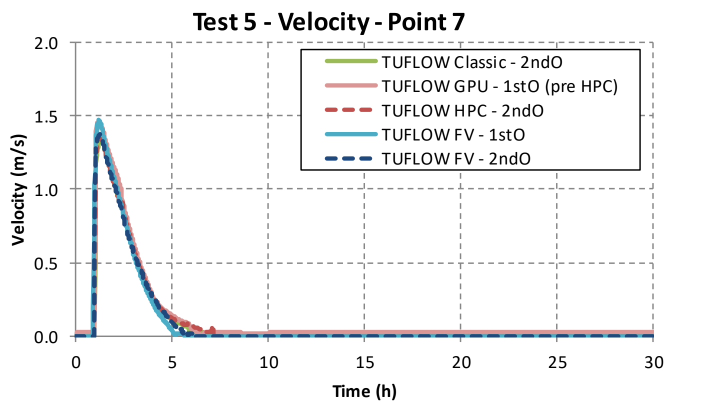
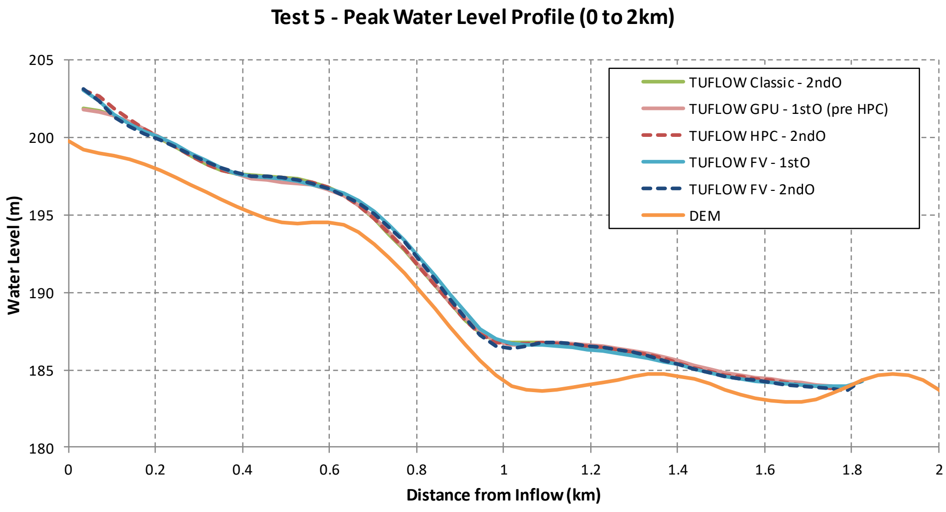
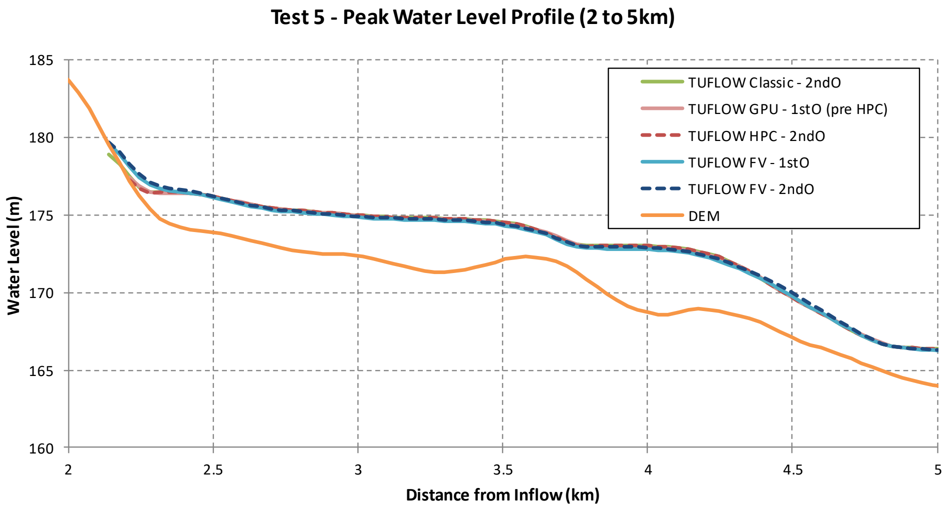
<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Point 5 in Figure 11</td><td>
</td><td>
</td></tr>
<tr><td>Refer to Point 7 in Figure 11</td><td>
</td><td>
</td></tr>
</table>

Table 15 Test 5 Long-section Water Level Results

Reporting Location	Model Result
Refer to green line in Figure 11	
Refer to green line in Figure 11	

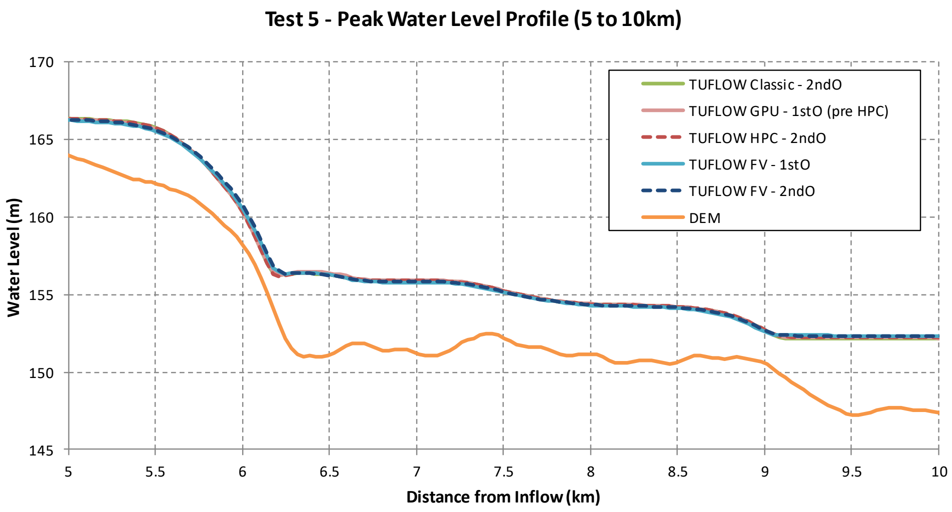
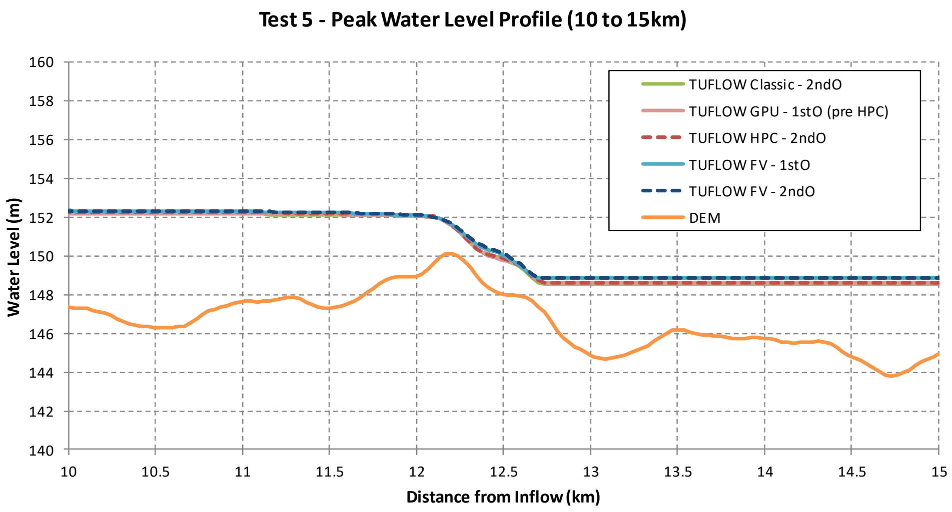
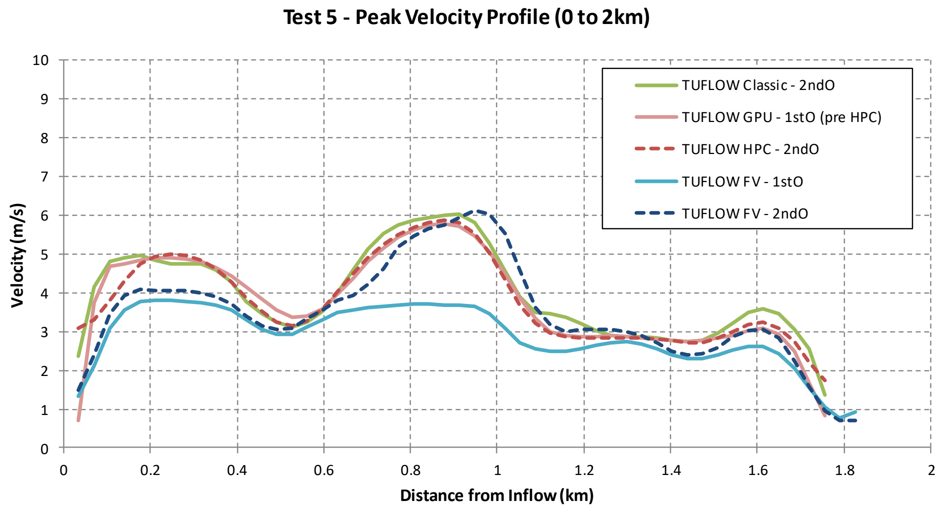
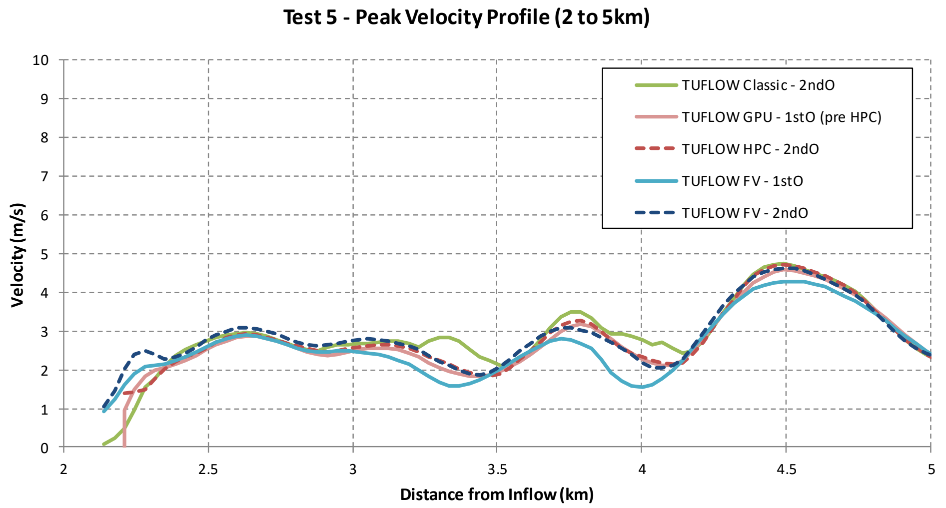
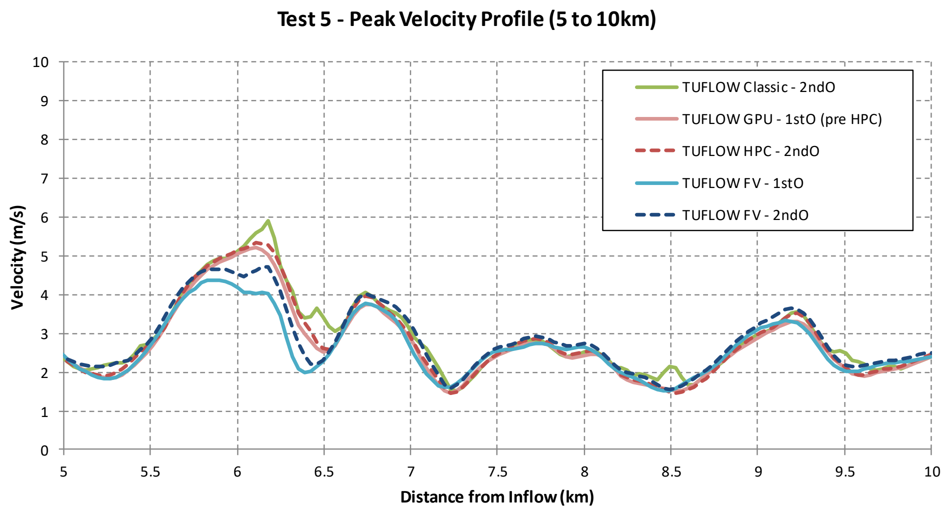
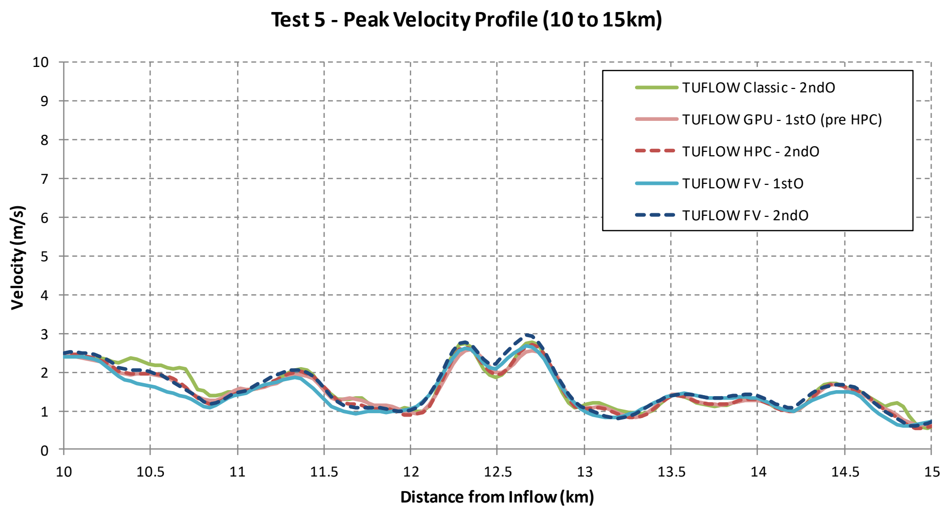
Reporting Location	Model Result
Refer to green line in Figure 11	
Refer to green line in Figure 11	

Table 16 Test 5 Long-section Velocity Results

Reporting Location	Model Result
Refer to green line in Figure 11	
Refer to green line in Figure 11	

Reporting Location	Model Result
Refer to green line in Figure 11	
Refer to green line in Figure 11	

6.4 Simulation Summary Table

Table 17 Test 5 Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.04	0.04	0.04	0.04	0.04
Grid resolution	50m	50m	50m	Flexible Mesh 8,862 elements	Flexible Mesh 8,862 elements
Time-stepping	Adaptive (5 to 18s)	Adaptive (5.0 to 7.5s)	Adaptive (2.4 to 3.3s)	Adaptive (1 to 1.8s)	Adaptive (1 to 1.8s)
Total simulation time (hrs)	0.0049 (17s)	0.0045[1] (16s)	0.0052[1] (18s)	0.0225 (81s)	0.033 (117s)
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

7 Test 6A and 6B: Flume Dam Break Against Building Test

7.1 Objective

This tests the capability of each package to be benchmarked against flume results of a dam failure against a building causing a hydraulic jump to form and migrate upstream in front of the building, and form complex wake zones behind the building.

7.2 Description

This dam-break test case has been adapted from a 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.

7.2.1 Test 6A

Test 6A is the original test proposed in Soares-Frazao and Zech 2002, where the dimensions used for the benchmarking test are identical to those of the laboratory flume model. The test involves a simple topography, a dam (gate) with a 1 m wide opening and an idealised representation of a single building downstream of the dam, as shown in Figure 15. An initial condition is applied, consisting of reservoir of uniform depth (0.4 m) upstream of the gate, and 0.02 m downstream from the gate as adopted for the laboratory tests. The flow is contained by side walls with no water leaving the model. Water levels and velocities were recorded at six (6) gauges denoted as G1 to G6 in the figure. The downstream (right-side) end of the model is sufficiently far away that it has no influence on the flume gauging (i.e. there is no reflective wave from the downstream end during the 30 s of measurements at the gauges). Model results have been compared against the flume gauge recordings.

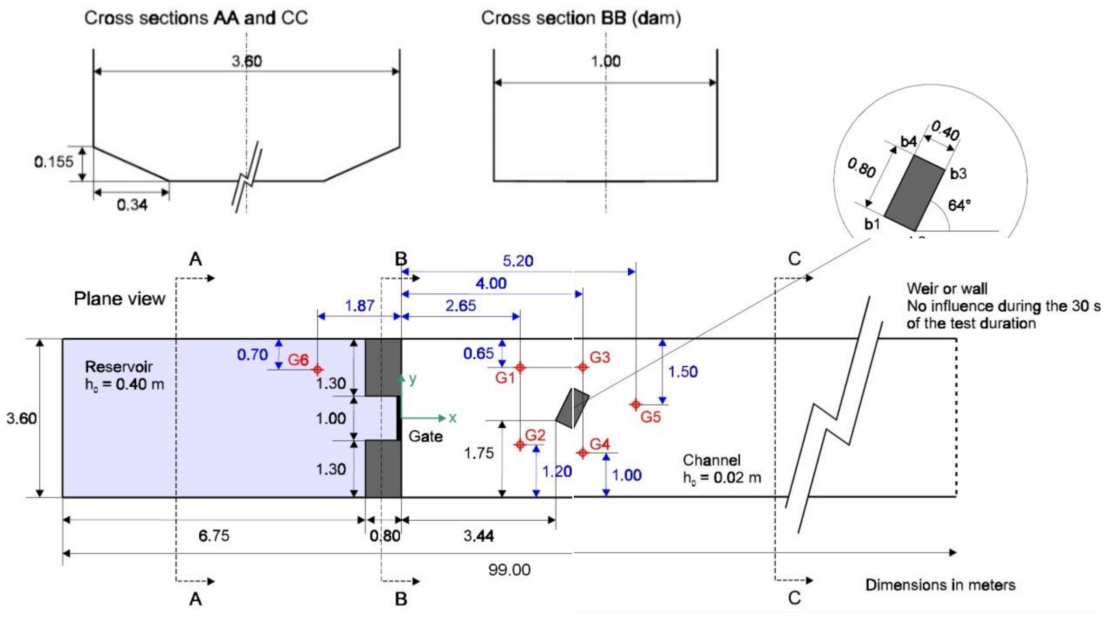


Figure 15 Test 6A Flume Dimensions (adapted from Soares-Frazao and Zech, 2002).

Initial and Boundary Conditions

- No boundary condition specified. Flow is generated by the sudden release of the gate representing the dam wall.
- Initial condition depth upstream from the gate = 0.4 m
- Initial condition depth downstream from the gate = 0.02 m

Model Parameter Values

- Manning's n = 0.01 (uniform).
- Model grid resolution: 0.1m or ~36000 nodes.
- Simulation start time = 0 hours.
- Simulation end time = 120 seconds (2 minutes).

7.2.2 Test 6B

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

Boundary and Initial Conditions

- No boundary condition specified. Flow is generated by the sudden release of the gate representing the dam wall.
- Initial condition depth upstream from the dam wall = 8 m.
- Initial condition depth downstream from the dam wall = 0.4 m.

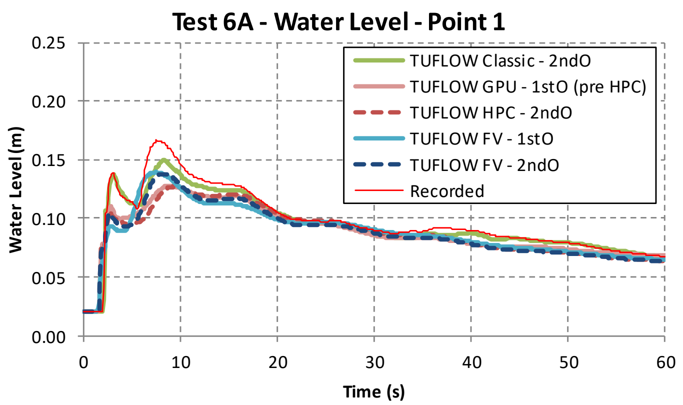
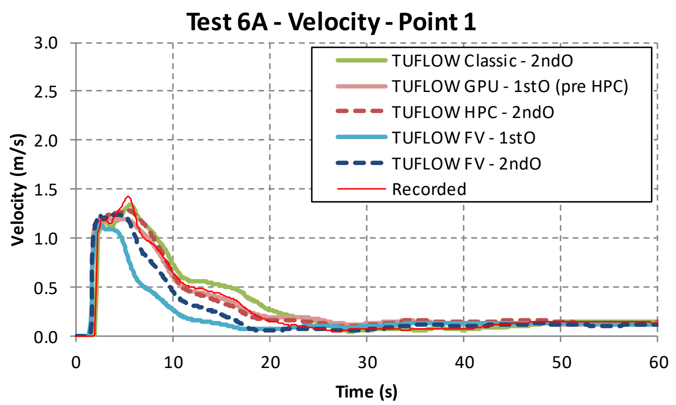
Model Parameter Values

- Manning's n = 0.05 (uniform).
- Model grid resolution: 2m or ~36000 nodes.
- Simulation start time = 0 hours.
- Simulation end time = 0.5 hours.

7.3 Hydraulic Results

7.3.1 Test 6A

Table 18 Test 6A Point Location Results

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 15</td><td>
</td><td>
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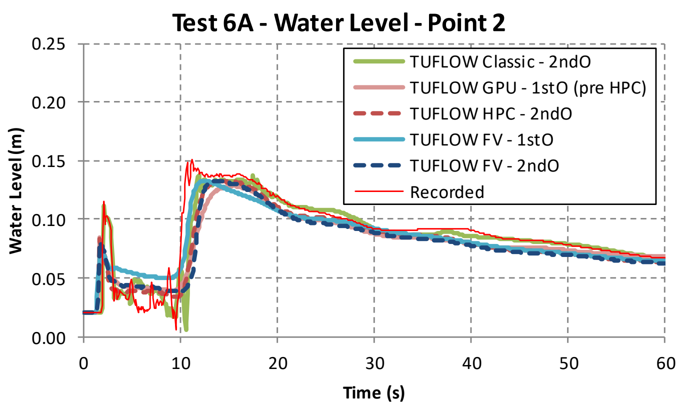
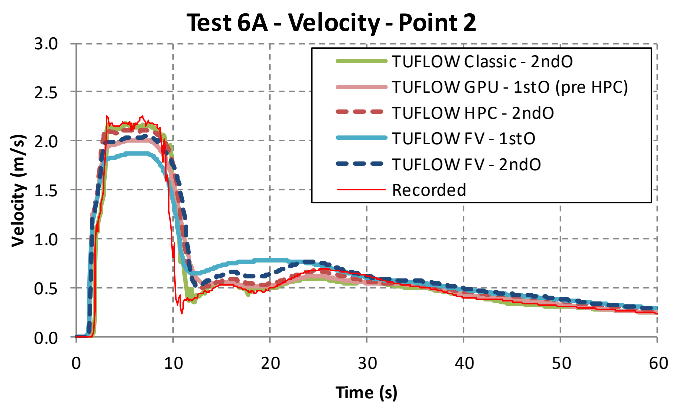
<tr><td>Refer to Figure 15</td><td>
</td><td>
</td></tr>
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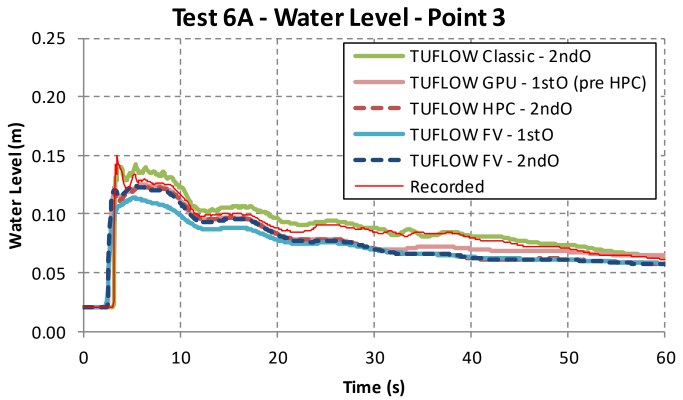
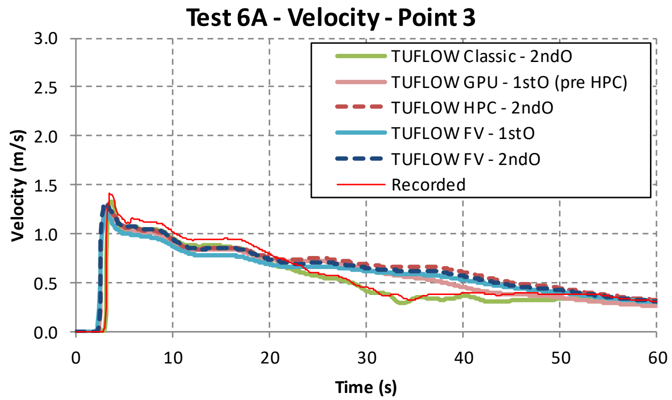
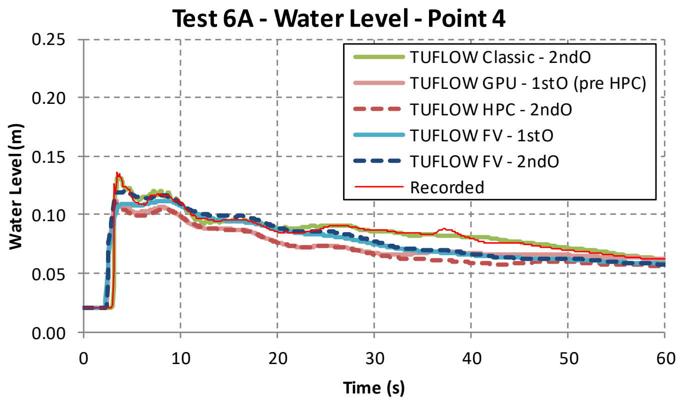
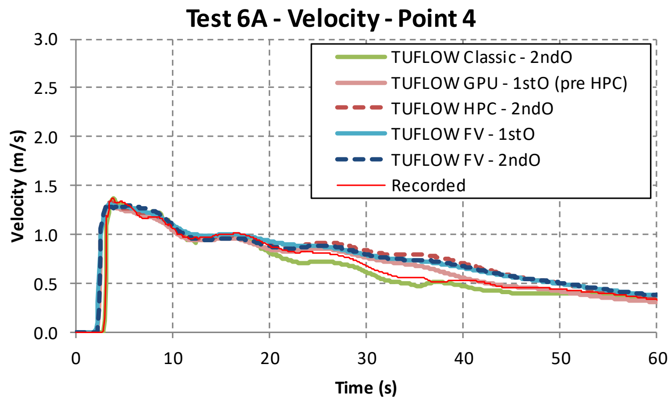
Test 6A and 6B: Flume Dam Break Against Building Test

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 15</td><td>
</td><td>
</td></tr>
<tr><td>Refer to Figure 15</td><td>
</td><td>
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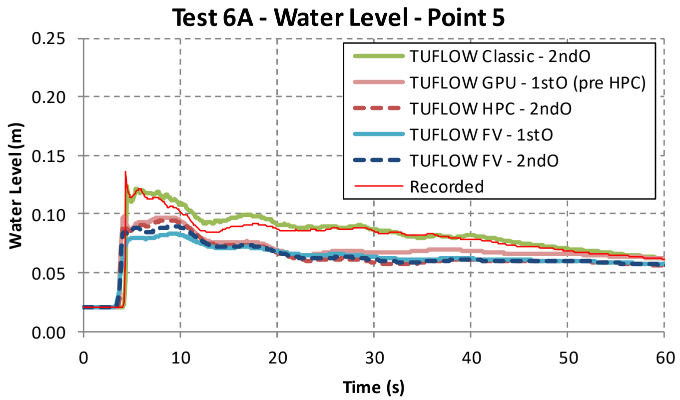
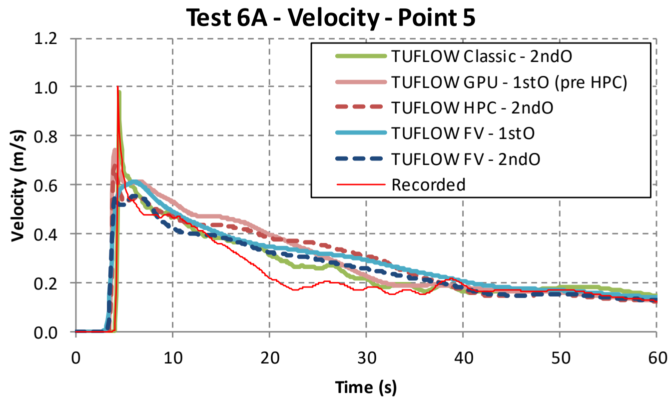
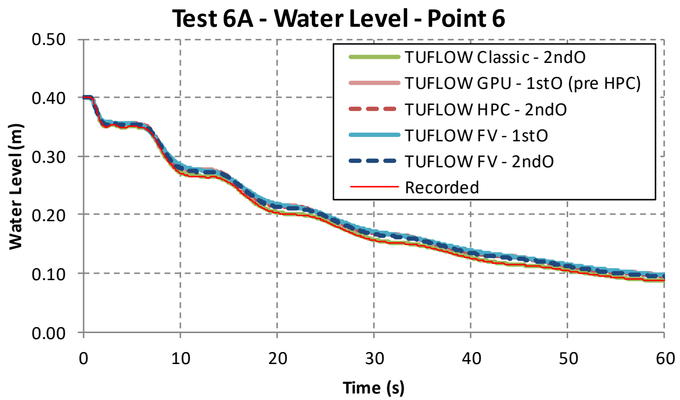
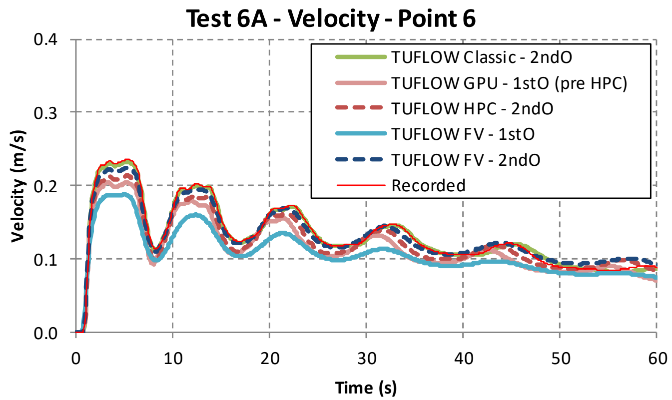
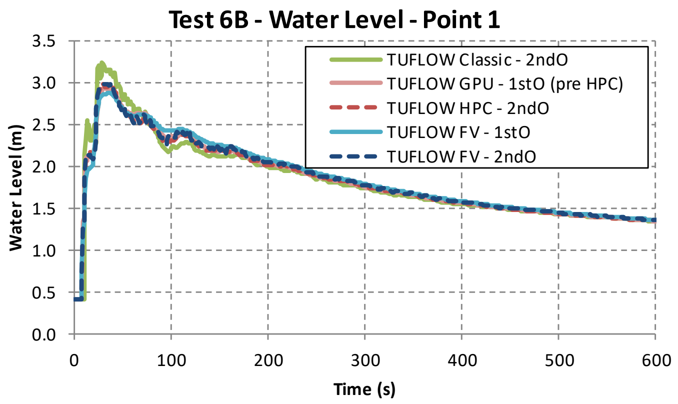
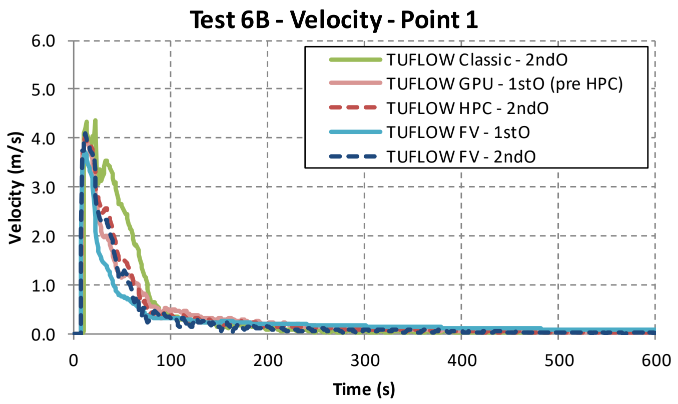
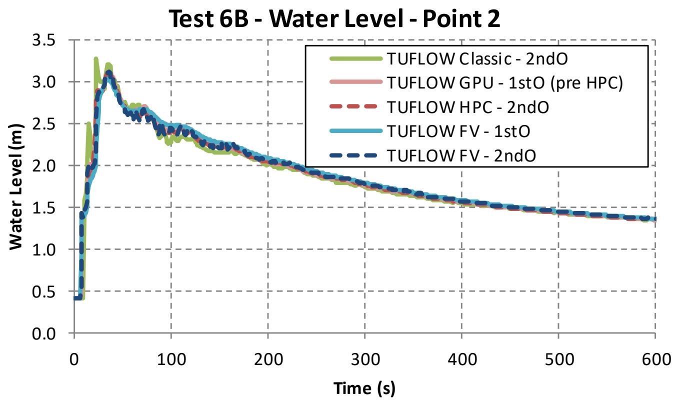
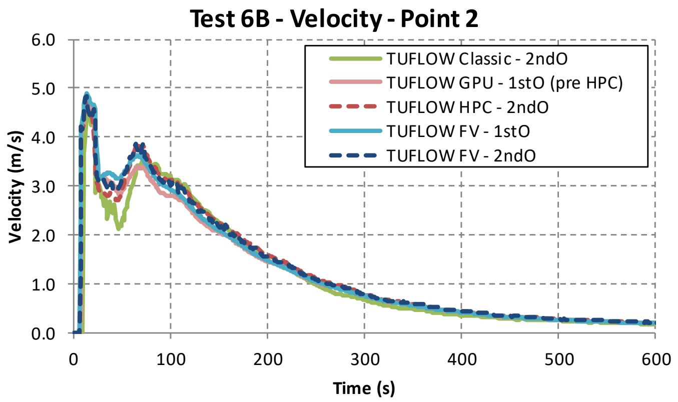
Test 6A and 6B: Flume Dam Break Against Building Test

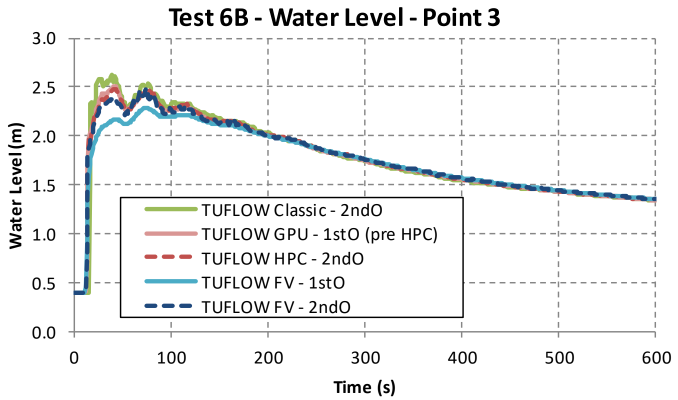
Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 15		
Refer to Figure 15		

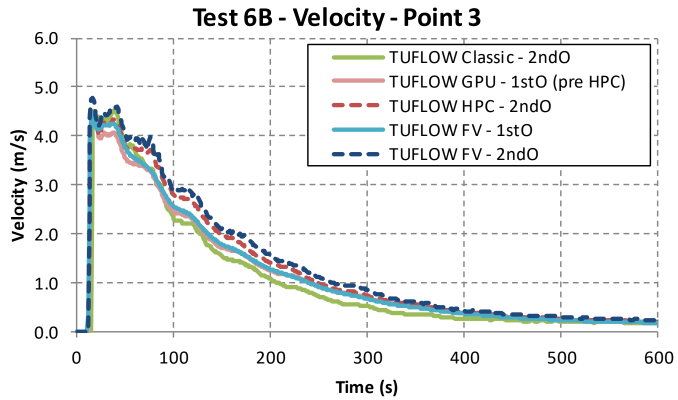
7.3.2 Test 6B

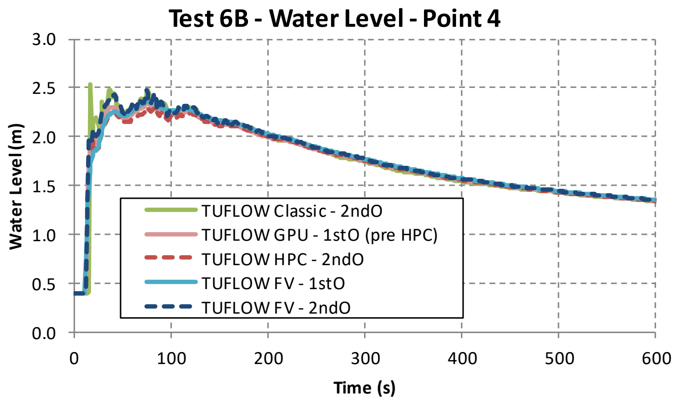
Table 19B Test 6B Point Location Results

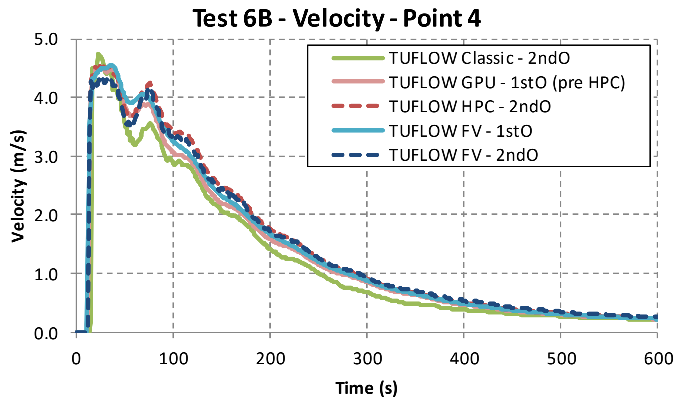
Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 15		
Refer to Figure 15		

Test 6A and 6B: Flume Dam Break Against Building Test

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 15</td><td>


</td><td>


</td></tr>
<tr><td>Refer to Figure 15</td><td>


</td><td>


</td></tr>
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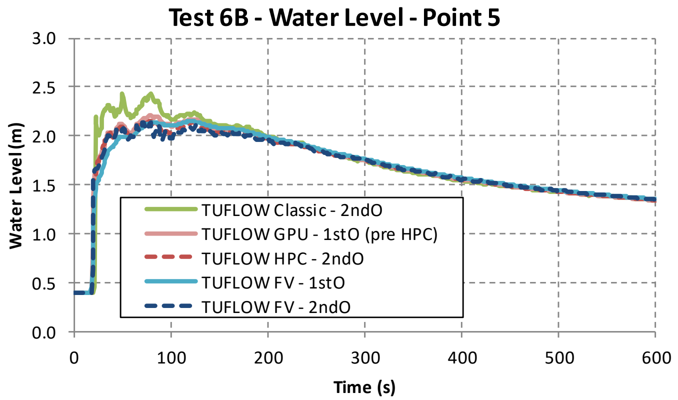
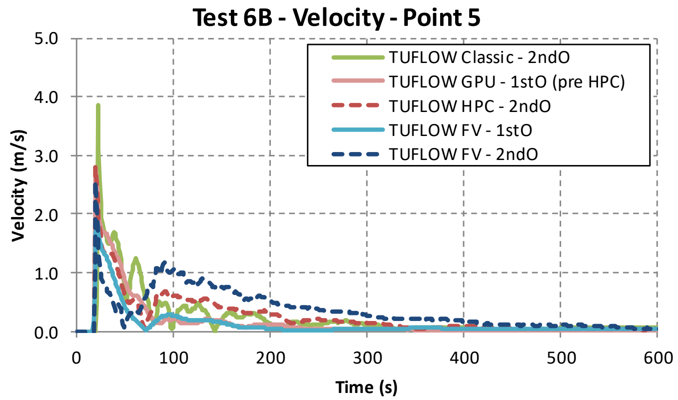
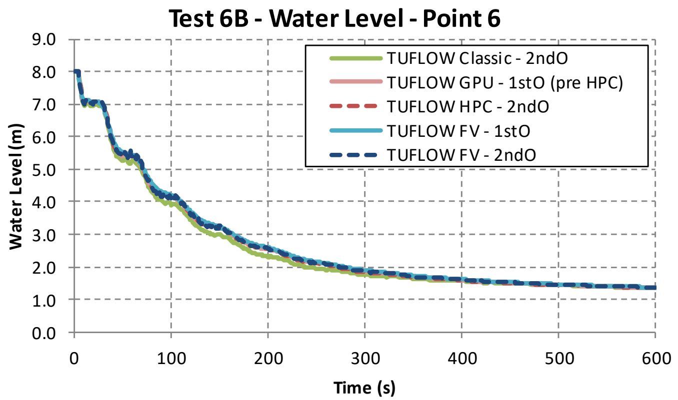
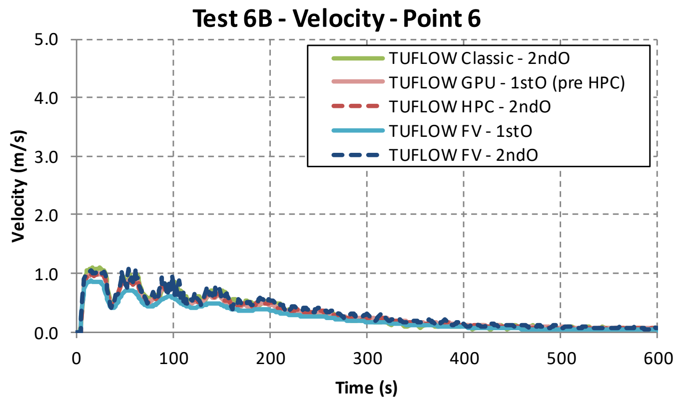
Test 6A and 6B: Flume Dam Break Against Building Test

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 15		
Refer to Figure 15		

Cross-section results have been extracted from the locations shown in Figure 16.

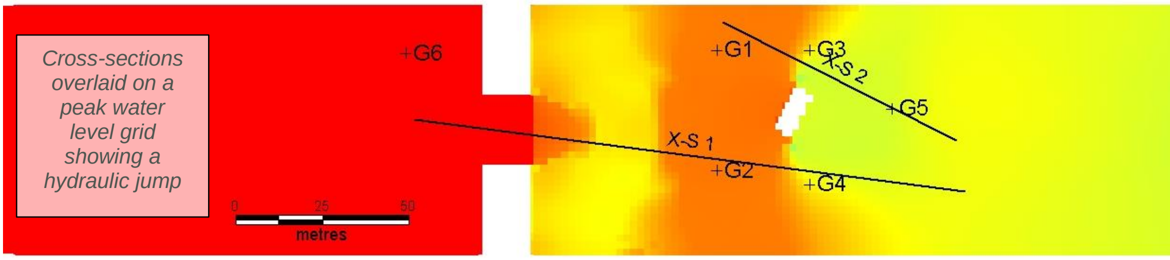
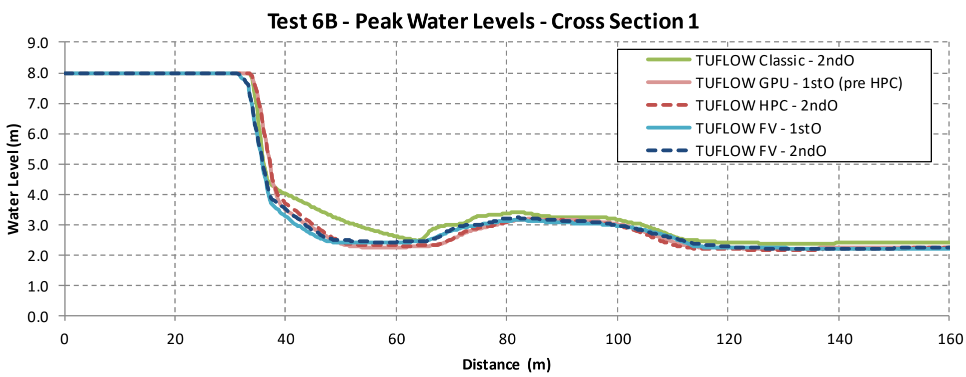


Figure 16 Test 6B Cross-section Locations

Table 20 Test 6B Cross-section Water Level Results

<table>
<tr><th>Reporting Location</th><th>Model Result</th></tr>
<tr><td>Refer to Figure 16</td><td>
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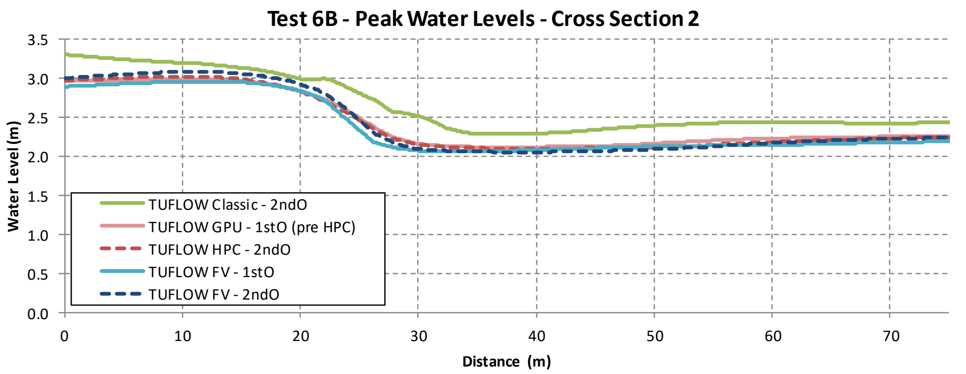
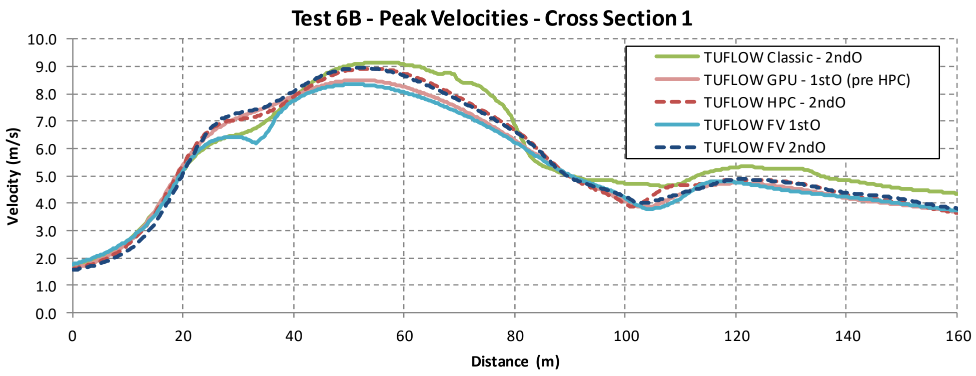
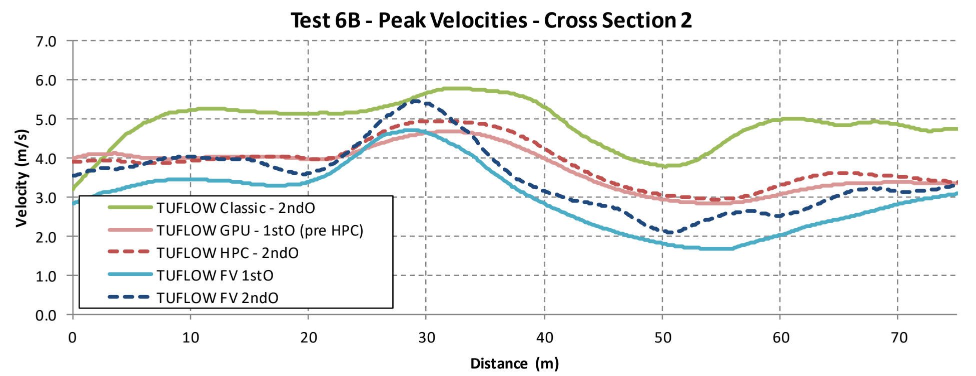
<tr><td>Refer to Figure 16</td><td>
</td></tr>
</table>

Table 21 Test 6B Cross-section Velocity Results

Reporting Location	Model Result
Refer to Figure 16	
Refer to Figure 16	

7.4 Simulation Summary Table

7.4.1 Test 6A

Table 22 Test 6A Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.01	0.01	0.01	0.01	0.01
Eddy viscosity	Spatially and time varying[1].				
Grid resolution	0.1 m	0.1 m	0.1 m	Flexible Mesh 35,456 elements	Flexible Mesh 35,456 elements
Time-stepping	Adaptive (0.01 to 0.26s)	Adaptive (0.001 to 0.05s)	Adaptive (0.001 to 0.014s)	Adaptive (0.0003 to 0.03s)	Adaptive (0.0003 to 0.03s)
Total simulation time (hrs)	0.007 (23s)	0.0024[1] (8s)	0.0031[1] (11s)	0.015 (53s)	0.019 (67s)

[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.

[2] Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"

7.4.2 Test 6B

Table 23 Test 6B Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
Manning's n used	0.05	0.05	0.05	0.05	0.05
Eddy viscosity	Spatially and time varying[1].				
Grid resolution	2m	2m	2m	Flexible Mesh 35,456 elements	Flexible Mesh 35,456 elements
Time-stepping	Adaptive (0.1 to 3.1s)	Adaptive (0.02 to 0.5s)	Adaptive (0.07 to 0.025s)	Adaptive (0.035 to 0.08s)	Adaptive (0.035 to 0.08s)
Total simulation time (hrs)	0.0069 (25s)	0.0019[2] (6s)	0.0017[2] (6s)	0.016 (57s)	0.0258 (102s)
[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. [2] Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

8 Test 7: Real-World 1D-2D River / Floodplain Linking

8.1 Objective

The objective of this test is to assess the package's ability to simulate fluvial flooding of floodplains separated by man-made levees along the river banks and across the floodplains, using a 1D river, 2D floodplain modelling approach. The following capabilities are also tested:

- 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;
- The ability to build the river component using 1D cross-sections;
- The ability to process floodplain topography features, particularly the levees, accurately into the model using the supplied as 3D breaklines.

8.2 Description

The site to be modelled is approximately 7 km long by 0.75 to 1.75 km wide and consists of a set of three distinct floodplains (Figure 17) in the vicinity of the English village of Upton-upon-Severn. The River Severn that flows through the site is modelled for a total distance of ~20 km. Boundary conditions are a hypothetical inflow hydrograph for the Severn (a single flood event with a rising and a falling limb, resulting in below bank full 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 levee embankments along which flood depths are expected to be relatively small.

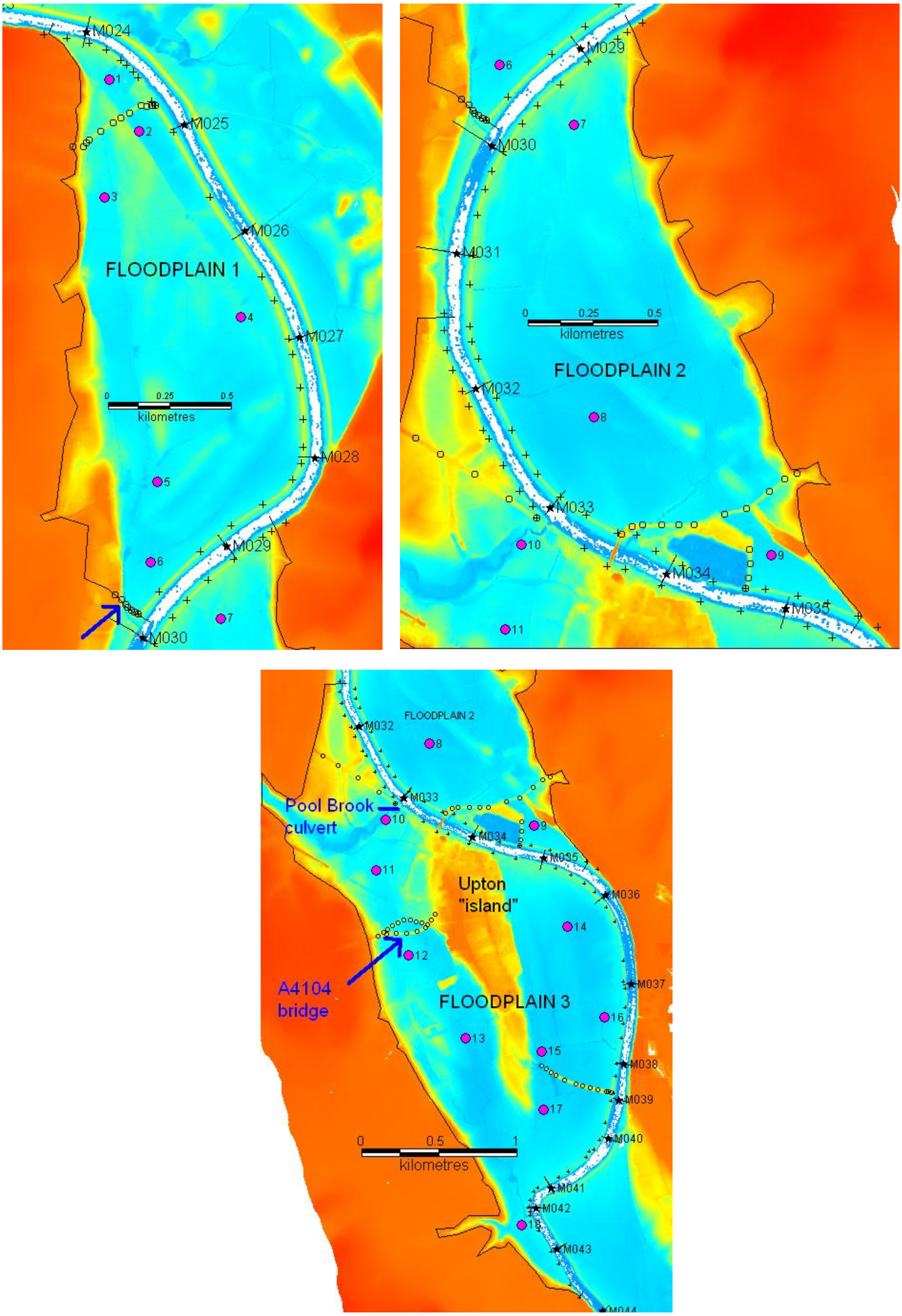


Figure 17 Test 7 Modelled Features

The United Kingdom Environment Agency (EA) provided the following description with the benchmark dataset.

River Channel Geometry

The channel geometry was provided in the form of a text file with cross-sections labelled M013 to M054 (a separate comma delimited (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:

- The boundary between the river channel and the area expected to be modelled in 2D, and
- 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 was 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 Figure 17):

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

(1) 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.

(2) 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 XY 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. Two ‘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. Details of these were not provided and were not required to be modelled.

A masonry culvert immediately upstream from the village of Upton (“Pool Brook”) is however modelled, see Map 4. It is assumed to be 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 modelled as a 10m wide opening (invert level 10m) offering a pathway from Floodplain 1 to the river at cross-section M030.

Other Environment Agency Comments

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 1 m DEM file, a coarsened 10 m 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 carried out, consisting of 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.

Initial and Boundary Conditions

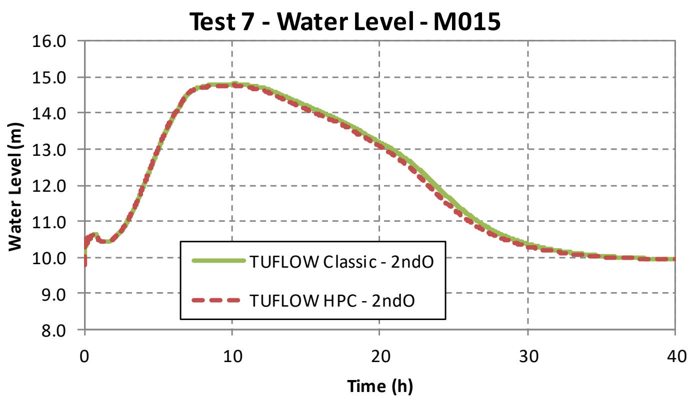
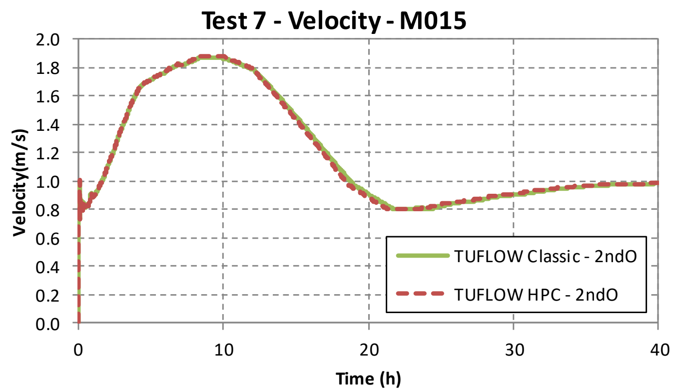
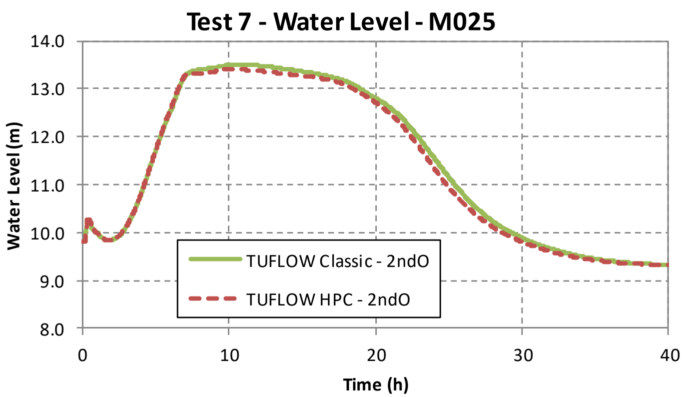
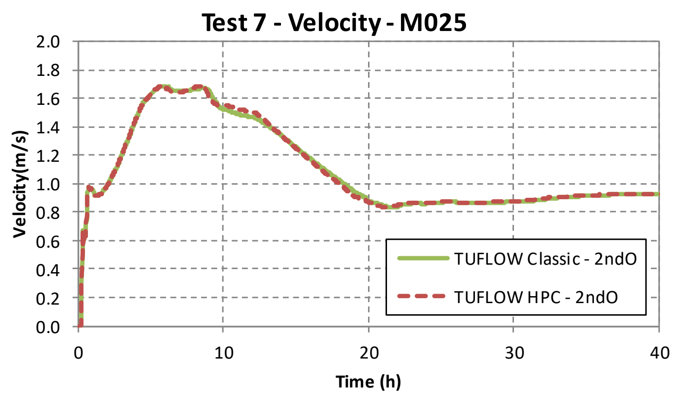
- Upstream: inflow versus time inflow is applied at the northernmost cross-section, cross-section M013.
- Downstream: a rating curve (flow versus head) is applied at the southernmost cross-section, cross-section M054.
- All other boundaries are closed (no flow).
- A uniform water level of 9.8 m is applied as the Initial condition.

Model Parameter Values

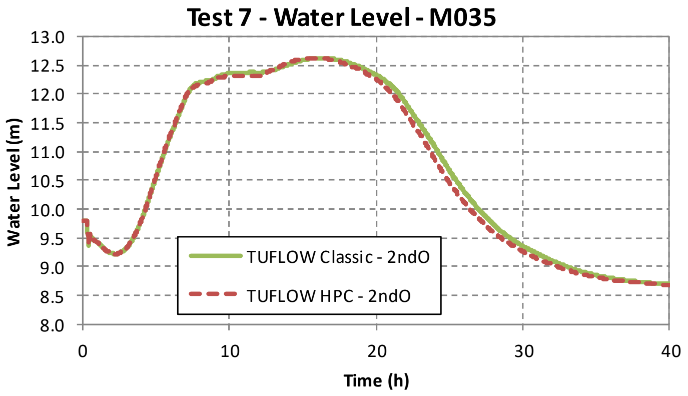
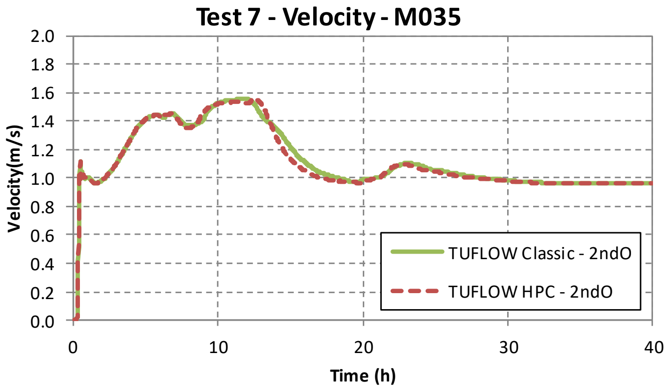
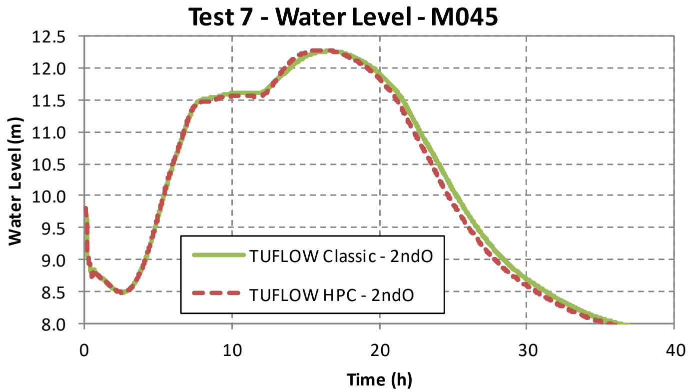
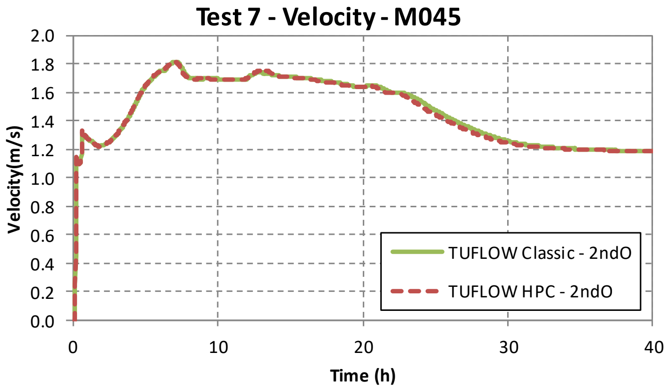
- Manning's n = 0.028 uniformly in river, 0.04 uniformly in floodplains.
- Model grid resolution: 20m or ~16700 nodes.
- Simulation start time = 0 hours.
- Simulation end time = 72 hours.

8.3 Hydraulic Results

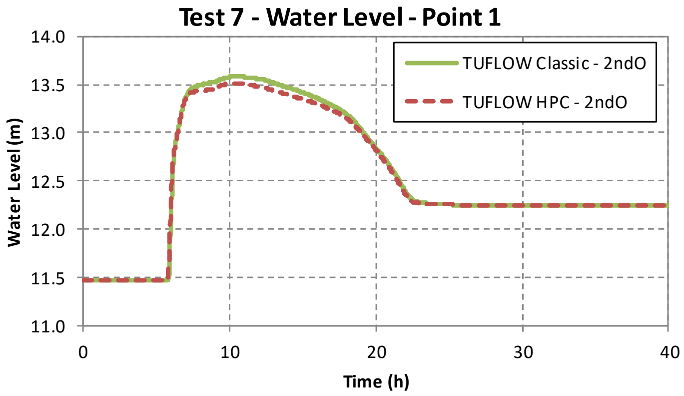
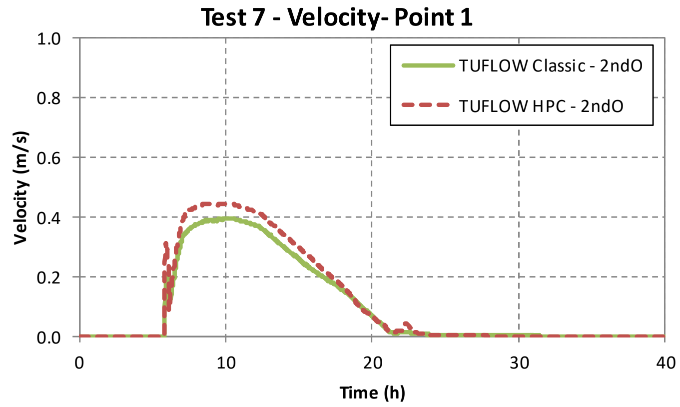
Table 24 Test 7 Point Location Results

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td colspan="3">1D Channel</td></tr>
<tr><td>Refer to Figure 17</td><td></td><td></td></tr>
<tr><td>Refer to Figure 17</td><td></td><td></td></tr>
</table>

Test 7: Real-World 1D-2D River / Floodplain Linking

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 17		
Refer to Figure 17		
Floodplain 1		

Test 7: Real-World 1D-2D River / Floodplain Linking

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 17</td><td>
</td><td>
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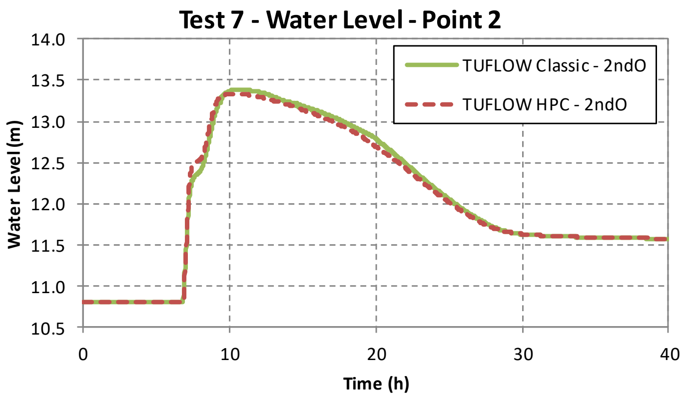
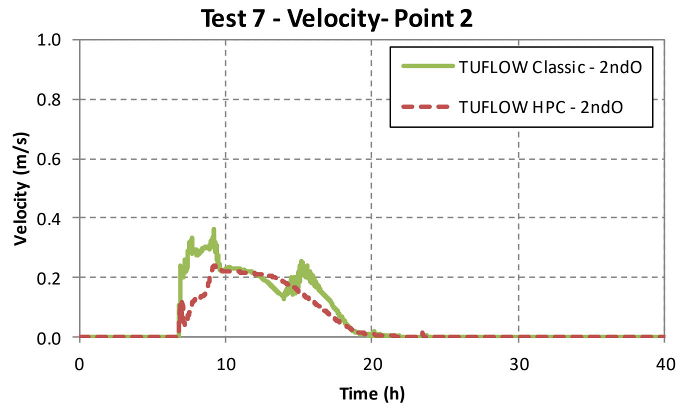
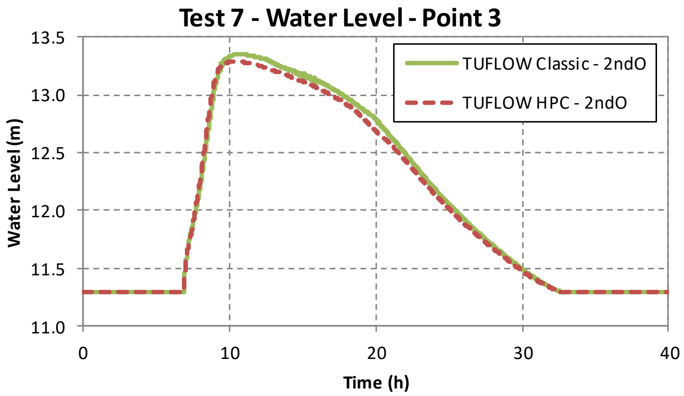
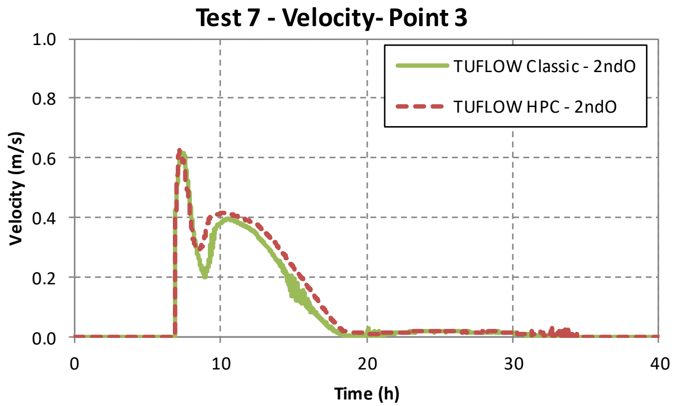
<tr><td>Refer to Figure 17</td><td>
</td><td>
</td></tr>
</table>

Test 7: Real-World 1D-2D River / Floodplain Linking

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 17</td><td>
</td><td>
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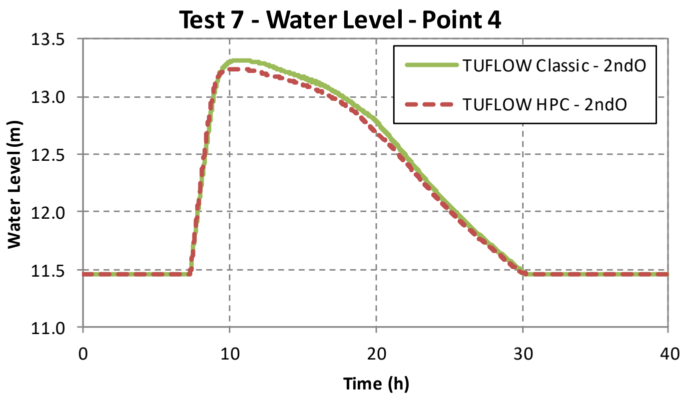
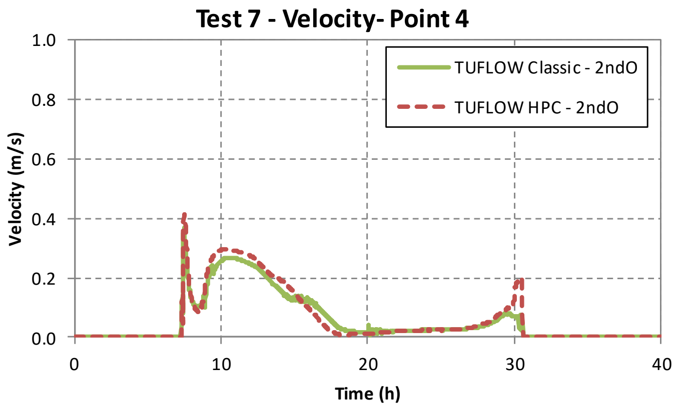
<tr><td>Refer to Figure 17</td><td>
</td><td>
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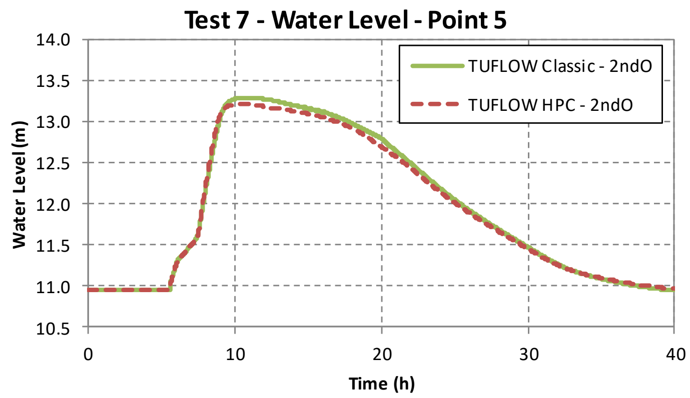
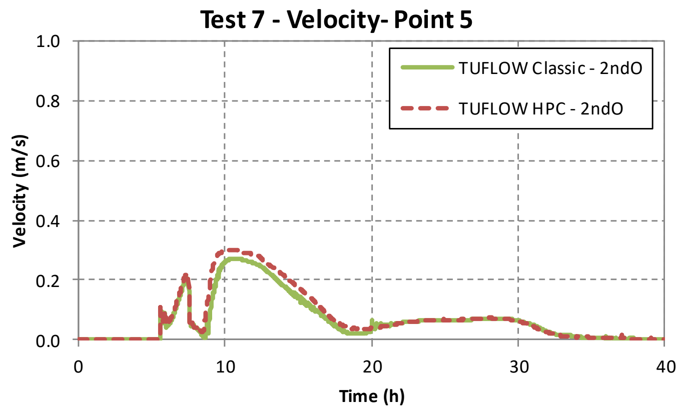
Test 7: Real-World 1D-2D River / Floodplain Linking

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 17</td><td>
</td><td>
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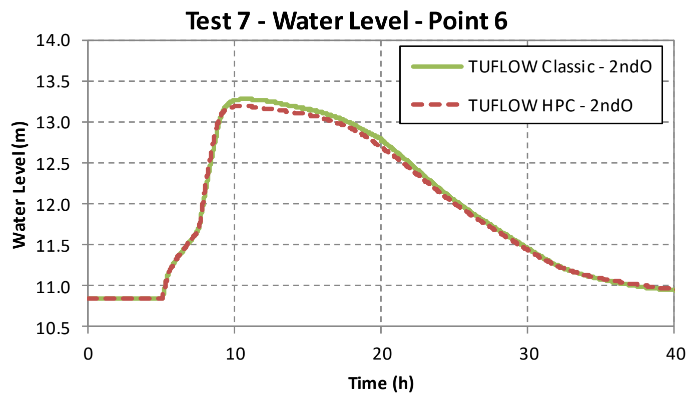
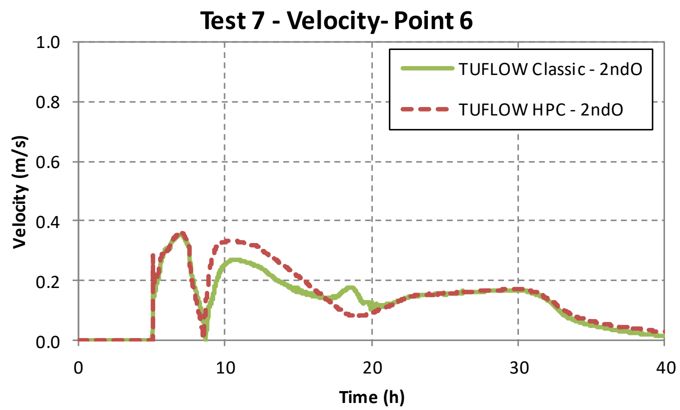
<tr><td>Refer to Figure 17</td><td>
</td><td>
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<tr><td colspan="3">Floodplain 2</td></tr>
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Test 7: Real-World 1D-2D River / Floodplain Linking

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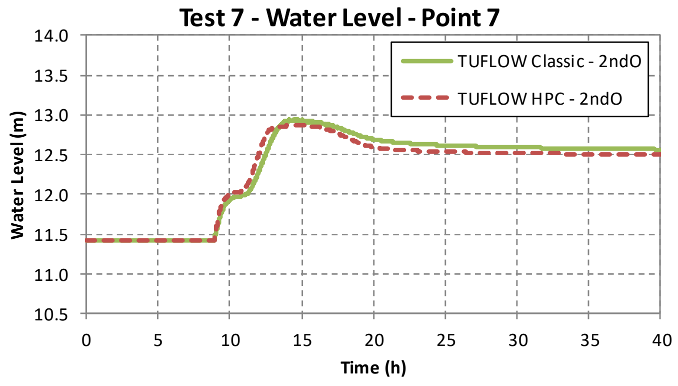
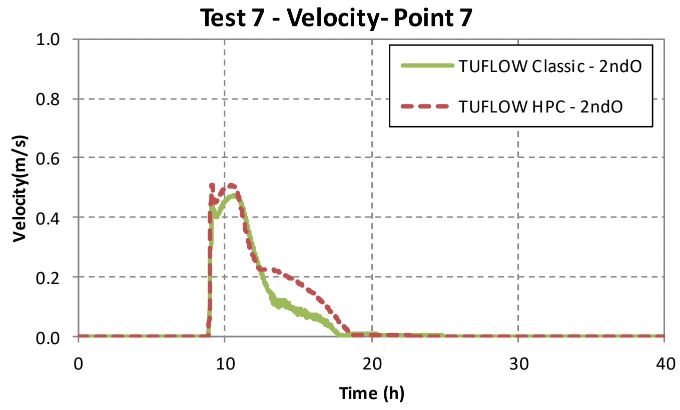
<tr><td>Refer to Figure 17</td><td>
</td><td>
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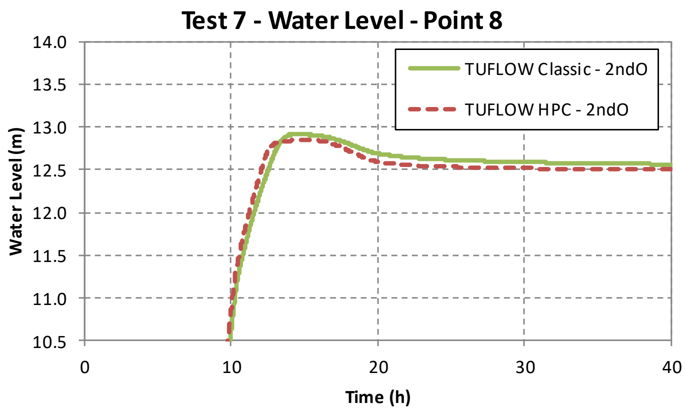
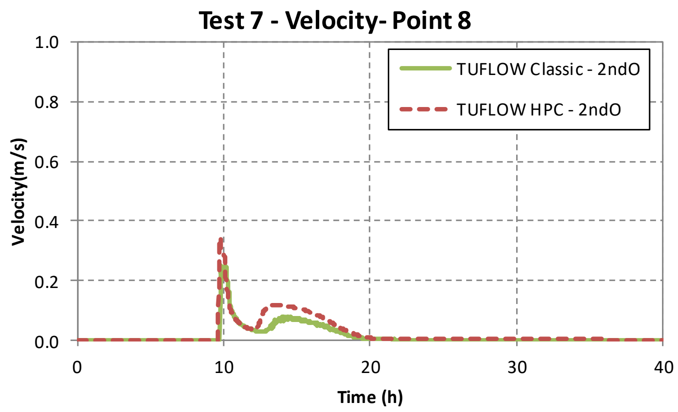
<tr><td>Refer to Figure 17</td><td>
</td><td>
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Test 7: Real-World 1D-2D River / Floodplain Linking

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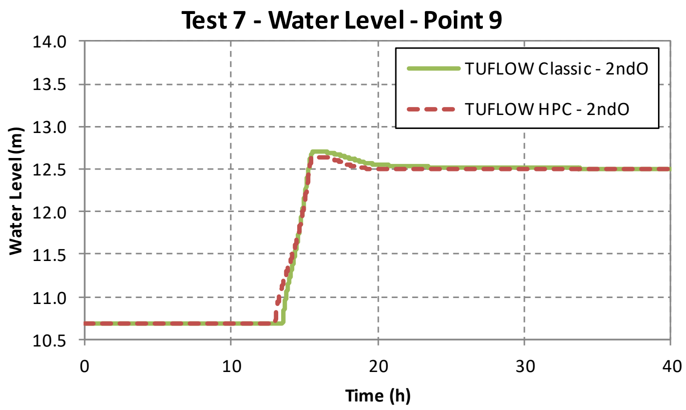
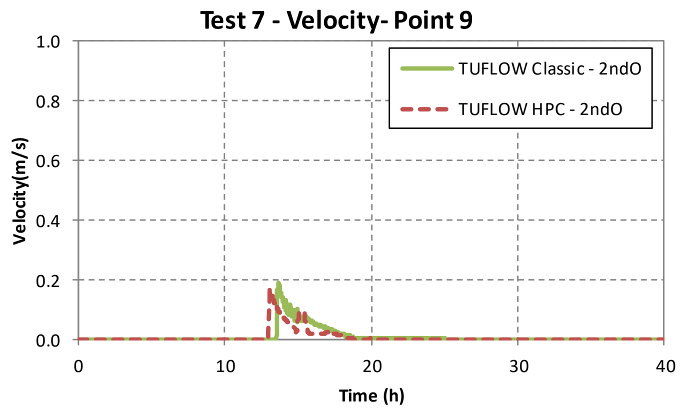
<tr><td>Refer to Figure 17</td><td>
</td><td>
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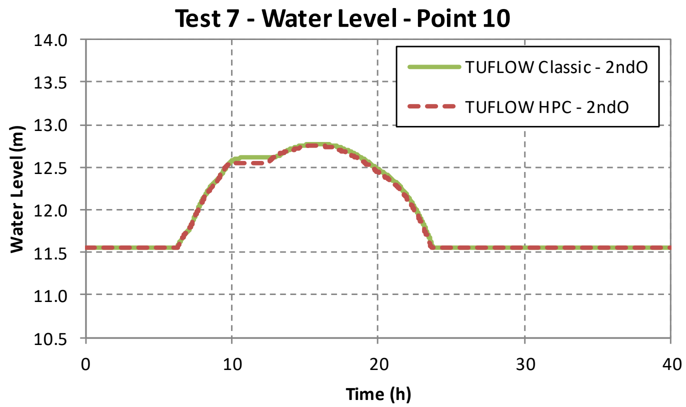
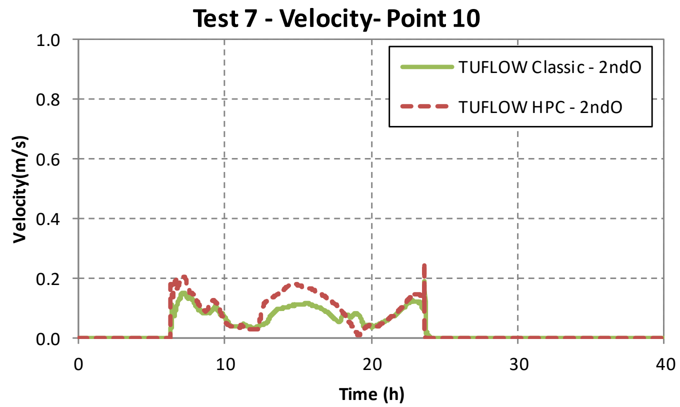
<tr><td colspan="3">Floodplain 3</td></tr>
<tr><td>Refer to Figure 17</td><td>
</td><td>
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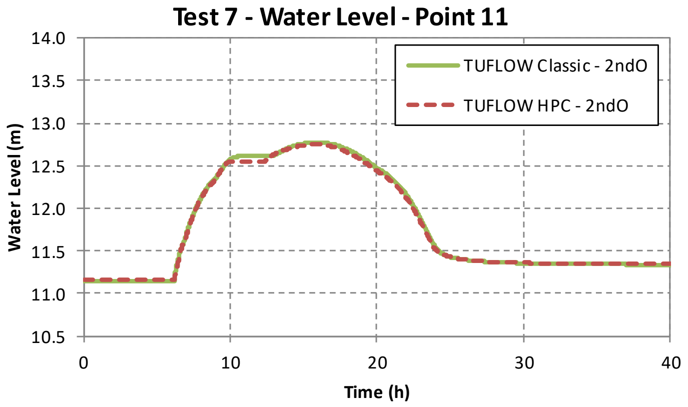
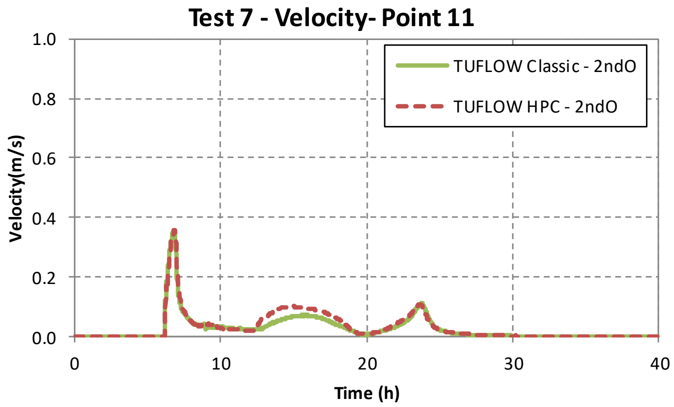
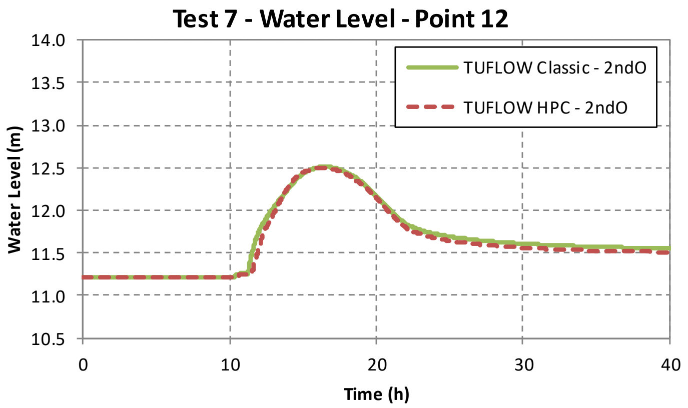
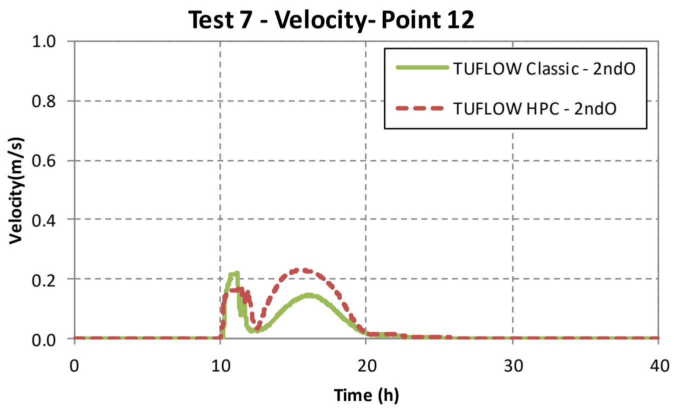
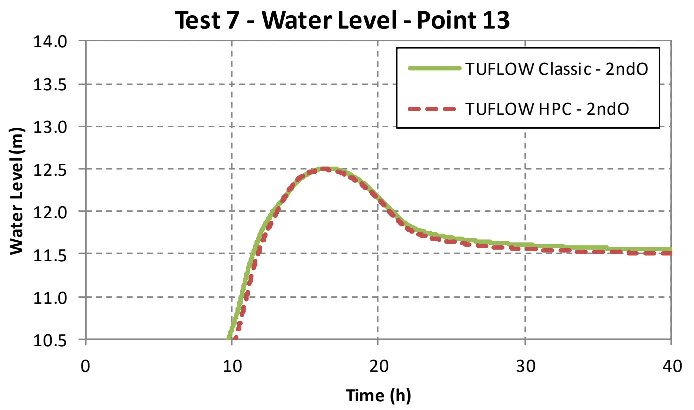
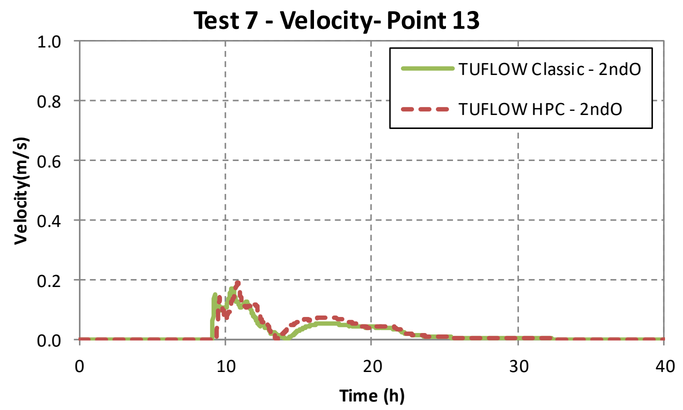
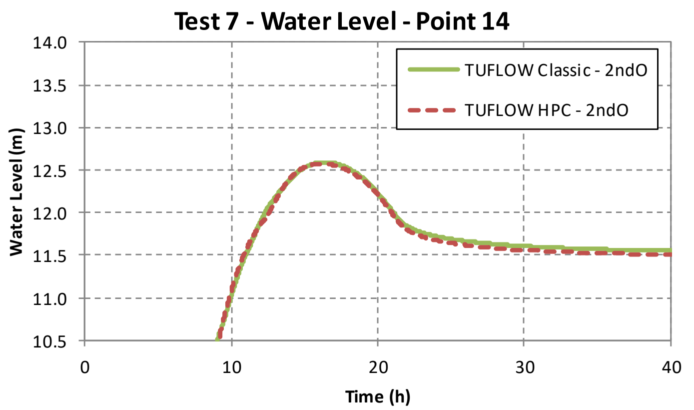
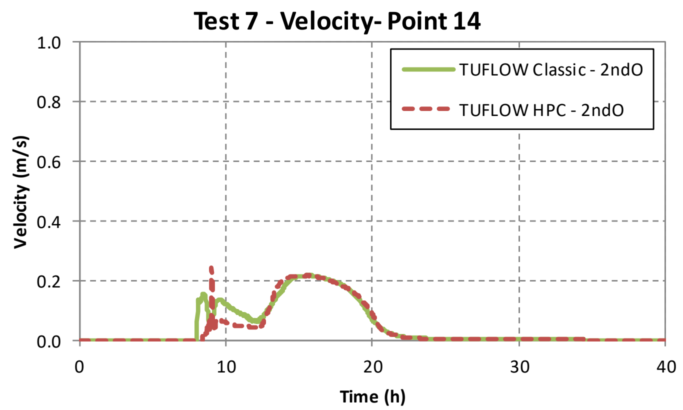
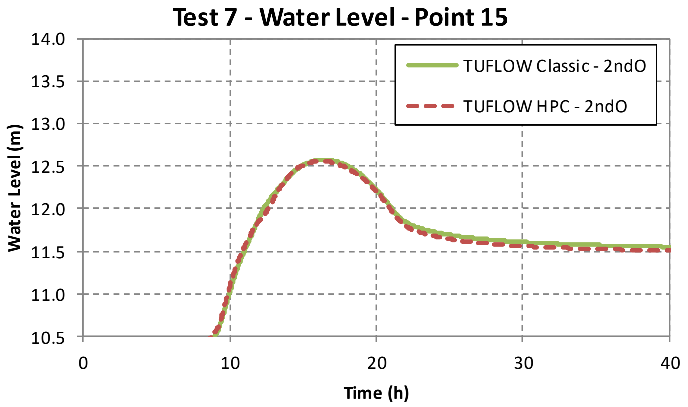
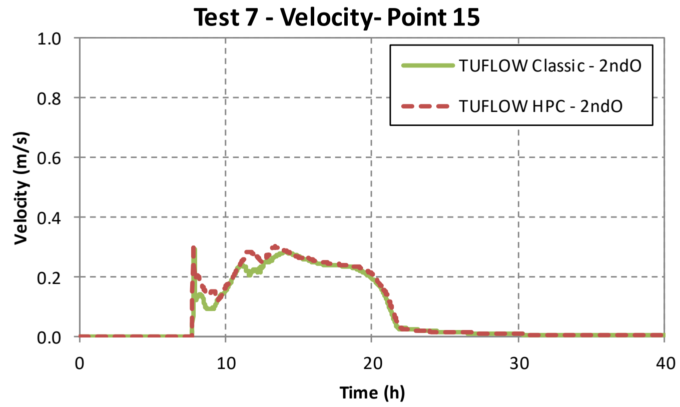
Test 7: Real-World 1D-2D River / Floodplain Linking

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 17		
Refer to Figure 17		

Test 7: Real-World 1D-2D River / Floodplain Linking

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 17		
Refer to Figure 17		

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 17</td><td>
</td><td>
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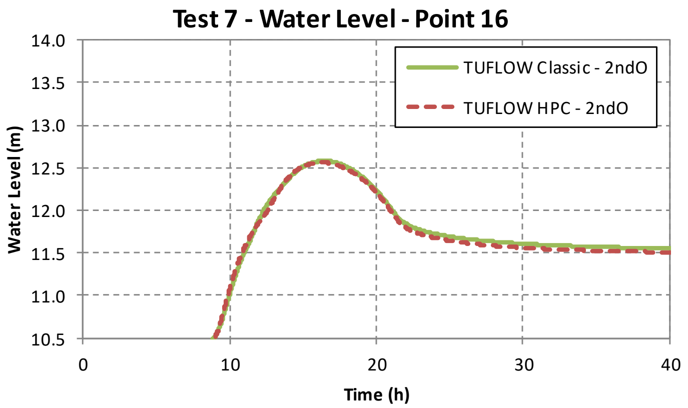
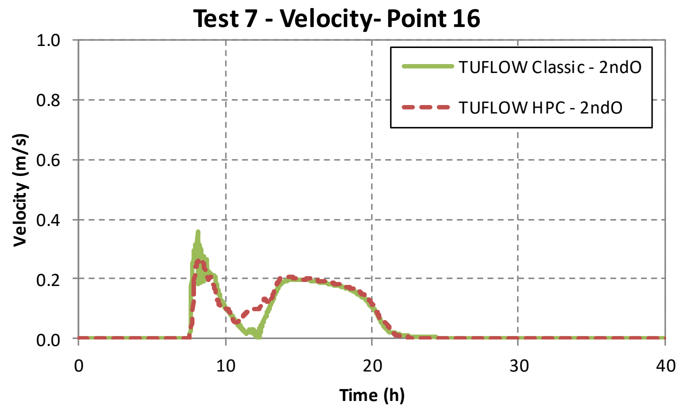
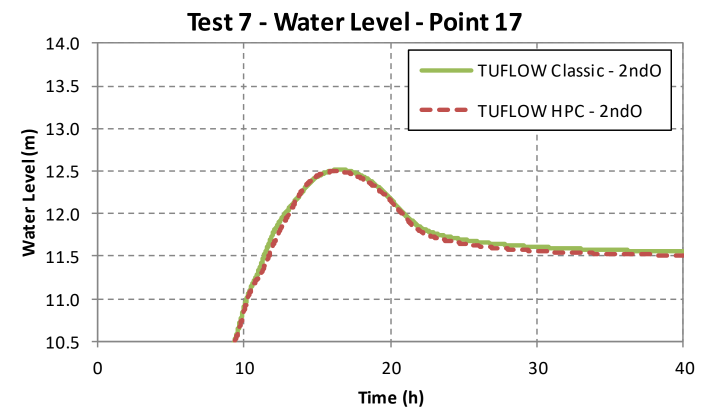
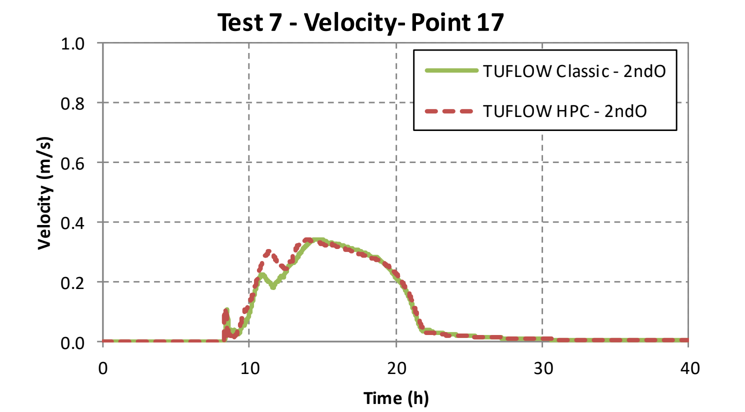
<tr><td>Refer to Figure 17</td><td>
</td><td>
</td></tr>
</table>

Test 7: Real-World 1D-2D River / Floodplain Linking

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 17</td><td>
</td><td>
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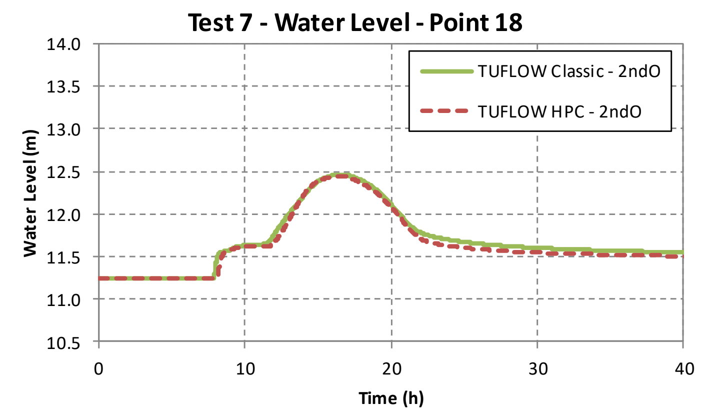
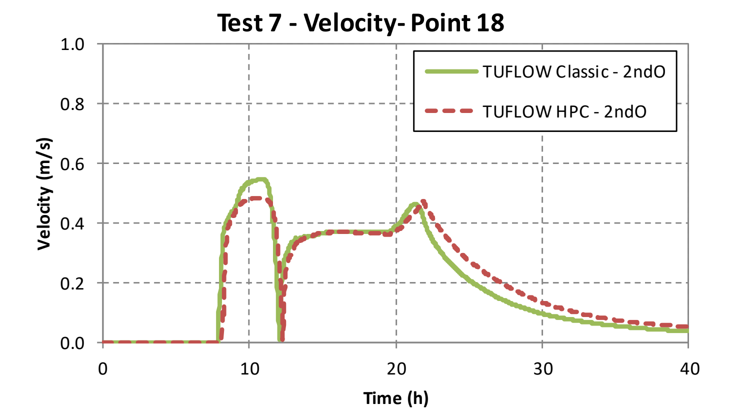
<tr><td>Refer to Figure 17</td><td>
</td><td>
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Test 7: Real-World 1D-2D River / Floodplain Linking

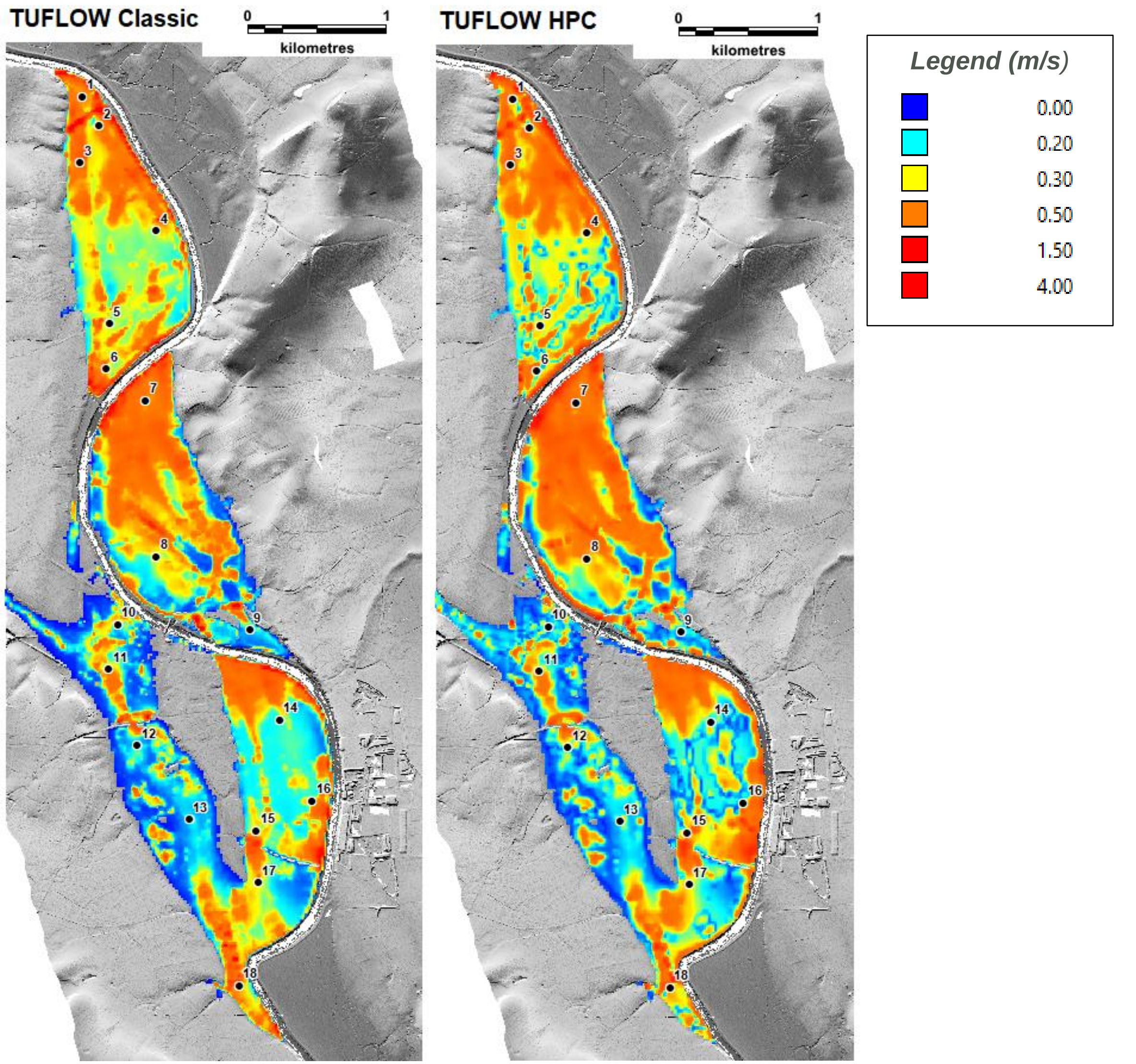


Figure 18 Test 7 Peak Velocity Results

8.4 Simulation Summary Table

Table 25 Test 7 Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3 - Single Precision (SP) build.					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Not used as no 1D linking.	Not used as no 1D linking (yet).	
Manning's n used	0.028 river 0.04 floodplain	0.028 river 0.04 floodplain			
Grid resolution	20m	20m			
Time-stepping	2D: 15s 1D: 3s	2D: (~3.2s) 1D: 3s			
Total simulation time (hrs)	0.039 (140s)	0.037[1] (134s)			
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

9 Test 8A: Rainfall and Sewer Surcharge in Urban Areas

9.1 Objective

Test 8A assesses the software's capability to simulate shallow inundation originating from a point source and from rainfall applied directly to the model grid, at relatively high resolution.

9.2 Description

The modelled area is approximately 0.4 km by 0.96 km and covers the entire DEM provided, shown in Figure 19. Ground elevations range from ~21 m to ~37 m.

The flooding is assumed to arise from two sources:

(1) A uniformly distributed rainfall event, illustrated by the hyetograph in Figure 20. This is applied to the modelled area only (the rest of the catchment is ignored).

(2) A point source at the location represented in Figure 19 and illustrated by the inflow time series in Figure 21 (this may for example be assumed to arise from a burst or surcharging culvert).

The DEM is a 0.5 m resolution Digital Terrain Model (no vegetation or buildings) created from LiDAR data collected on 13th August 2009 and provided by the EA (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 for 5 hours to allow the flood to settle in the lower parts of the modelled domain.

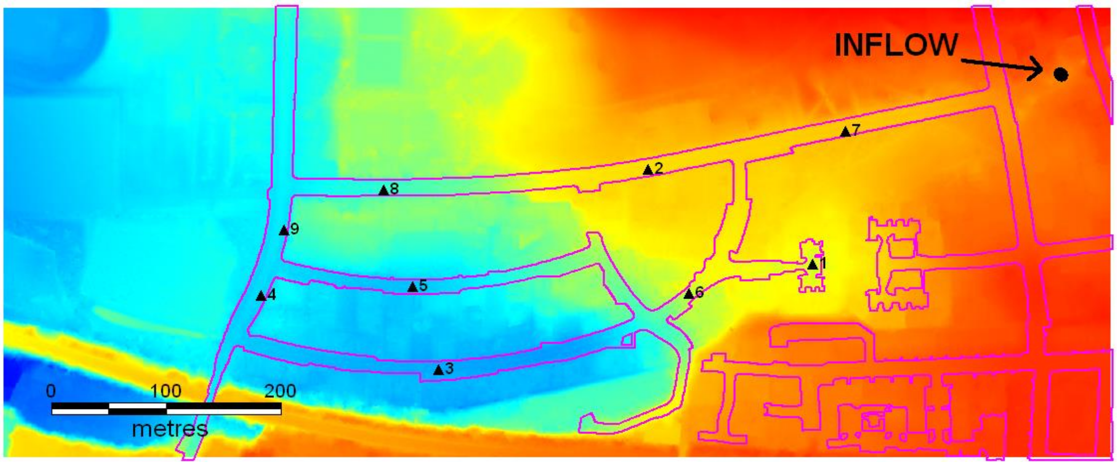


Figure 19 Test 8 DEM, Inflow and Result Output Locations

Test 8A: Rainfall and Sewer Surcharge in Urban Areas

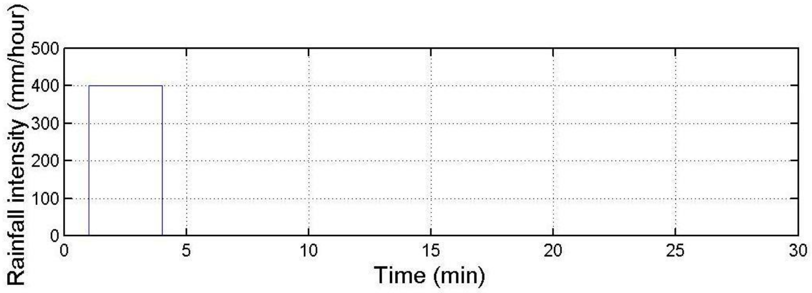


Figure 20 Test 8A Rainfall Hyetograph

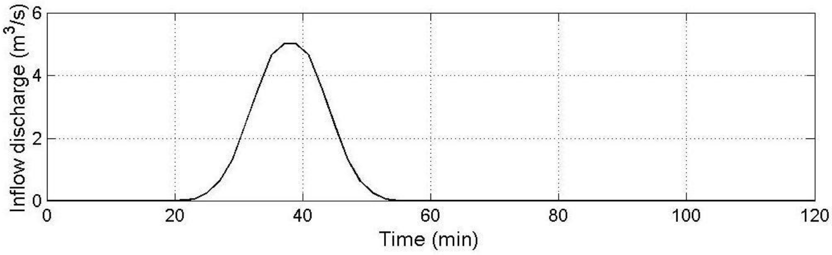


Figure 21 Test 8A Inflow Hydrograph

Initial Boundary and Conditions

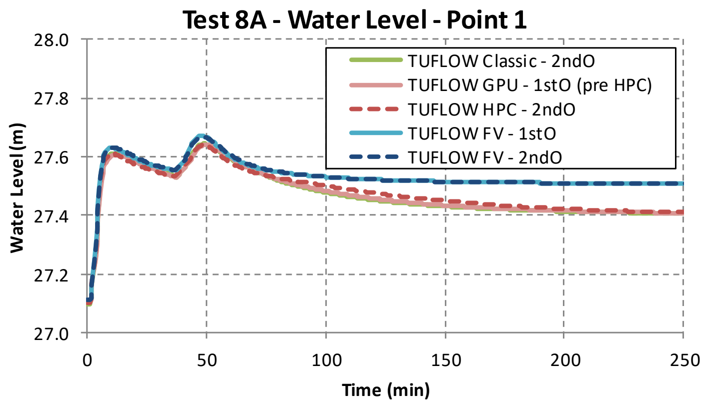
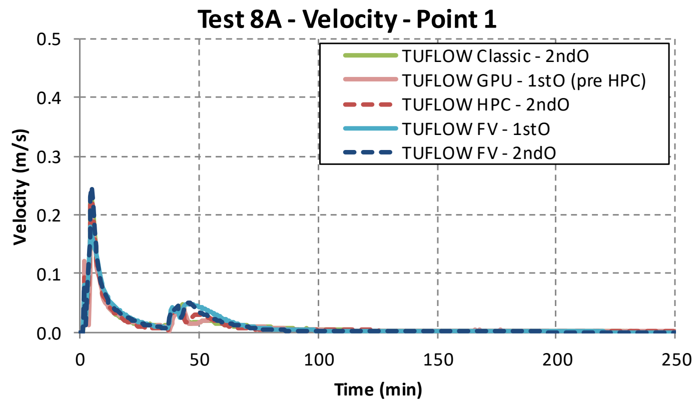
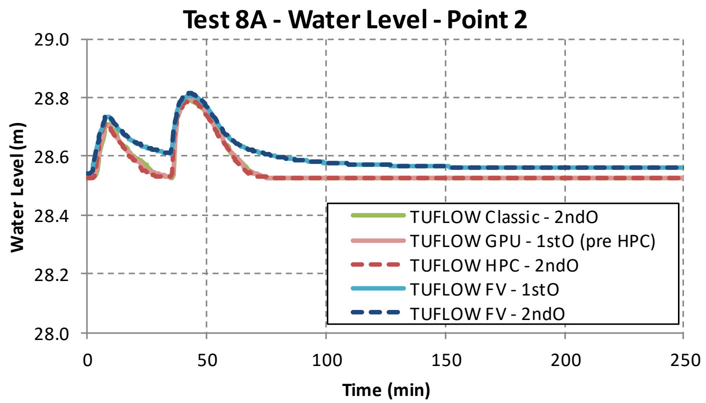
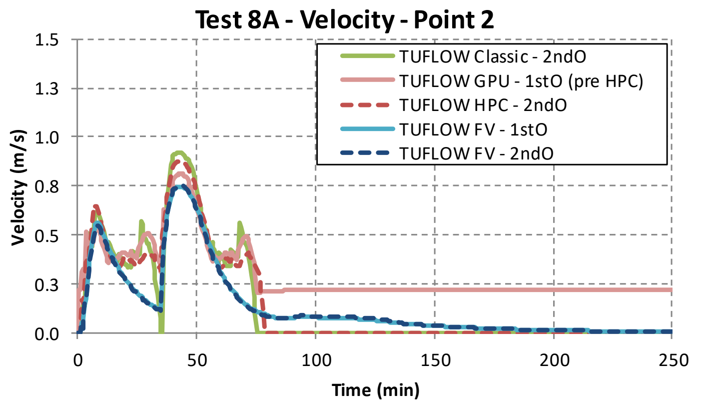
- Initial condition = dry bed.
- Rainfall as described above.
- The point source inflow is applied as described above.
- All boundaries of the modelled area are closed (no flow).

Model Parameter Values

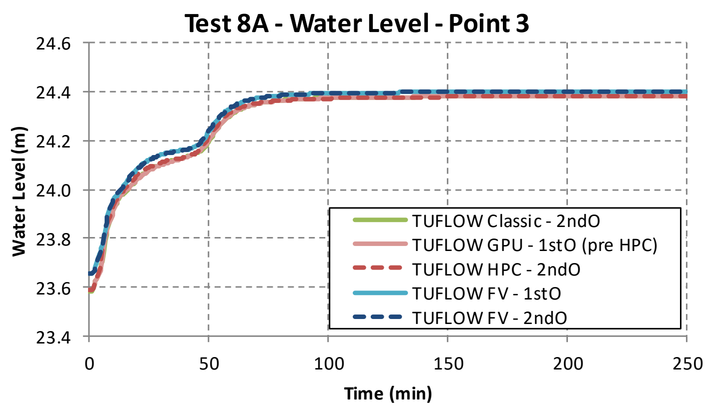
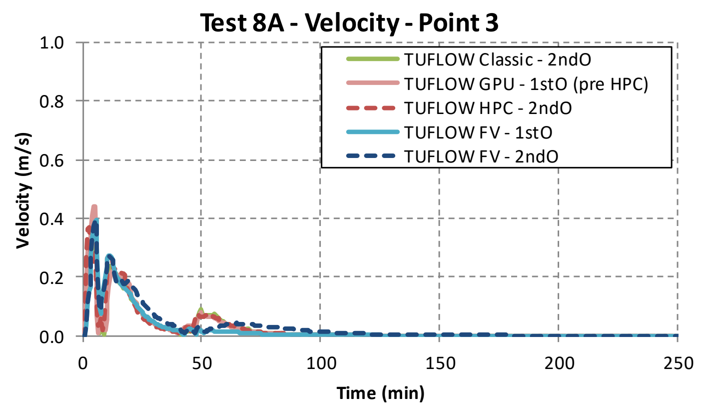
- Manning's n = 0.02 for roads and pavements, 0.05 everywhere else.
- Model grid resolution: 2m (or ~97000 nodes in the 0.388 km^2 area modelled).
- Simulation start time = 0 hours.
- Simulation end time = 5 hours.

9.3 Hydraulic Results

Table 26 Test 8A Point Location Results

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 19		
Refer to Figure 19		

Test 8A: Rainfall and Sewer Surcharge in Urban Areas

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 19</td><td>
</td><td>
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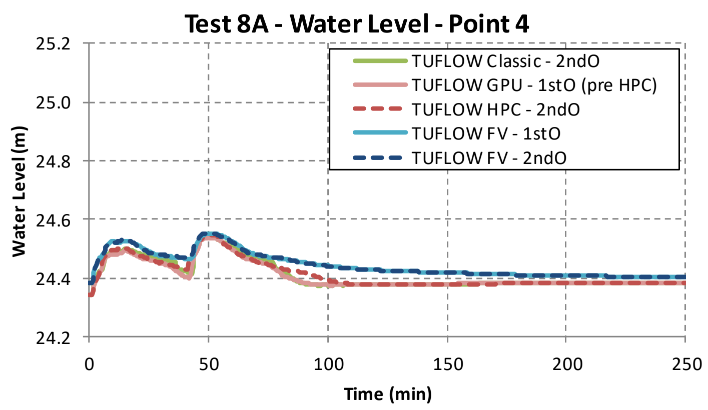
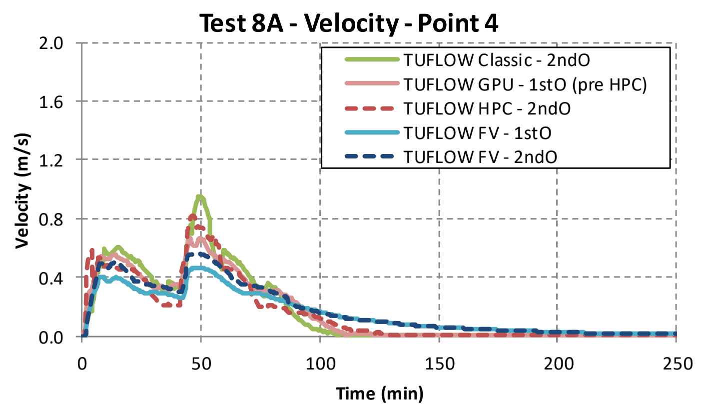
<tr><td>Refer to Figure 19</td><td>
</td><td>
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Test 8A: Rainfall and Sewer Surcharge in Urban Areas

<table>
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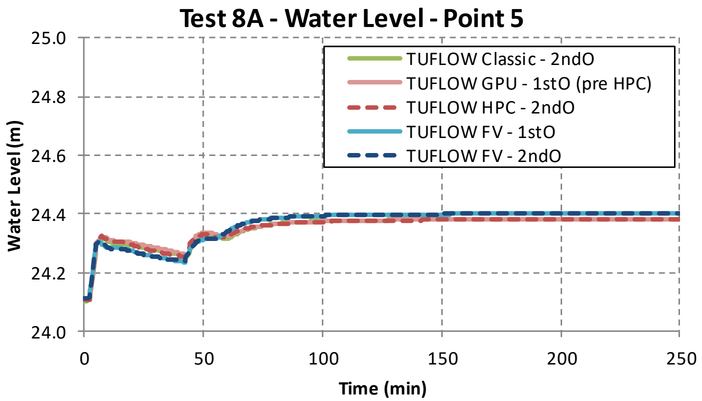
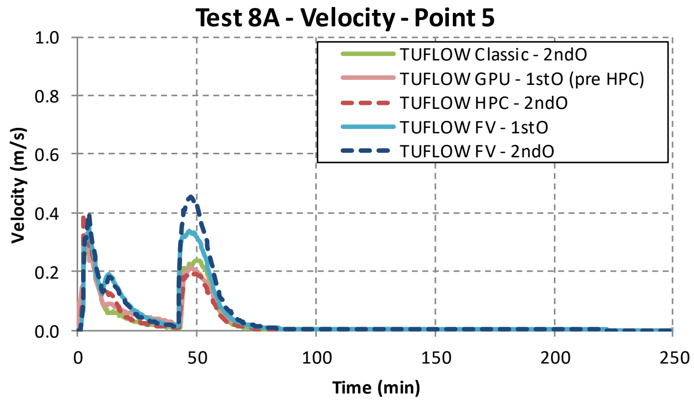
<tr><td>Refer to Figure 19</td><td>
</td><td>
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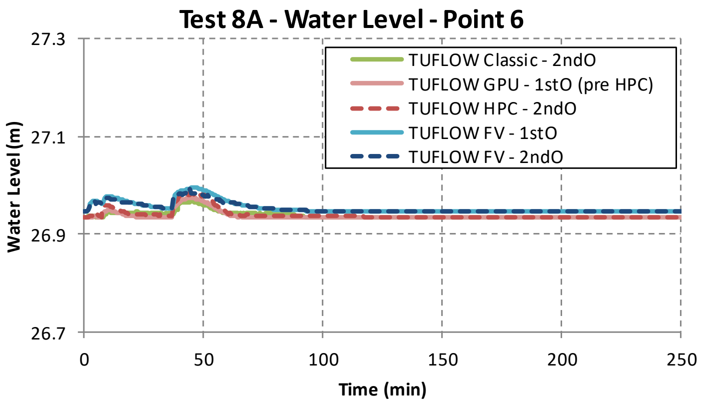
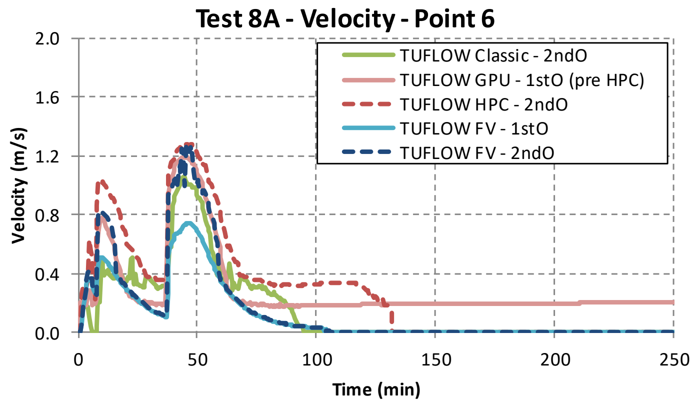
<tr><td>Refer to Figure 19</td><td>
</td><td>
</td></tr>
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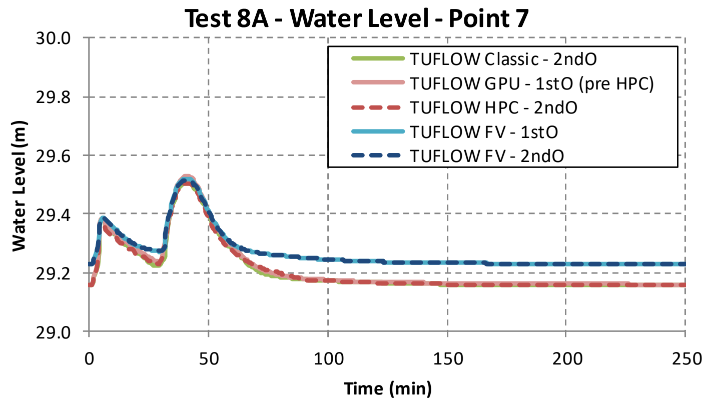
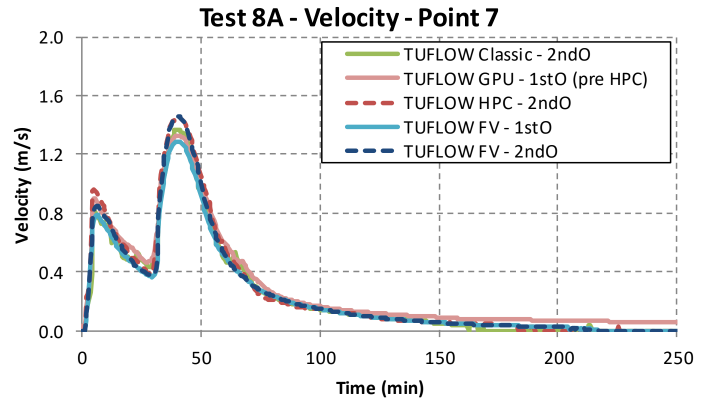
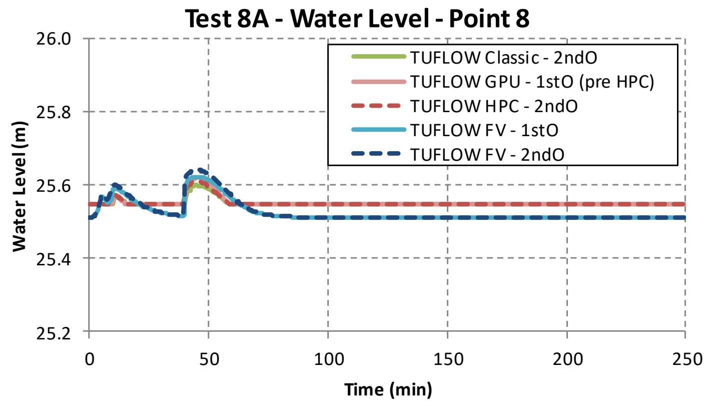
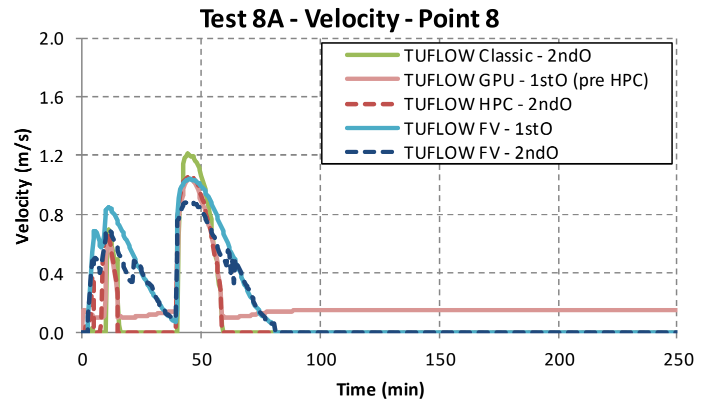
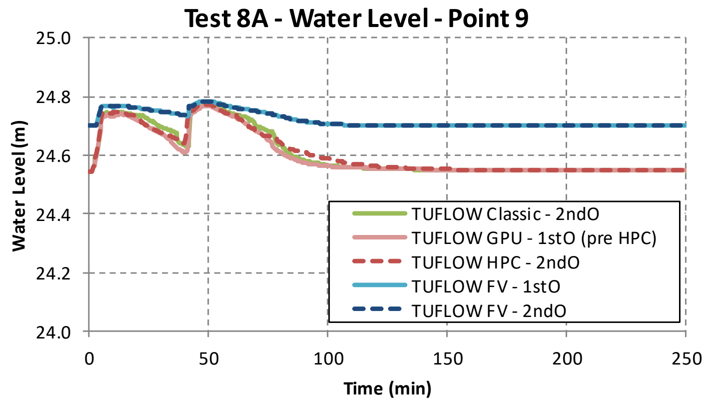
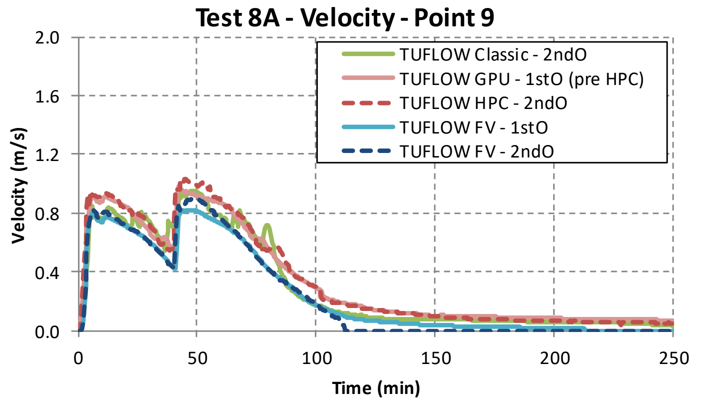
Test 8A: Rainfall and Sewer Surcharge in Urban Areas

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 19		
Refer to Figure 19		

Test 8A: Rainfall and Sewer Surcharge in Urban Areas

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 19		

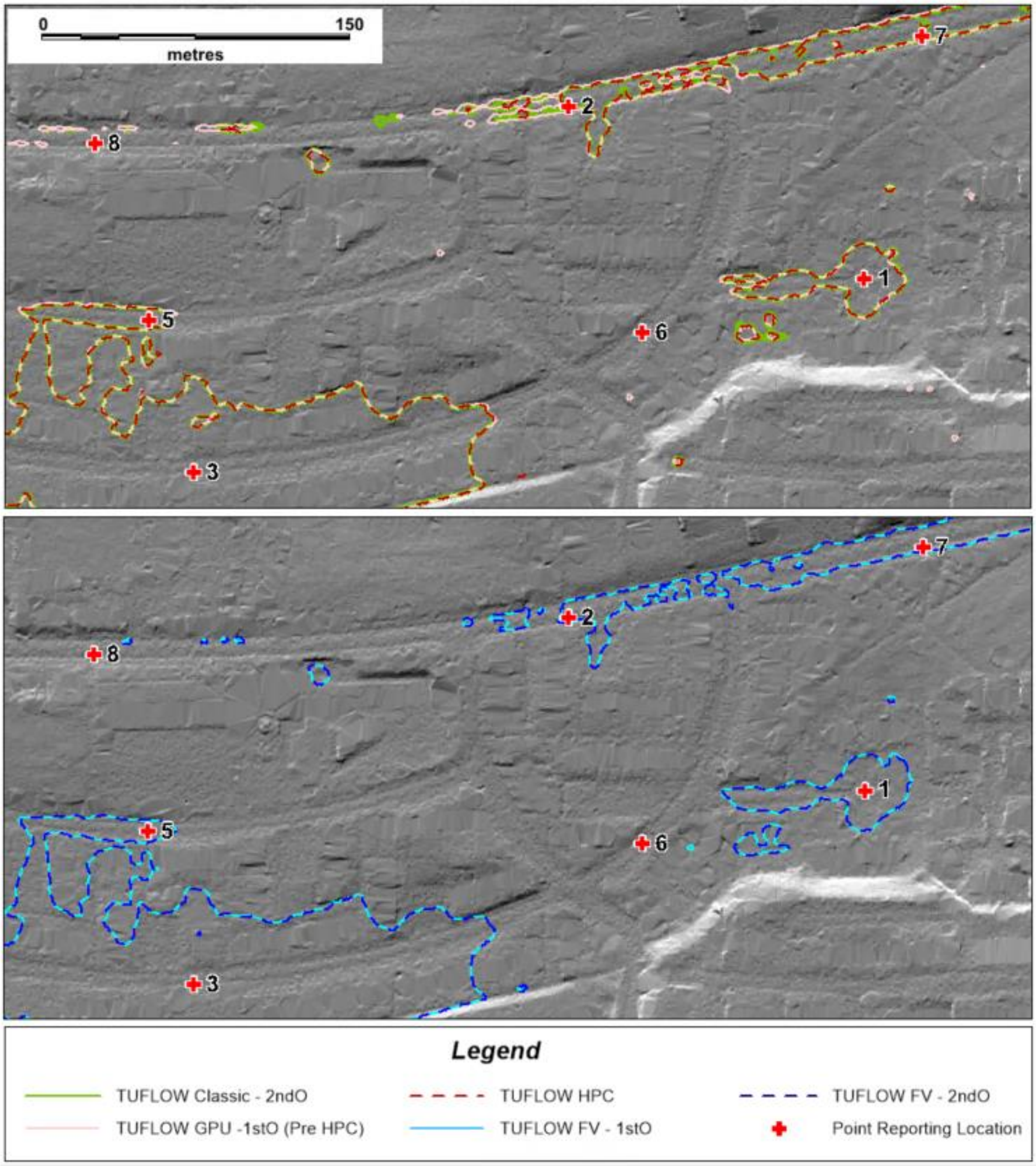


Figure 22 Test 8A Peak Depth 0.2 m Contour Lines

9.4 Simulation Summary Table

Table 27 Test 8A Simulation Summary Table

	TUFLOW Classic (2nd Order)	TUFLOW HPC (2nd Order)	TUFLOW GPU (1st Order)	TUFLOW FV (1st Order)	TUFLOW FV (2nd Order)
Software Version: Refer to Table 3. Double Precision (DP) build was used for TUFLOW Classic. All others used Single Precision (SP)					
Hardware Used: Refer to Table 4					
Minimum recommended hardware for a simulation of this type: Refer to Table 4					
Multi-processing	No	Yes 3584 GPU Cores	Yes 3584 GPU Cores	Yes 16 CPU cores	Yes 16 CPU cores
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	0.02 roads, 0.05 elsewhere
Grid resolution	2m	2m	2m	2m	2m
Time-stepping	1.0s	Adaptive (0.3 to 0.5s)	Adaptive (0.4 to 0.9s)	Adaptive (0.13 to 1.0s)	Adaptive (0.13 to 1.0s)
Total simulation time (hrs)	0.152 (545s)	0.016[1] (56s)	0.005[1] (19s)	0.2286 (787s)	0.3596 (1294.6s)
[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, "Overall Summary of Performance"					

10 Test 8B: Urban Surface Flow from a Surcharging Sewer

10.1 Objective

Test 8B aims to evaluate the software's ability to simulate shallow inundation originating from a surcharging underground pipe, at relatively high 2D resolution. The pipe is modelled in 1D and connected to the overland 2D grid through a manhole.

10.2 Description

The modelled area is approximately 0.4 km by 0.96 km and covers the entire DEM provided and shown in Figure 23. Ground elevations range from ~21 m to ~37 m.

A culverted watercourse of circular section, 1400 mm in diameter, ~1070 m in length, and with invert level uniformly 2 m 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 24A. Surcharge is expected to occur at a vertical manhole of 1 m^2 cross-section located 467 m from the top end of the culvert, and at the location shown in Figure 23.

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

The DEM is a 0.5 m resolution Digital Terrain Model (no vegetation or buildings) created from LiDAR data collected on 13th August 2009 and provided by the EA (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 1 m 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 for 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).

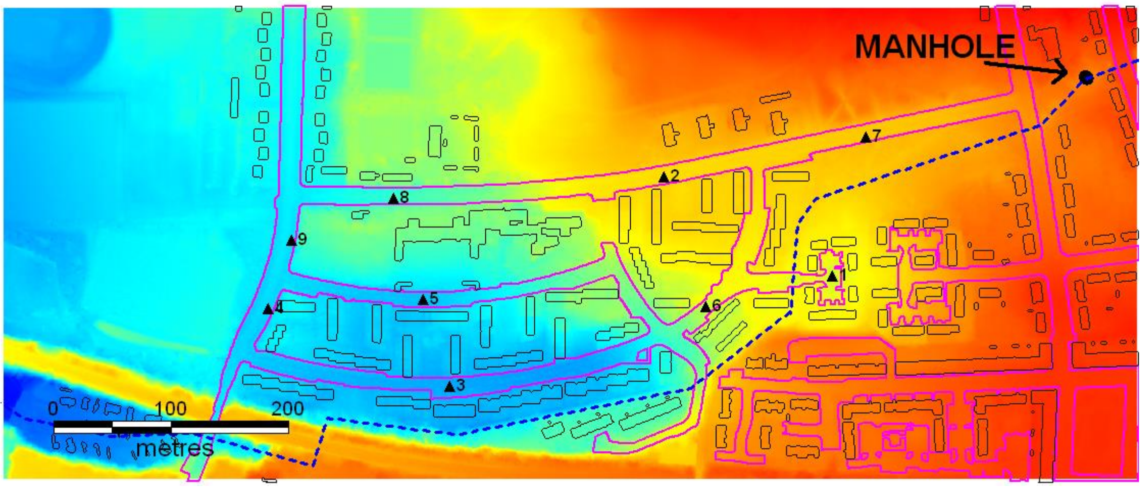


Figure 23 Test 8B DEM, Inflow and Result Output Locations

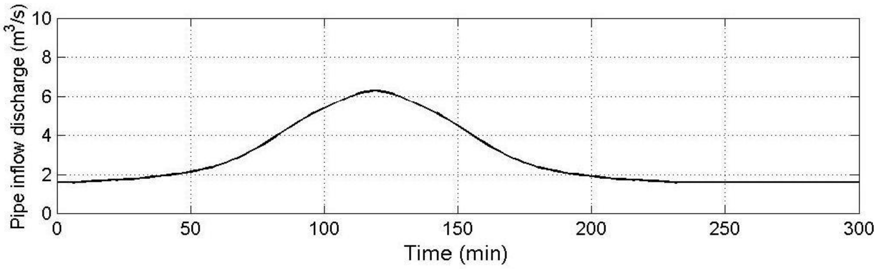


Figure 24 Test 8B Inflow Hydrograph (at upstream end of culvert)

Initial and Boundary Conditions

- Underground pipe
  - Baseflow (uniform initial condition): 1.6 m^3/s.
  - Upstream boundary condition: discharge versus time provided as part of dataset.
  - Downstream boundary condition: free outfall (critical flow).
- 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: 2 m (or ~97000 nodes in the 0.388 km2 area modelled)
- Simulation start time = 0 hours.
- Simulation end time = 5 hours.

10.3 Hydraulic Results

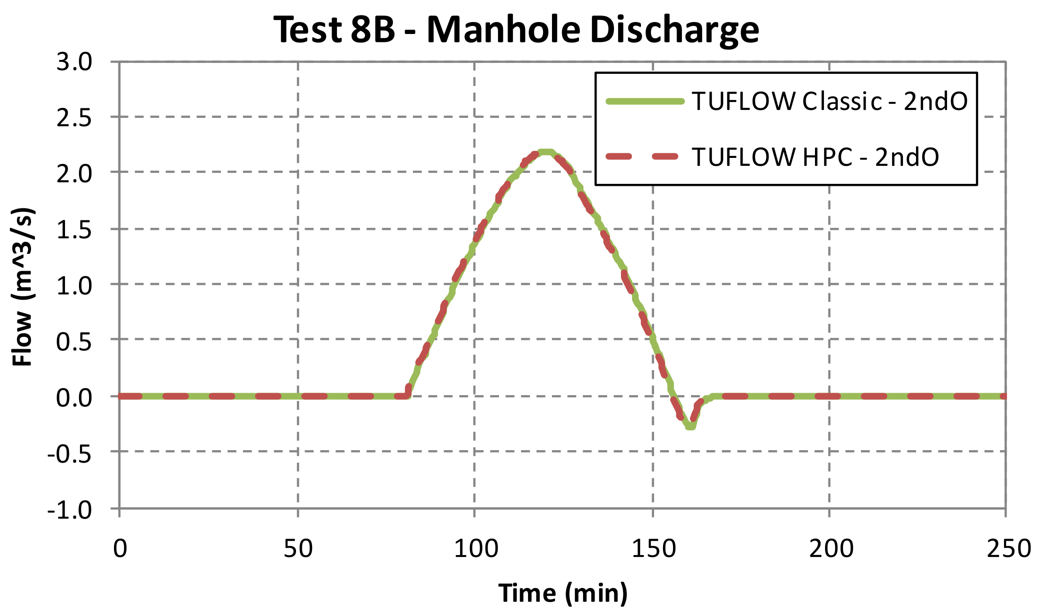
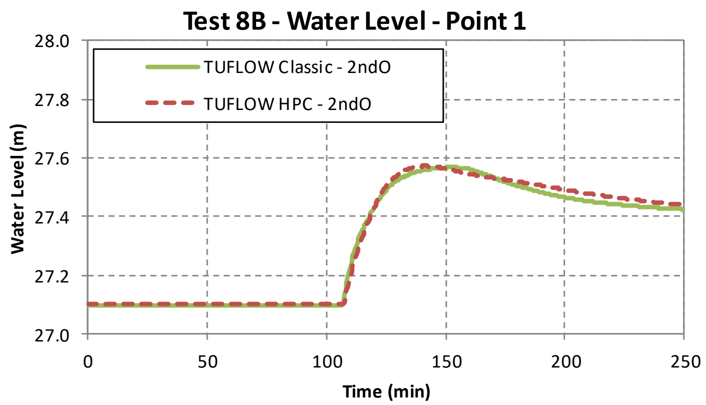
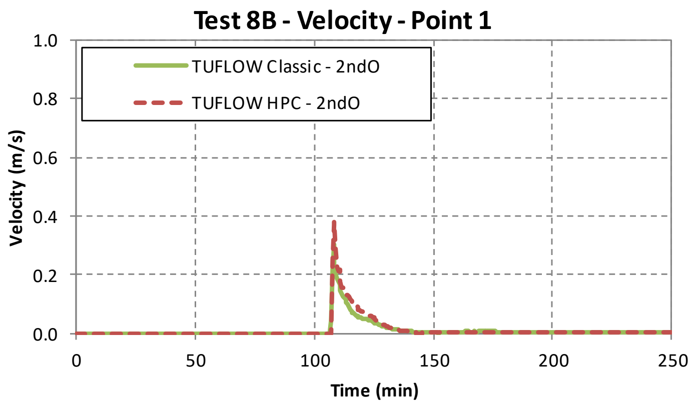
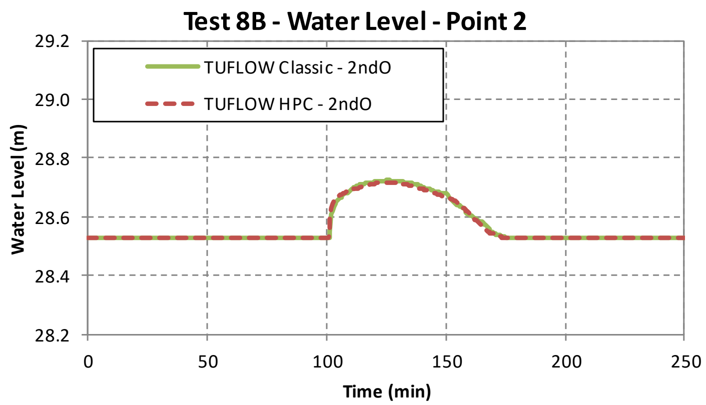
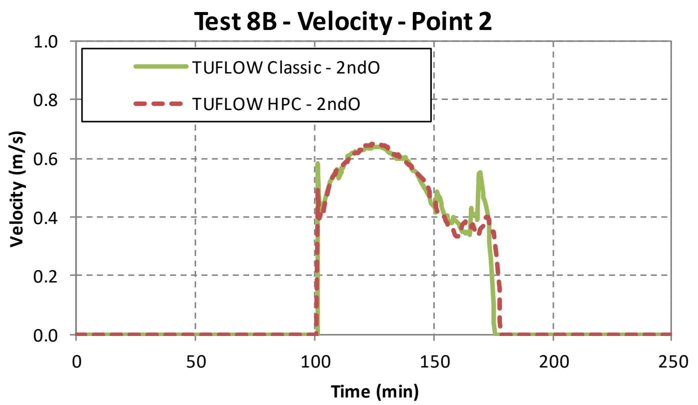
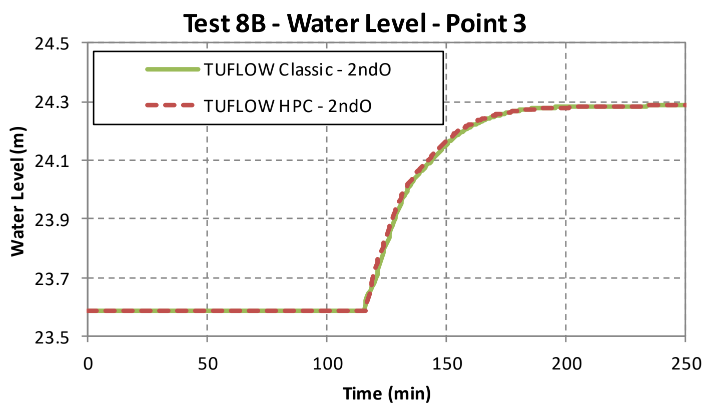
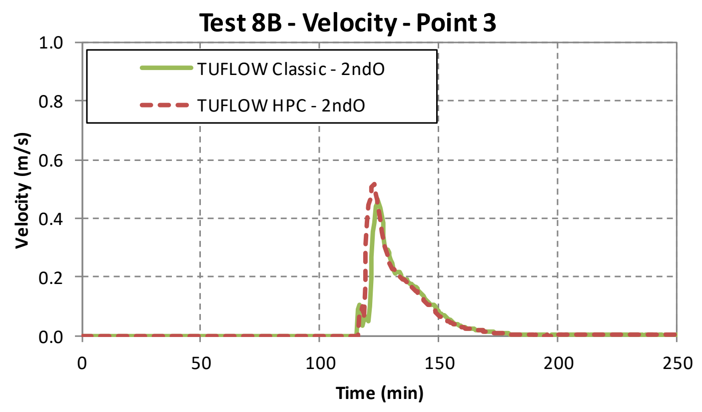
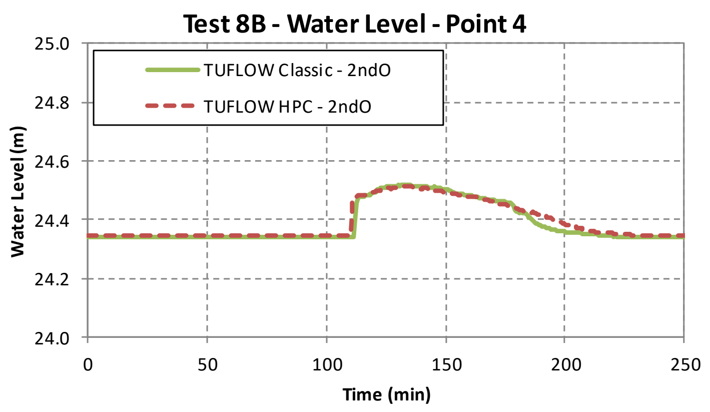
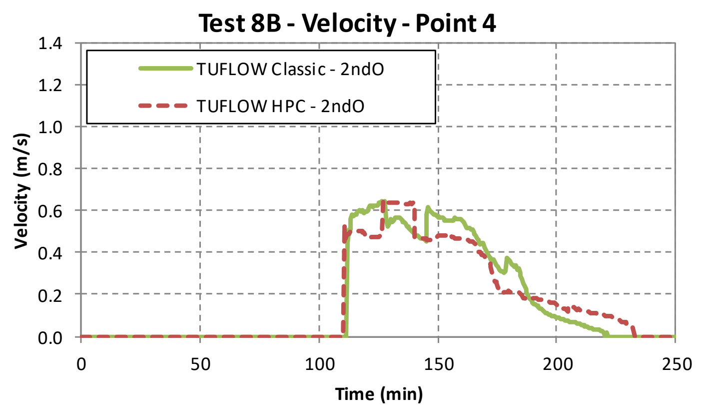
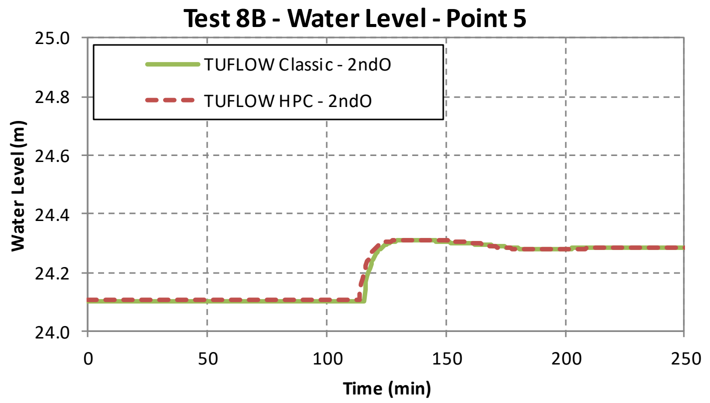
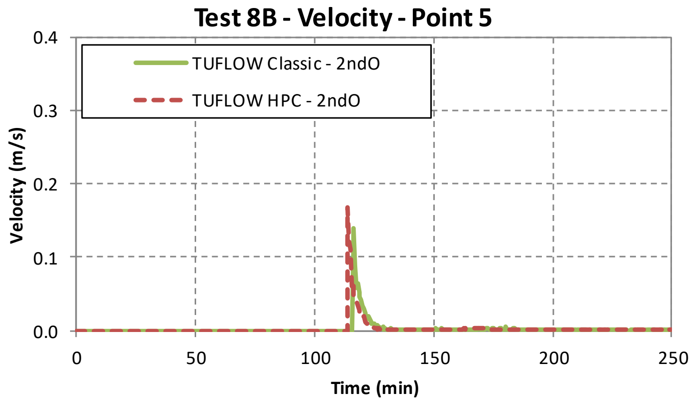
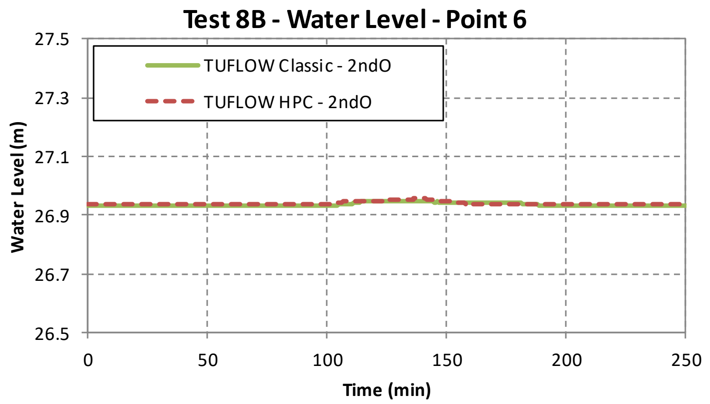
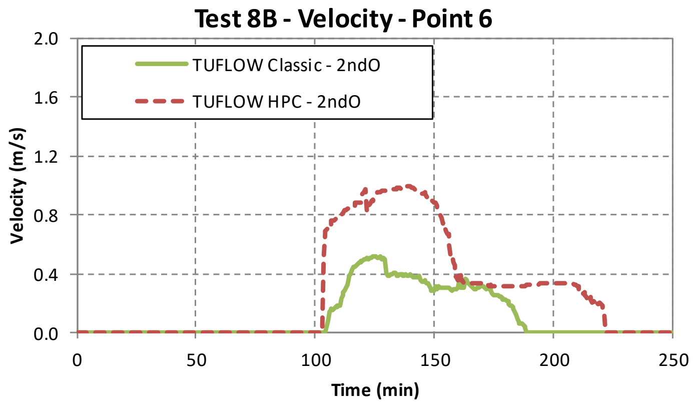


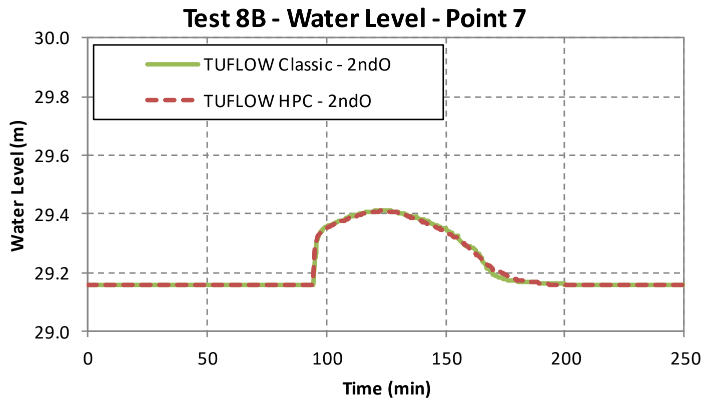
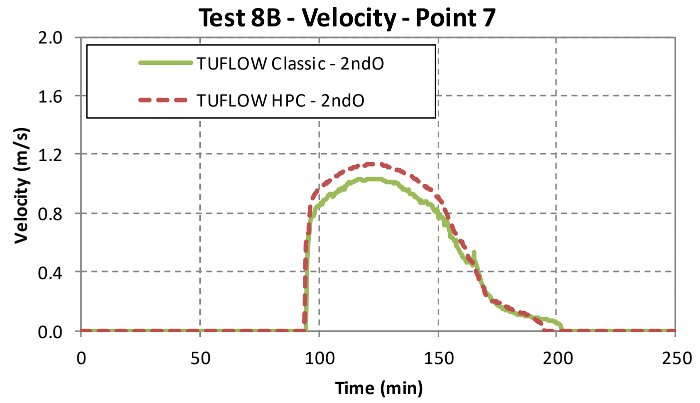
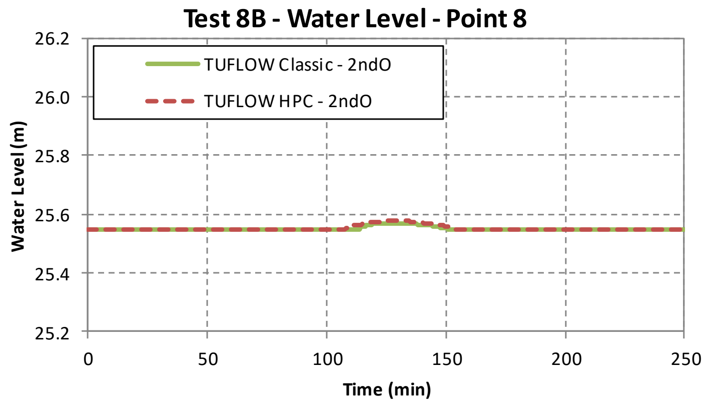
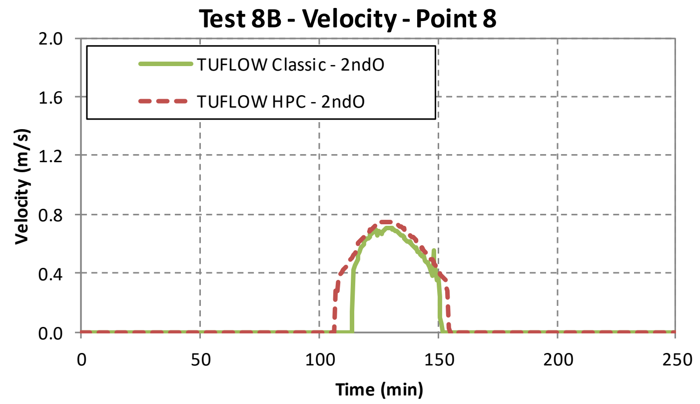
Figure 25 Manhole Discharge

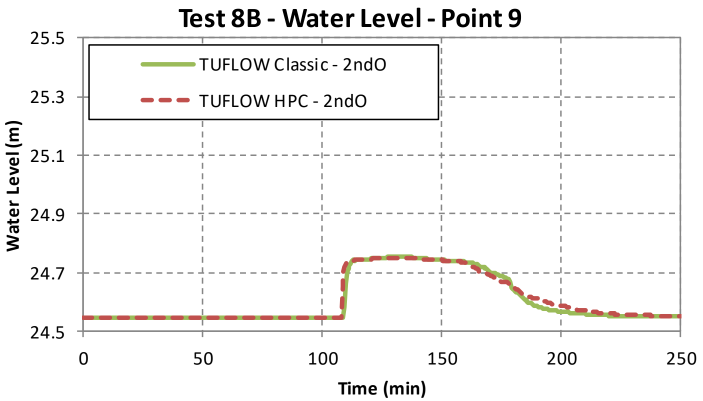
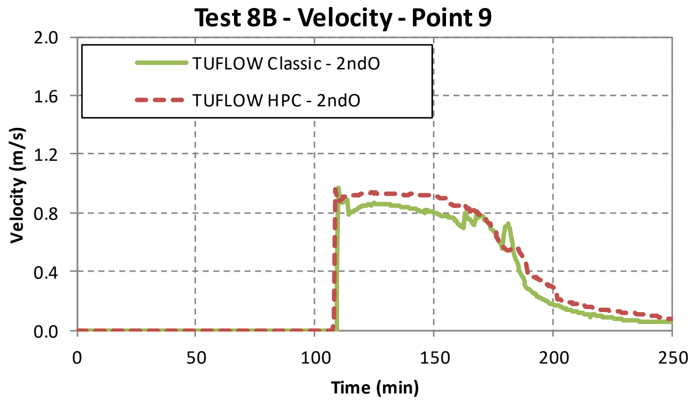
Table 28 Test 8B Point Location Results

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 23		
Refer to Figure 23Figure 19		

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 23		
Refer to Figure 23		

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 23		
Refer to Figure 23		

Reporting Location	Water Level Model Result	Velocity Model Result
Refer to Figure 23		
Refer to Figure 23		

<table>
<tr><th>Reporting Location</th><th>Water Level Model Result</th><th>Velocity Model Result</th></tr>
<tr><td>Refer to Figure 23</td><td>
</td><td>
</td></tr>
</table>

10.4 Simulation Summary Table

Table 29 Test 8A Simulation Summary Table

<table>
<tr><th></th><th>TUFLOW Classic (2nd Order)</th><th>TUFLOW HPC (2nd Order)</th><th>TUFLOW GPU (1st Order)</th><th>TUFLOW FV (1st Order)</th><th>TUFLOW FV (2nd Order)</th></tr>
<tr><td colspan="6">Software Version: Refer to Table 3.
Double Precision (DP) build was used for TUFLOW Classic.
TUFLOW HPC used Single Precision (SP)</td></tr>
<tr><td colspan="6">Hardware Used: Refer to Table 4</td></tr>
<tr><td colspan="6">Minimum recommended hardware for a simulation of this type: Refer to Table 4</td></tr>
<tr><td>Multi-processing</td><td>No</td><td>Yes
3584 GPU Cores</td><td rowspan="5">Not used as no 1D linking.</td><td colspan="2" rowspan="5">Not used as no 1D linking (yet).</td></tr>
<tr><td>Manning's n used</td><td>0.02 roads, 0.05 elsewhere</td><td>0.02 roads, 0.05 elsewhere</td></tr>
<tr><td>Grid resolution</td><td>2m</td><td>2m</td></tr>
<tr><td>Time-stepping</td><td>1.5s</td><td>Adaptive (0.5 to 0.9s)</td></tr>
<tr><td>Total simulation time (hrs)</td><td>0.037 (133s)</td><td>0.013[1] (45s)</td></tr>
<tr><td colspan="6">[1]Refer to note on TUFLOW HPC and GPU Module run times in Section 11, “Overall Summary of Performance”</td></tr>
</table>

11 Overall Summary of Performance

The table below lists common Environment Agency applications and the predictions required to accurately assess them. It shows which benchmark tests can be used to prove the predictions required can be achieved.

Table 30 Environment Agency Appropriate Application Summary Table

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.

TUFLOW Classic, TUFLOW HPC (CPU and GPU), TUFLOW GPU (superseded in 2017 by TUFLOW HPC) and TUFLOW FV are suitable for all of the above applications. They have demonstrated consistent results between each other, and their results are consistent or superior to the other fully dynamic schemes presented in the 2012 UK EA report.

The TUFLOW software developers provide the following comments:

- Enhancements to TUFLOW since 2010 have significantly improved the prediction of peak velocities for dambreak modelling.
- TUFLOW HPC is particularly well suited to dambreak modelling due to its unconditional stability, finite volume shock capturing and very fast run times for large models if using GPU hardware.
- Improvements to the GPU scheme since the 2012 UK EA Report have resulted in the development of TUFLOW HPC. Compared to the original TUFLOW GPU solver, referred to in this document as TUFLOW GPU, TUFLOW HPC includes the following improvements:

(1) By default, uses a higher 2nd order spatial scheme. A 1st order spatial scheme is also available, however, is not recommended especially for complex, highly transient, flows.

(2) Improved cell discretisation using cell mid-side elevation points in addition to cell centred elevations allowing higher resolution sampling of elevations and land-use, and the specification of thin breaklines (i.e. same as TUFLOW Classic). TUFLOW GPU, TUFLOW FV and other 2D schemes typically use one elevation per element.

(3) Automatic switching to upstream controlled flow regimes (weir or super-critical flows) across cell mid-sides.

(4) Full 1D/2D link functionality.

(5) Full dynamic coupling with TUFLOW's 1D pipe network and open channel solver ESTRY and other 1D schemes in the same manner as for TUFLOW Classic.

- The simulation times for TUFLOW HPC and TUFLOW GPU are not indicative of the significant GPU hardware speed gains achieved for larger models. For short simulation models, the time transferring memory between the GPU card and CPU can be a considerable portion of the run time. For large models (>1,000,000 cells), TUFLOW HPC and GPU are typically 10 to 100 times faster than TUFLOW "Classic" depending on the GPU card specifications and the type of model.

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