US Army Corps
of Engineers
Hydrologic Engineering Center

Benchmarking of the HEC-RAS Two-Dimensional Hydraulic Modeling Capabilities

April 2018

RD-51

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* April 2018	**2. REPORT TYPE** Research Document	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Benchmarking of the HEC-RAS Two-Dimensional Hydraulic Modeling Capabilities	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Gary W. Brunner, CEIWR-HHT	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5F. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S .Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (CEIWR-HEC) 609 Second Street Davis, CA 95616-4687	**8. PERFORMING ORGANIZATION REPORT NUMBER** RD-51
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/ MONITOR'S ACRONYM(S)**
	11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research document summarizes how the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) software performed in the two-dimensional (2D) modeling benchmark tests developed by the United Kingdom's (UK) Joint Defra (Department for Environmental Food and Rural Affairs) Environment Agency. These tests were developed under Defra's Flood and Coastal Erosion Risk Management Research and Development (R&D) program's two-dimensional research project. The purpose of performing these tests with HEC-RAS is to demonstrate that the HEC-RAS two-dimensional modeling capabilities can produce similar results to the two-dimensional models documented by the United Kingdom Environmental Agency research report.

These Tests were run with HEC-RAS version 5.0.4.

15. SUBJECT TERMS
HEC-RAS; River Analysis System; HEC; Hydrologic Engineering Center; two-dimensional; R&D; research & development; United Kingdom; research project; models; hydraulic; benchmarking; test; grid cell sizes; grid; bathymetry; cell face; terrain; elevation; flow solver; time steps; result; water surface; velocities; computational interval

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
U	U	UU	UU	148	**19b. TELEPHONE NUMBER**

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

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Chapter 1

Overview

This research document summarizes how the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) software performed in the two-dimensional (2D) modeling benchmark tests developed by the United Kingdom's (UK) Joint Defra (Department for Environmental Food and Rural Affairs) Environment Agency. These tests were developed under Defra's Flood and Coastal Erosion Risk Management Research and Development (R&D) program's two-dimensional research project. The title of the report is "Delivering Benefits through Evidence - Benchmarking the latest generation of 2D hydraulic modeling packages" (Report - SC120002), published in August 2013.

A direct comparison of the HEC-RAS results to the plots shown in the report are contained in Appendix A of this document.

To obtain a copy of the official report, you can contact the United Kingdom Environment Agency at fcerm.evidence@environment-agency.gov.uk, or download the report from:

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

The United Kingdom Environmental Agency states the following about the set of benchmark tests:

"The overall objectives of this research are to provide:

- *an evidence base to ensure that 2D flood inundation modelling packages used for flood risk management by the Environment Agency and its consultants are capable of adequately predicting the variables on which flood risk management decisions are based*
- *a data set against which such packages can be evaluated by their developers"*

The purpose of performing these tests with HEC-RAS is to demonstrate that the HEC-RAS two-dimensional modeling capabilities can produce similar results to the leading two-dimensional models documented by the United Kingdom Environmental Agency research report.

This research document also shows the utility of the HEC-RAS two-dimensional capabilities for producing similar results for larger grid cell sizes, due to the software's ability to utilize the detailed subgrid bathymetry for developing detailed cell and cell face property tables (HEC-RAS 2D Modeling User's Manual, Version 5.0, February 2016). The use of detailed hydraulic property tables takes into account all the details of the underlying terrain which allows HEC-RAS to use larger grid cells than models that reduce each cell down to a single average elevation and each cell face to a straight line. This capability is demonstrated in the results of Benchmark Tests 4, 5, 7, and 8. In addition, Benchmark Test 5 was used to demonstrate that the HEC-RAS two-dimensional flow solver has the ability to use an extremely wide range of time steps and converge to the same result. Benchmark Test 5 was run with time steps of 10, 5, 2, and 1 seconds. Result plots for water surface and velocities are shown at multiple locations. The results demonstrated that HEC-RAS can converge to a result as the computational interval is reduced.

Note: The text and figures in this research document that describe the benchmark test cases were taken from the United Kingdom Environmental Agencies Model specifications document for each benchmark test.

The benchmark tests were run using version 5.0.4 of HEC-RAS in April 2018. The benchmark tests were configured and simulated by Mr. Gary Brunner of the HEC-RAS team and Table 1 contains a description of the computer hardware used to run the benchmark tests. Table 2 contains a list and description of the benchmark tests.

Table 1. Hardware Specifications

Minimum recommended hardware specifications	
Make:	Windows based or compatible PC
Model:	No restrictions
Type:	No restrictions
CPU Cores:	One required, but four or more recommended
RAM:	2GB
Operating Systems:	Windows XP, 7, 8, and 10
CPU Processing:	32 or 64 bit
Graphics Card:	No restrictions
Hardware specifications used to carry out tests	
Make:	Dell
Model:	Precision T5610; Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode
Type:	Desktop
CPU Cores:	8
RAM:	16 GB
Operating System:	Windows 7 Professional
CPU Processing:	64 bit
Graphics card:	N/A No restrictions

Table 2. United Kingdom Environmental Agency Tests

Test	**Description**	**Test Completed/reason for not completing**
1	Flooding a disconnected water body	yes
2	Filling of floodplain depressions	yes
3	Momentum conservation over a small obstruction	yes
4	Speed of flood propagation over an extended floodplain	yes
5	Valley flooding	yes
6A	Flume Scale Dambreak	yes
6B	Full Scale Dambreak	yes
7	River and floodplain linking	yes
8A	Rainfall and point source surface flow in urban areas	yes
8B	Surface flow from a surcharging sewer in urban areas	No; HEC-RAS does not currently have the option to perform combined 2D surface flow connected to subsurface pipe flow

Chapter 2

Benchmark Test 1

Flooding a Disconnected Water Body

2.1 Objective

The objective of Benchmark Test 1 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 modeled domain is a perfect 700 meter x 100 meter rectangle. A varying water level (see Figure 2) is applied as a boundary condition along the entire length of the left-hand side of the rectangle, causing the water to rise to level 10.35 meters. This elevation is maintained long enough for the water to fill the depression and become horizontal over the entire domain. The water 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 (10.25 meters).

2.3 Boundary and Initial Conditions

- Varying water level along the red dashed line shown in Figure 1 (figures provided as part of the test input dataset).
- All other boundaries closed.
- Initial condition: water elevation equals 9.7 meters.

2.4 Parameter Values

- Manning's n equals 0.03 (uniform).
- Model grid resolution equals 10 meters (or 700 nodes in modeled area).
- Time of end: Model is to be run until time T equals twenty hours.

2.5 Results

Results for Benchmark Test 1 were extracted at Points 1 and 2 as shown in Figures 3 and 4. Table 3 provides additional information for Benchmark Test 1. HEC-RAS performed extremely well compared to the leading 2D models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK. The HEC-RAS results were right in the middle of the results from these models.

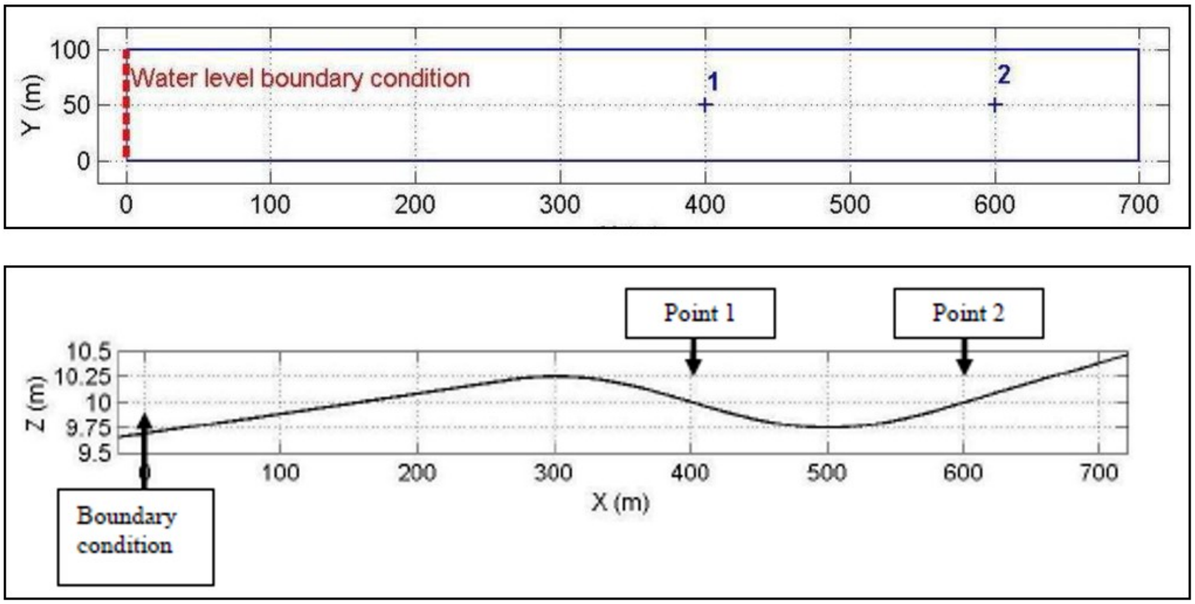


Figure 1. Plan and profile of DEM (digital elevation model) used in Benchmark Test 1. The area modeled is a perfect rectangle extending from X = 0 to X = 700 meters and from Y = 0 to Y = 100 meters as shown.

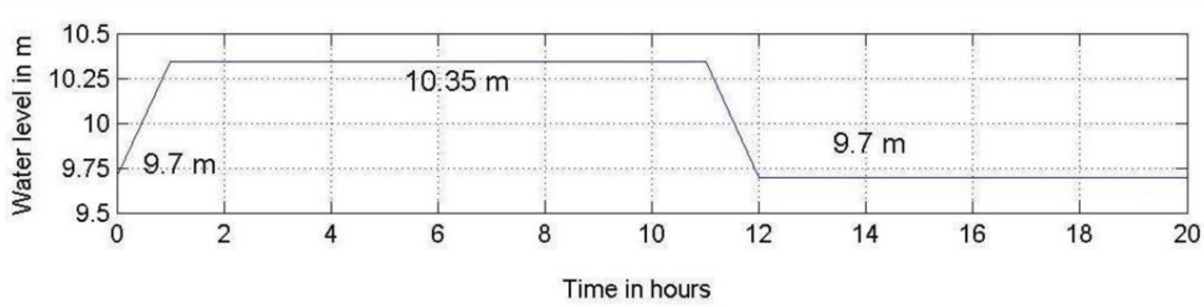


Figure 2. Water level hydrograph used as a boundary condition.

Table 3. Benchmark Test 1 Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	Variable Time Step (20 seconds starting value)
Grid resolution (or number of cells)	10 meters x 10 meters; 700 cells
Total computational time	3 seconds

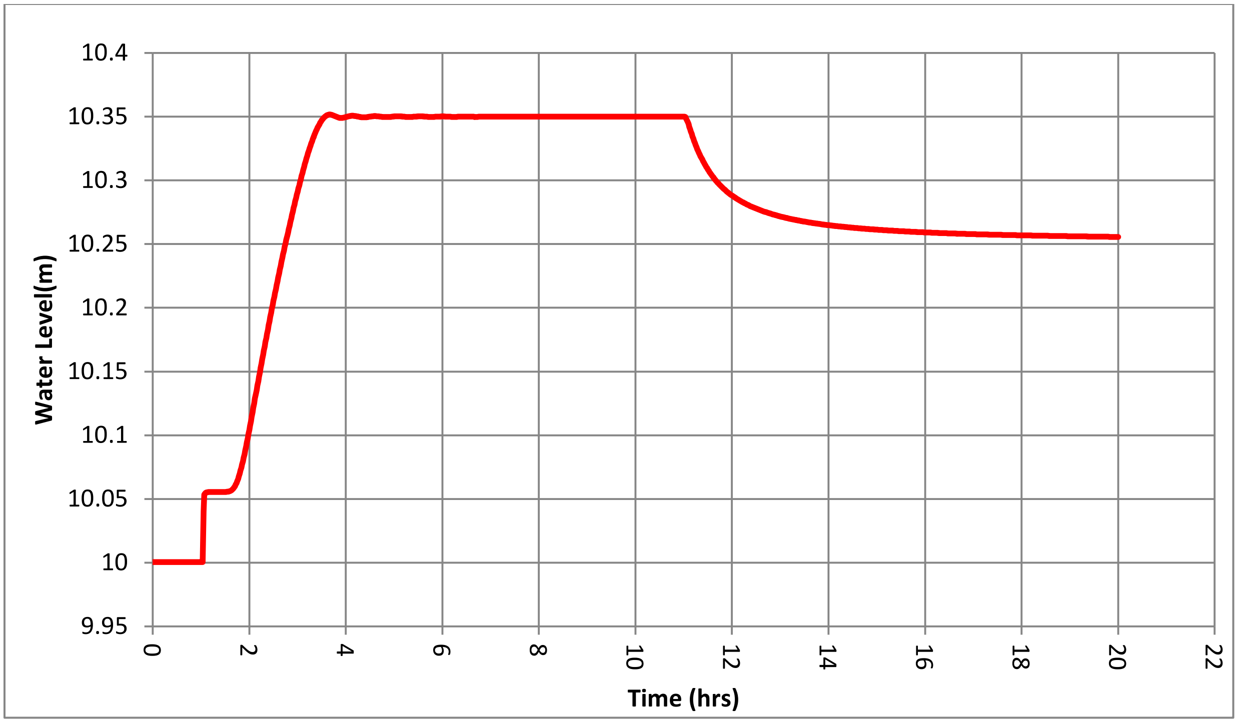


Figure 3. Test Point 1 - Water Level versus Time (output frequency 60 seconds).

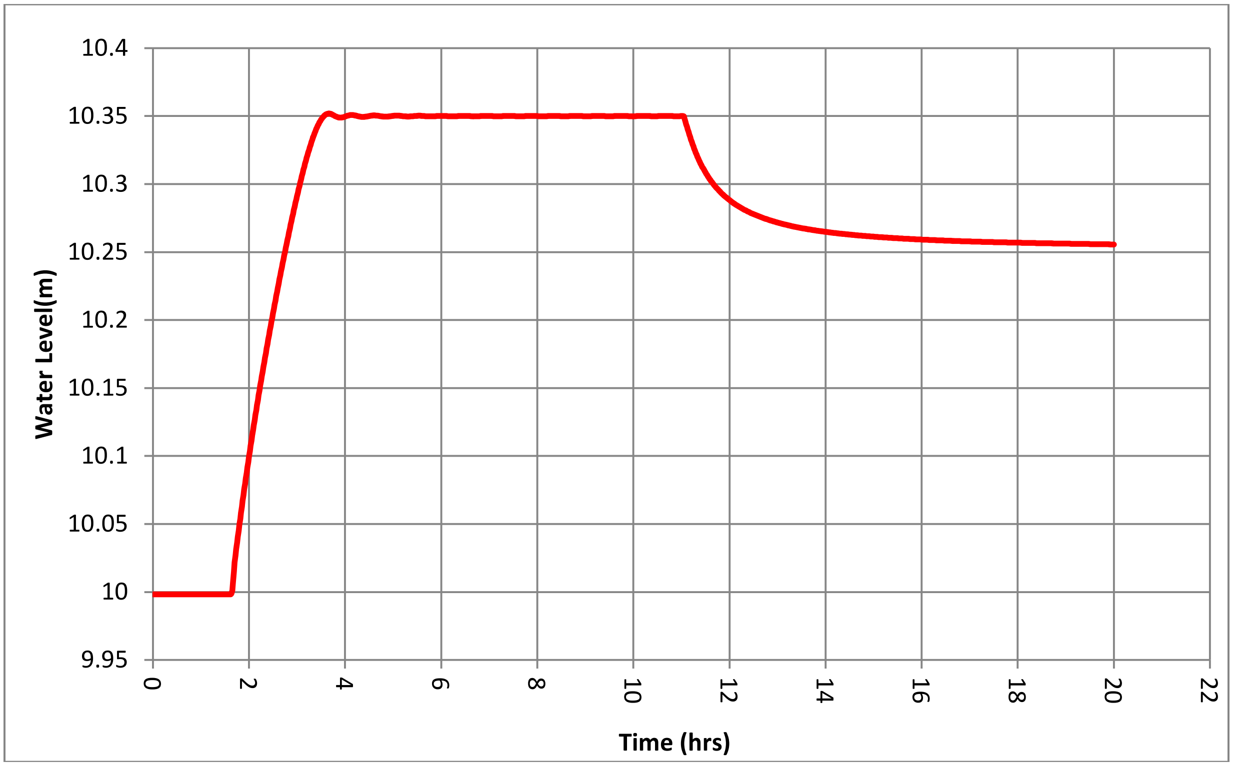


Figure 4. Test Point 2 - Water Level versus Time (output frequency 60 seconds).

Chapter 3

Benchmark Test 2

Filling of Floodplain Depressions

3.1 Objective

Benchmark Test 2 has been designed to evaluate the capability of a two-dimensional model to determine inundation extent and final flood depth, in a case involving low momentum flow over a complex topography.

3.2 Description

The area modeled, shown in Figure 5, is a perfect 2000 meter x 2000 meter square and consists of a 4 x 4 matrix of approximately 0.5 meter deep depressions with smooth topographic transitions. The DEM (digital elevation model) was obtained by multiplying sinusoids in the North to South and West to East directions and the depressions are all identical in shape. An underlying average slope of 1:1500 exists in the North to South direction, and of 1:3000 in the West to East direction, with approximately a two meter drop in elevation along the North-West to South-East diagonal. The inflow boundary condition is applied along a 100 meter line running South from the North Western corner of the modeled domain (see Figure 6). A flood hydrograph with a peak flow of 20 m^3/s and time base of approximately 85 minutes is used (Figure 6). The model is run for two days (48 hours) to allow the inundation to settle to its final state.

3.3 Boundary and Initial Conditions

- Inflow along the red line in Figure 5 (location and tables provided as part of dataset).
- All other boundaries are closed.
- Initial condition: Dry bed.

3.4 Parameter Values

- Manning's n: 0.03 (uniform)
- Model grid resolution: 20 meters (or approximately 10,000 nodes in the area modeled)
- Time of end: model is to be run until time t equals 48 hours

3.5 Results

Results shows that water did not make it to all the depressions on the right side of the modeling domains as water was stored in Depressions 1 through 10, excluding Depression 9. Water level versus time plots are shown in Figures 7 through 17, for both Full Saint Venant and Diffusion wave equations sets. HEC-RAS performed extremely well compared to the leading 2D models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK. The HEC-RAS results were right in the middle of the results from these models. The only locations with a difference was the Diffusion wave results at location 10 were a little lower than the models running the full equations. This is due to the fact that the diffusion wave equations do not include the acceleration terms, which would have provided more momentum in moving the flow towards location 10.

Note: Water level versus time (output frequency 300 seconds).

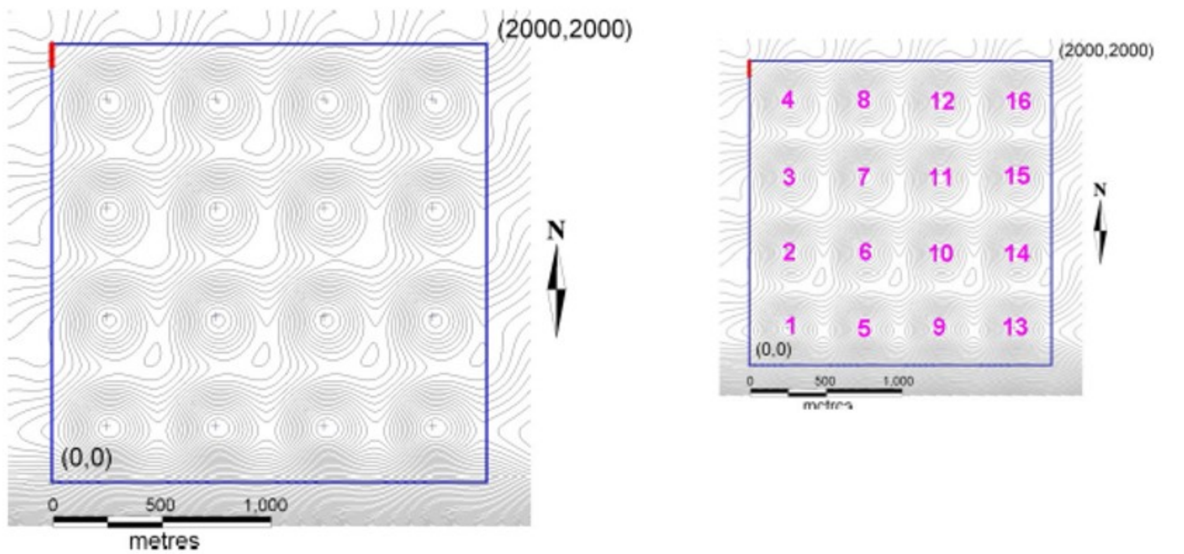


Figure 5. Map of the DEM showing the location of the upstream boundary condition (red line), ground elevation contour lines every 0.05 meters, and output point locations (numbers).

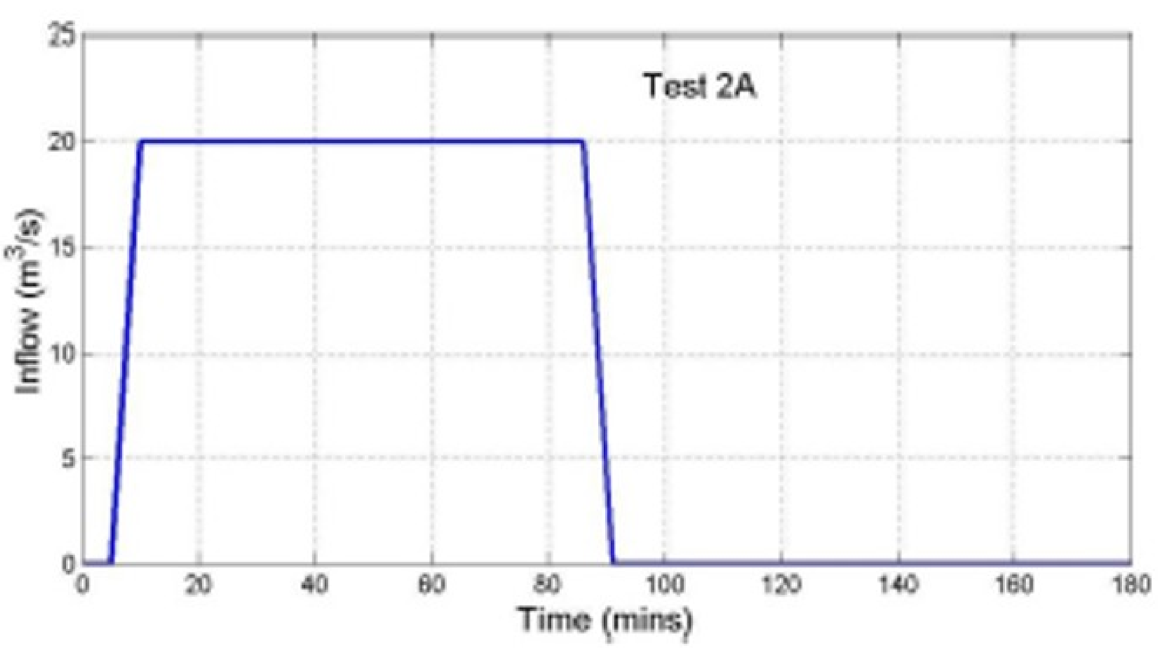


Figure 6. Inflow hydrograph used as upstream boundary condition.

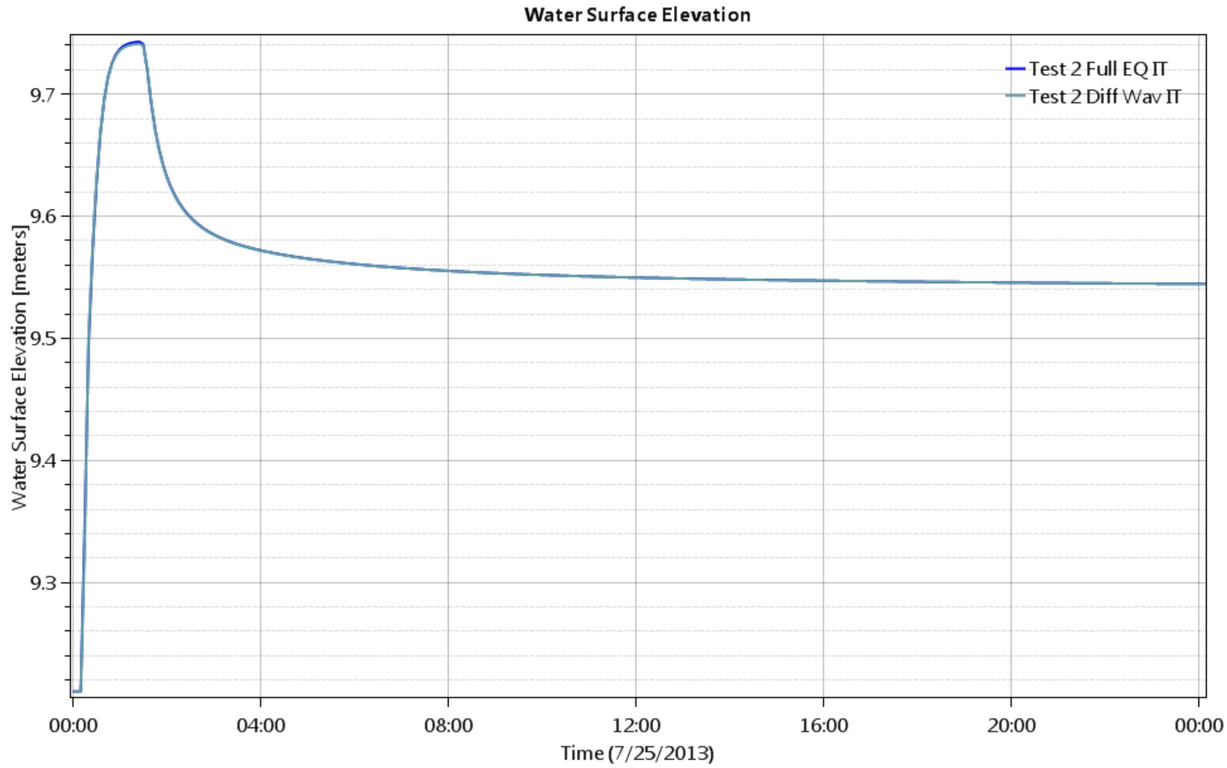


Figure 7. Test Point 4 - Water Level (m) versus Time (hrs).

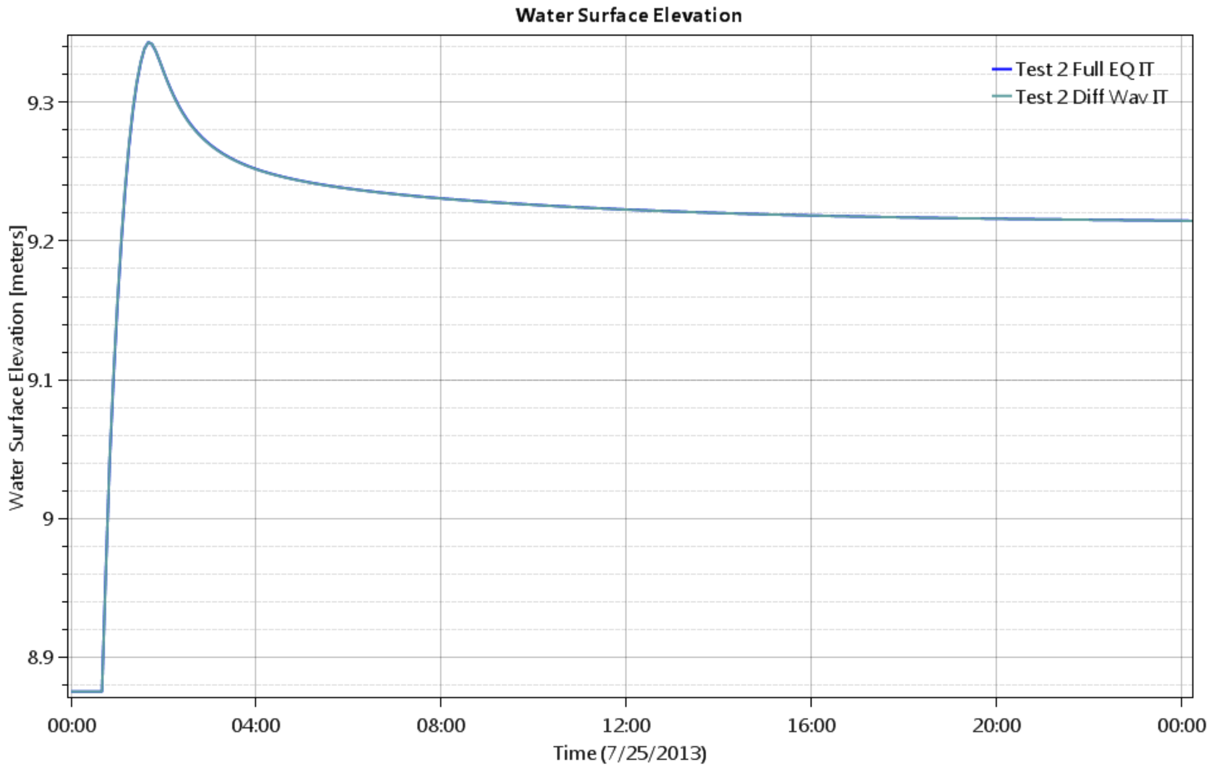


Figure 8. Test Point 3 - Water Level (m) versus Time (hrs).

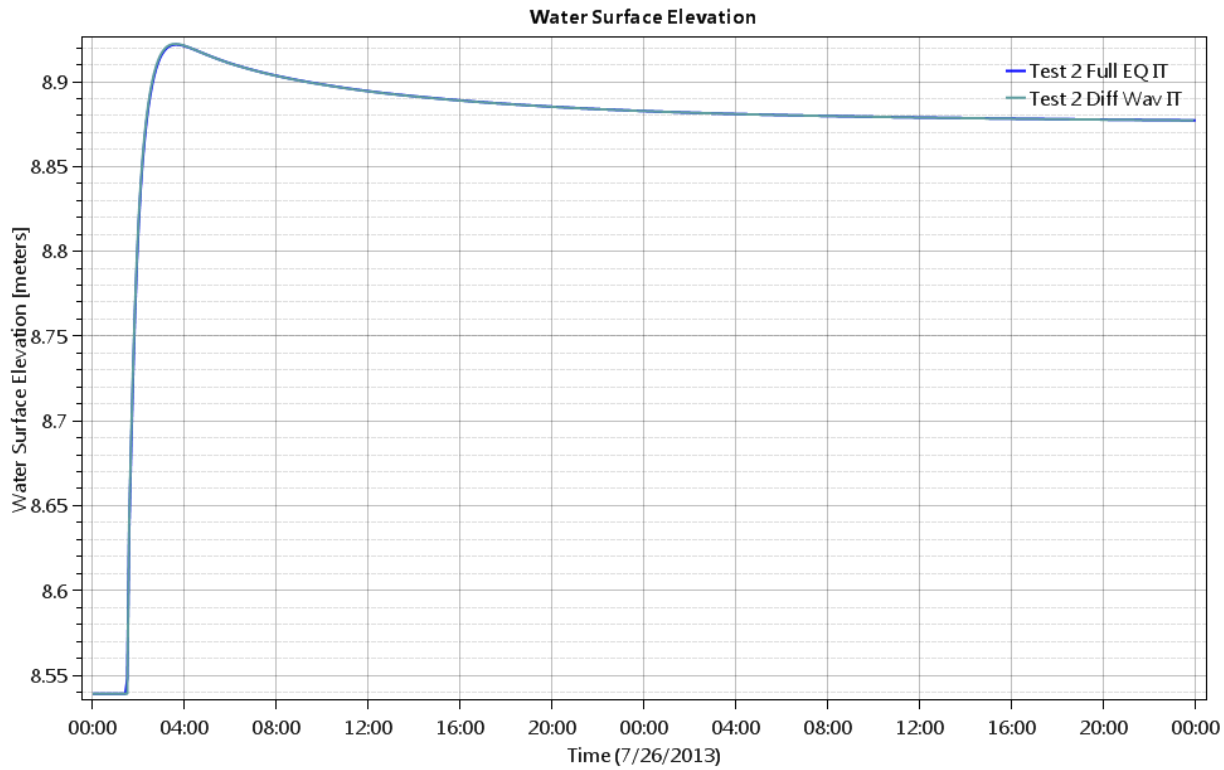


Figure 9. Test Point 2 - Water Level (m) versus Time (hrs).

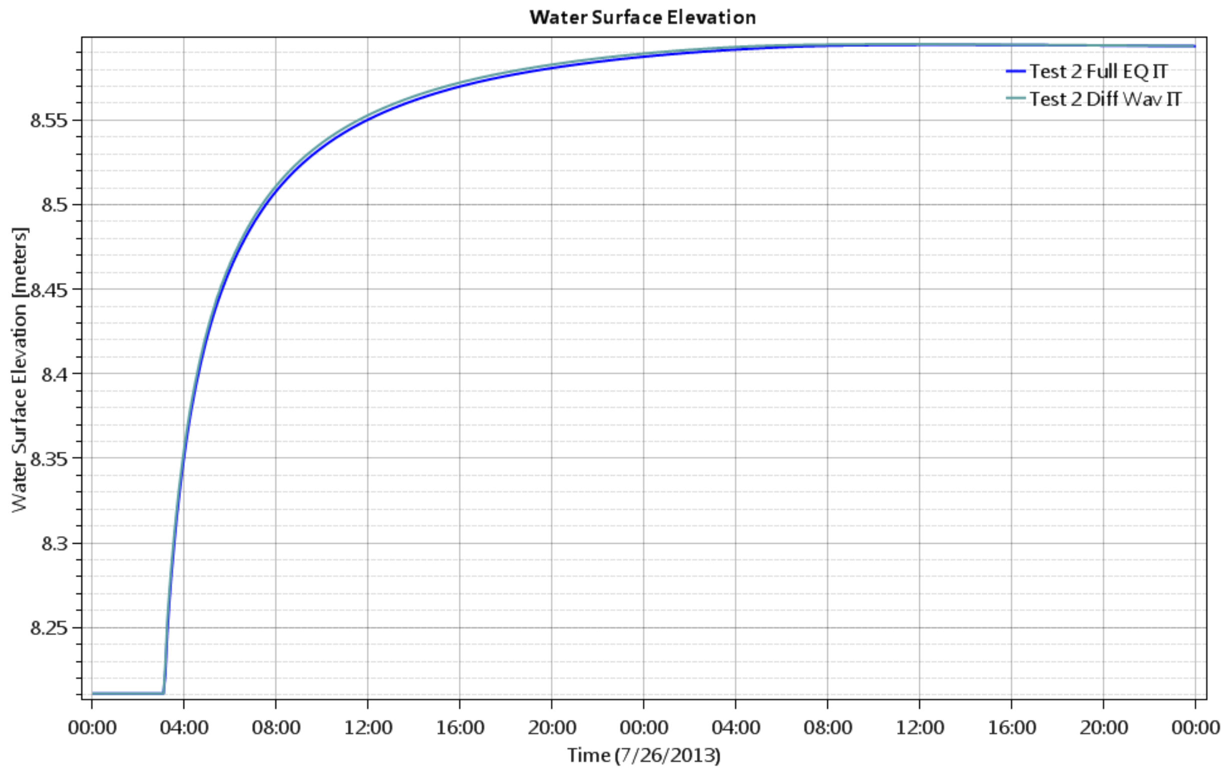


Figure 10. Test Point 1 - Water Level (m) versus Time (hrs).

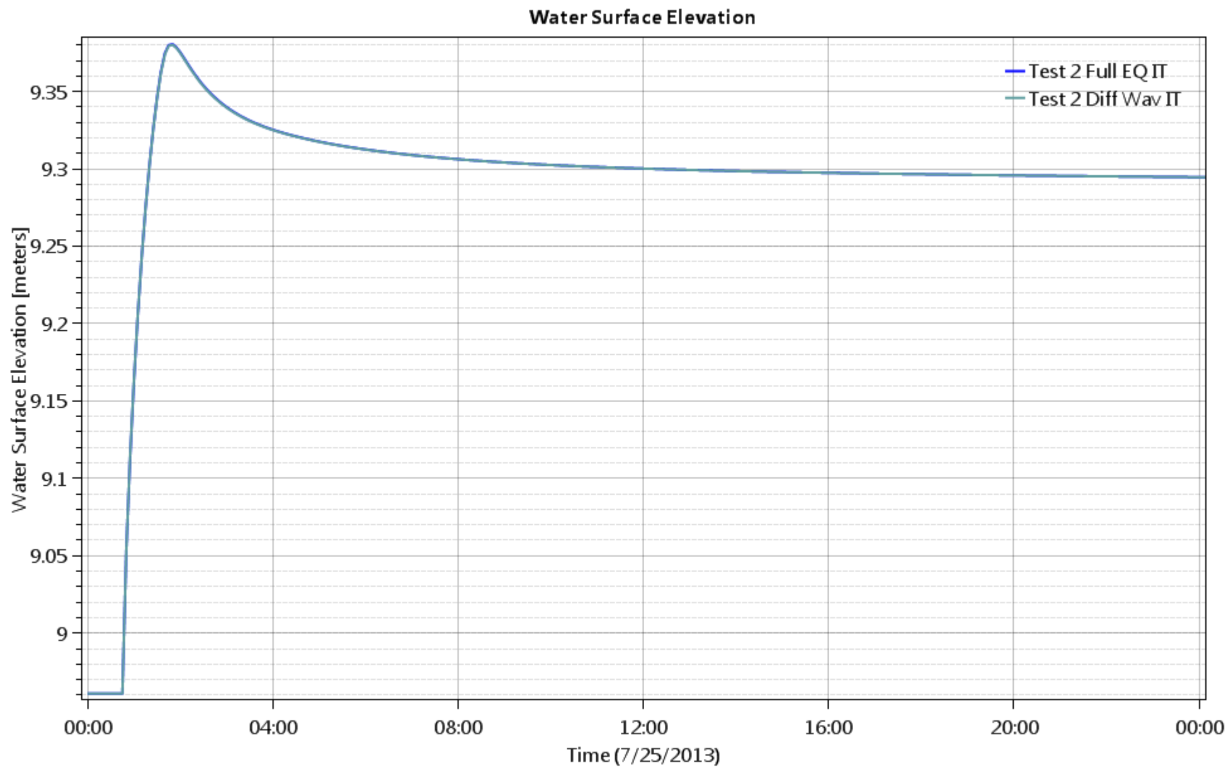


Figure 11. Test Point 8 - Water Level (m) versus Time (hrs).

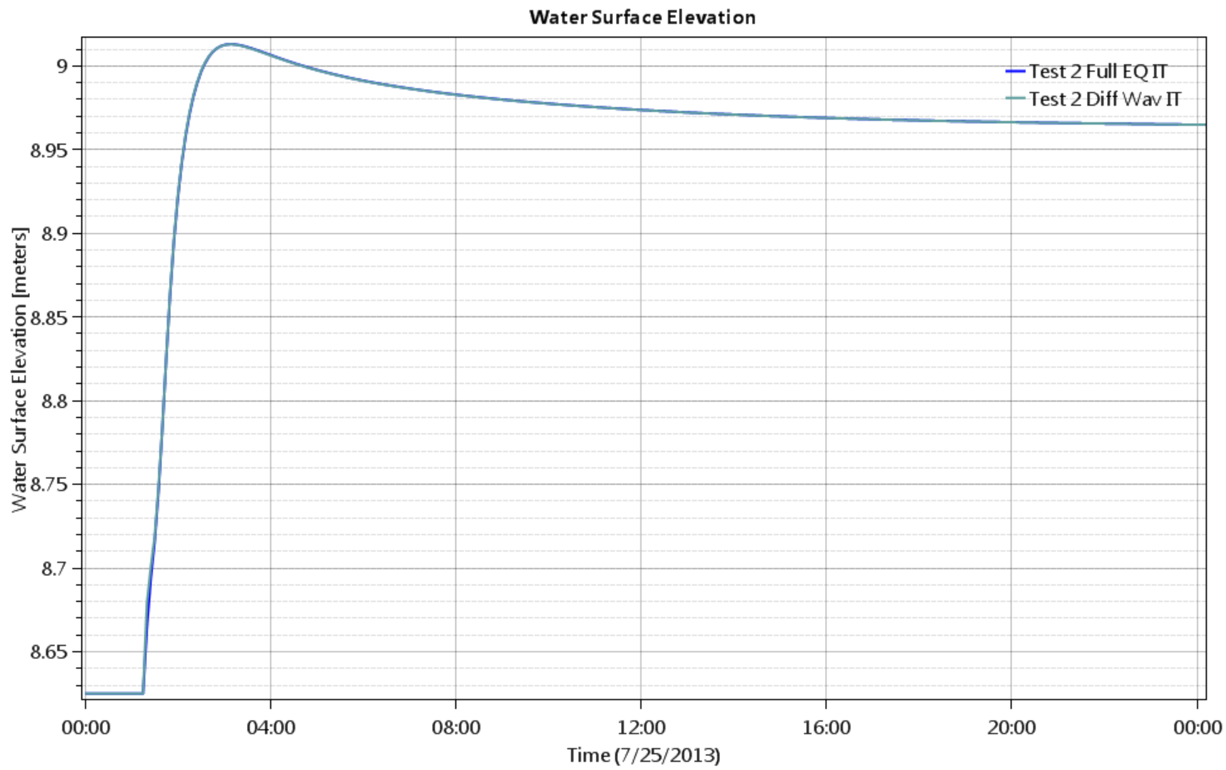


Figure 12. Test Point 7 - Water Level (m) versus Time (hrs).

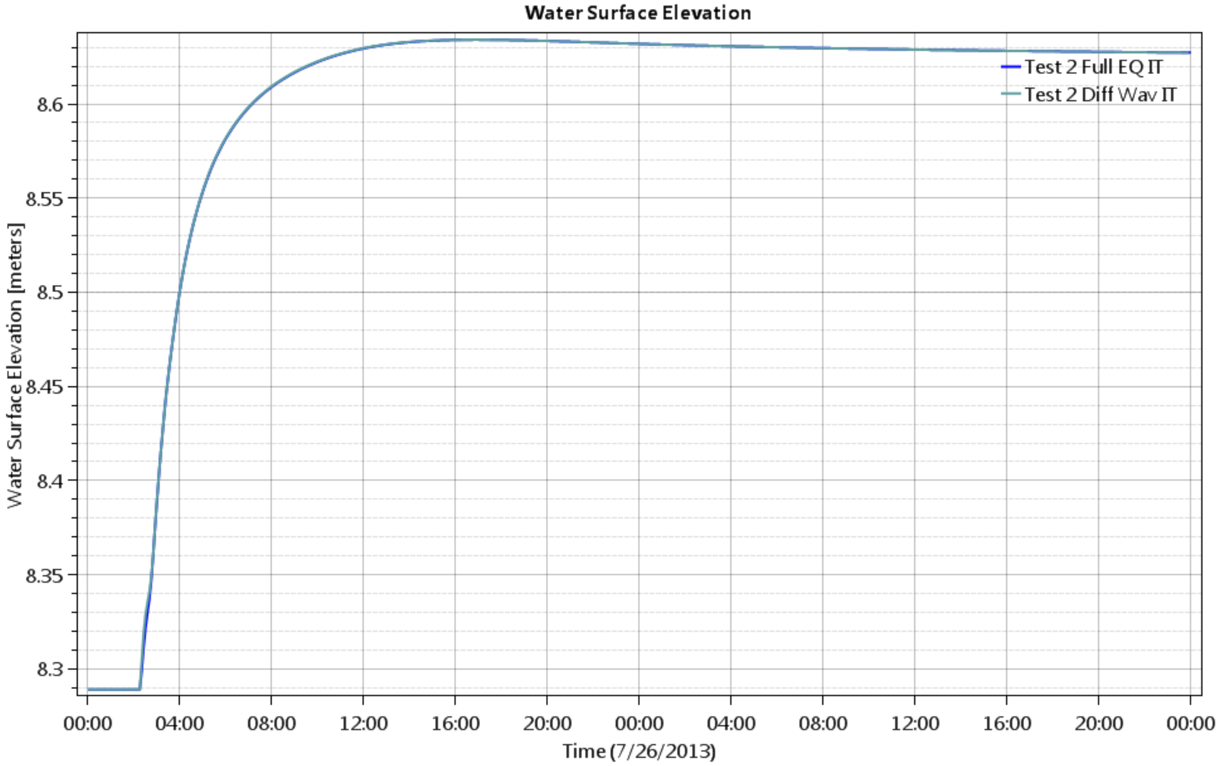


Figure 13. Test Point 6 - Water Level (m) versus Time (hrs).

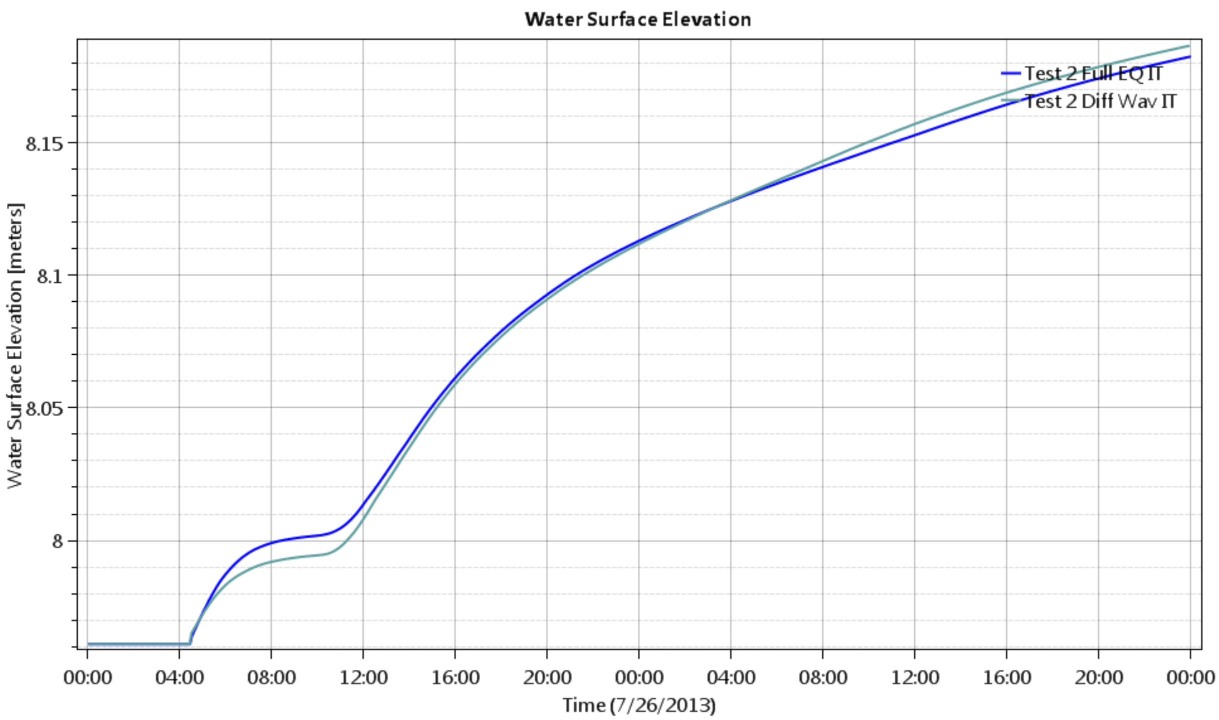


Figure 14. Test Point 5 - Water Level (m) versus Time (hrs).

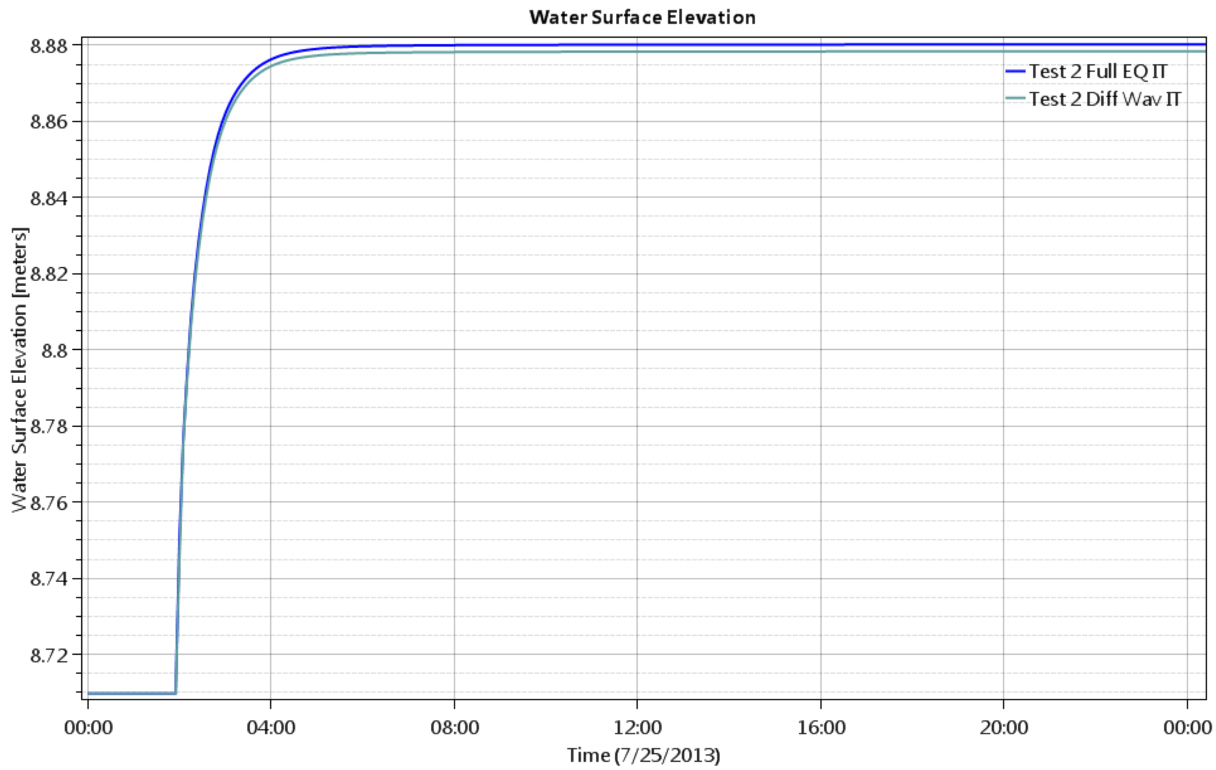


Figure 15. Test Point 12 - Water Level (m) versus Time (hrs).

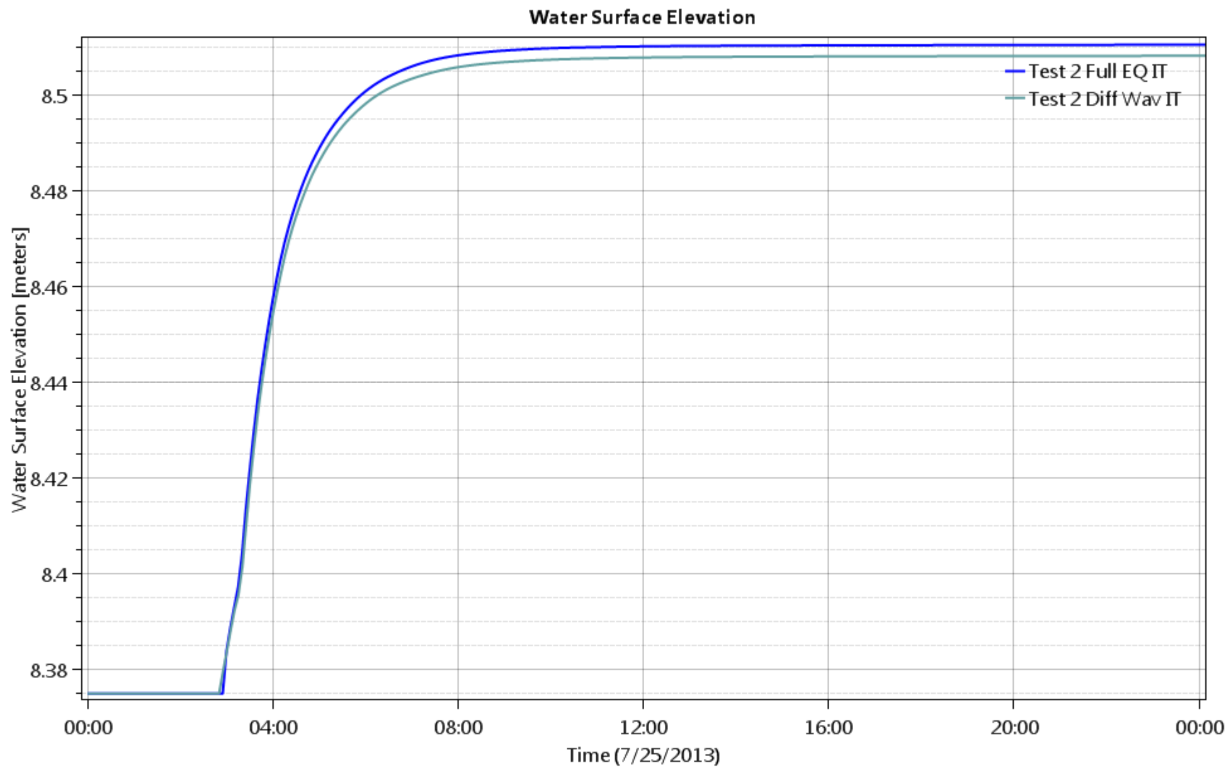


Figure 16. Test Point 11 - Water Level (m) versus Time (hrs).

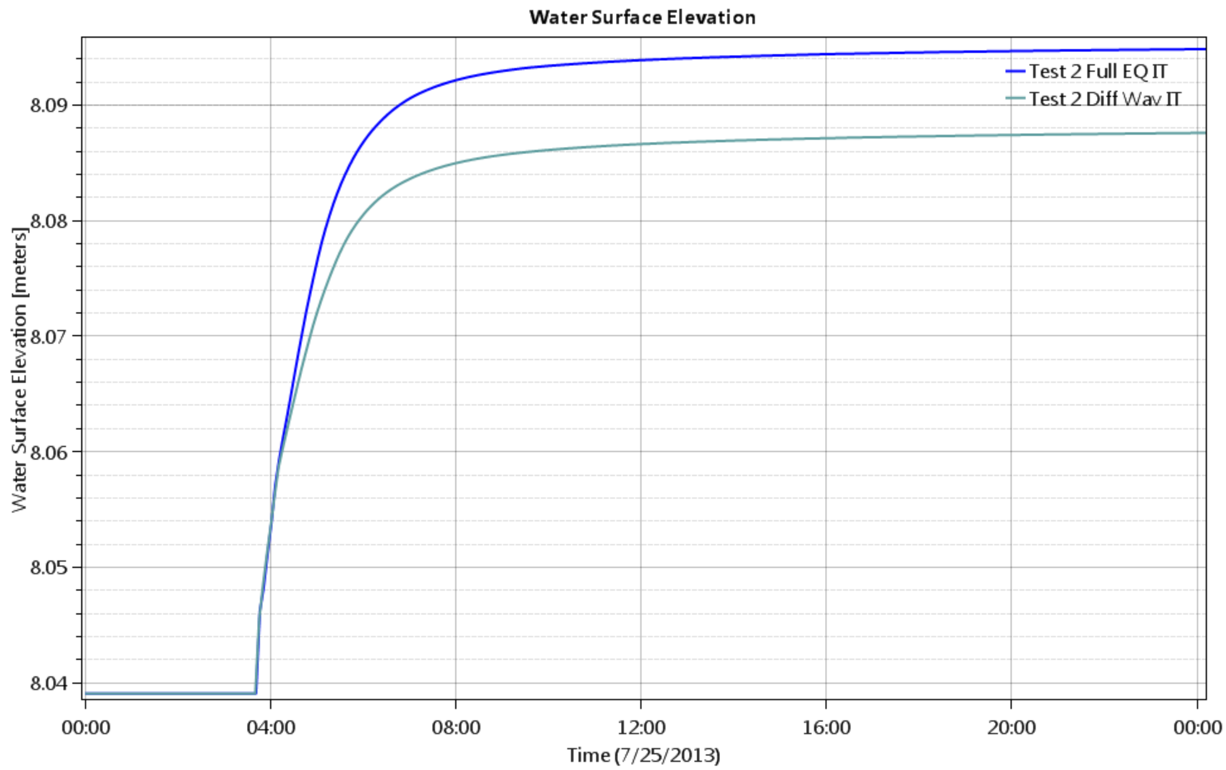


Figure 17. Test Point 10 - Water Level (m) versus Time (hrs).

Note: All other test point locations (9, 13, 14, 15, and 16) stayed dry.

Table 4. Benchmark Test 2 Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	Variable Time Step (30 seconds starting value)
Grid resolution (or number of cells)	20 meters x 20 meters; 10,000 cells
Total computational time	Full EQ: 30 seconds Diff Wav: 17 seconds

Chapter 4

Benchmark Test 3

Momentum Conservation over a Small Obstruction

4.1 Objective

The objective of Benchmark Test 3 is to assess the two-dimensional model's ability to conserve momentum over an obstruction in the topography. Momentum conservation is important when simulating sewer or pluvial flooding in urbanized floodplains. The barrier to the flow is designed to differentiate the performance of two-dimensional models without and with inertia terms. With inertia terms, some of the flood water will pass over the obstruction.

4.2 Description

This test consists of a sloping topography with two depressions separated by an obstruction as illustrated in Figure 18. The dimensions of the domain are 300 meters longitudinally (X) and 100 meters transversally (Y). A varying inflow (see Figure 19) 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 equals 150 meters, some of the volume is expected to overtop the obstruction because of momentum conservation and settle in the depression on the right-hand side at x equals 250 meters. The model is run until time T equals 900 seconds (15 minutes) to allow the water to settle.

4.3 Boundary and Initial Conditions

- Inflow boundary condition along the dashed red line in Figure 18 (table provided as part of the dataset).
- All other boundaries are closed.
- Initial condition: Dry bed.

4.4 Parameter Values

- Manning's n: 0.01 (uniform)
- Model grid resolution: 5 meters (or approximately 1,200 nodes in the area modeled)
- Time of end: model is to be run until T equals 15 minutes (900 seconds).

4.5 Results

Results for this test are shown in Figures 20 -23, and Table 5. Results for this test varied widely for the models show in the original Benchmark study. HEC-RAS performed extremely well compared to the leading 2D models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK. HEC-RAS results were in the middle of the results from these models.

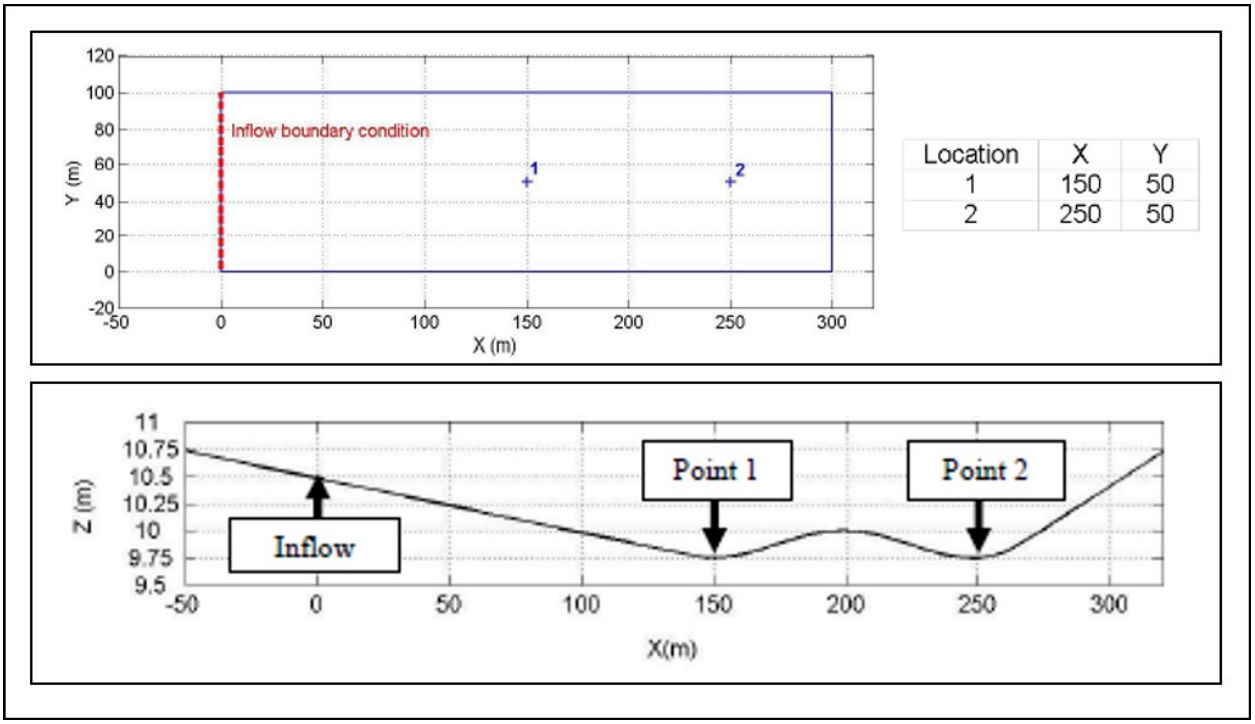


Figure 18. Profile of DEM used in Benchmark Test 3. The area modeled is a perfect rectangle extending from X = 0 to X = 300 meters and from Y = 0 to Y = 100 meters.

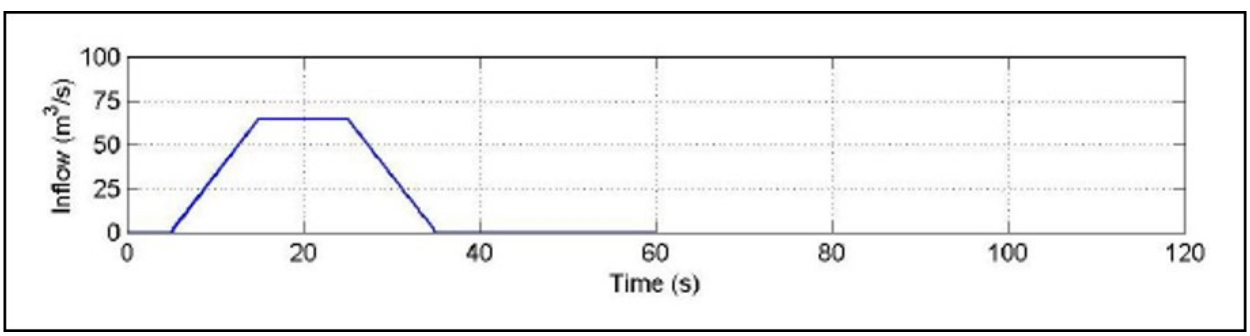


Figure 19. Inflow hydrograph used as an upstream boundary condition.

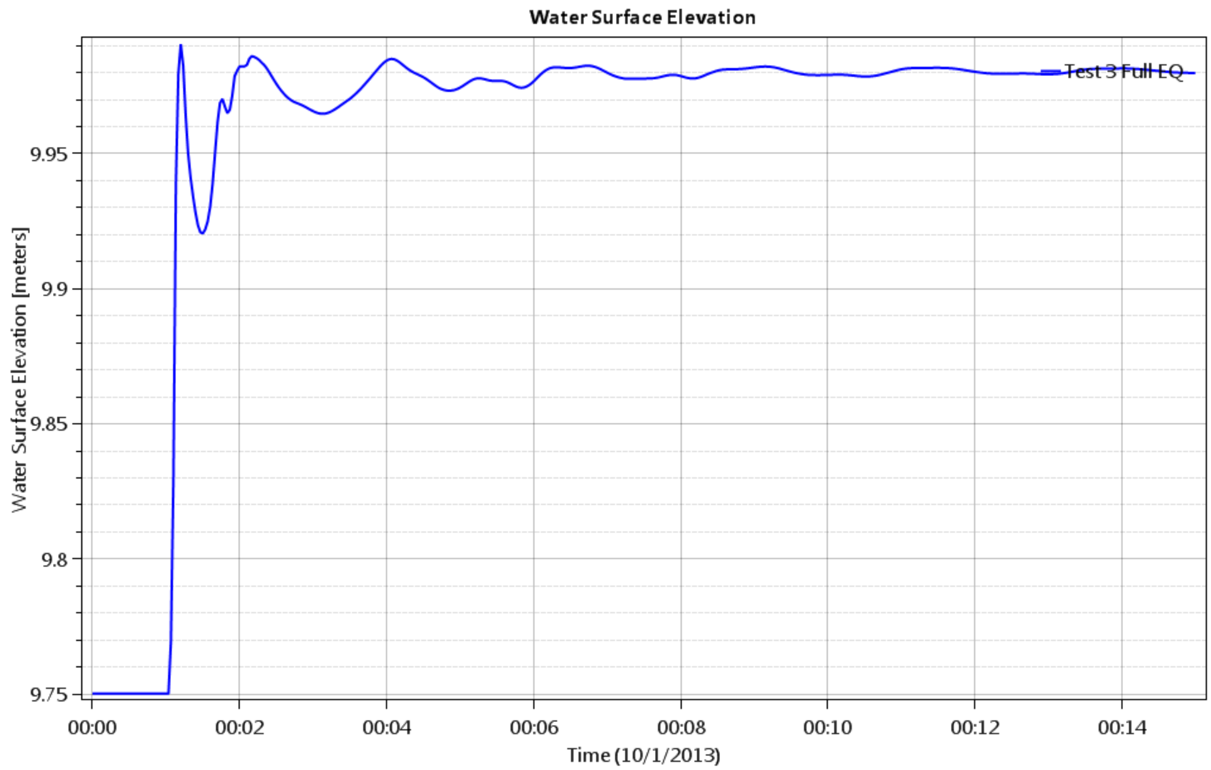


Figure 20. Test Point 1 - Water Level versus Time (minutes).

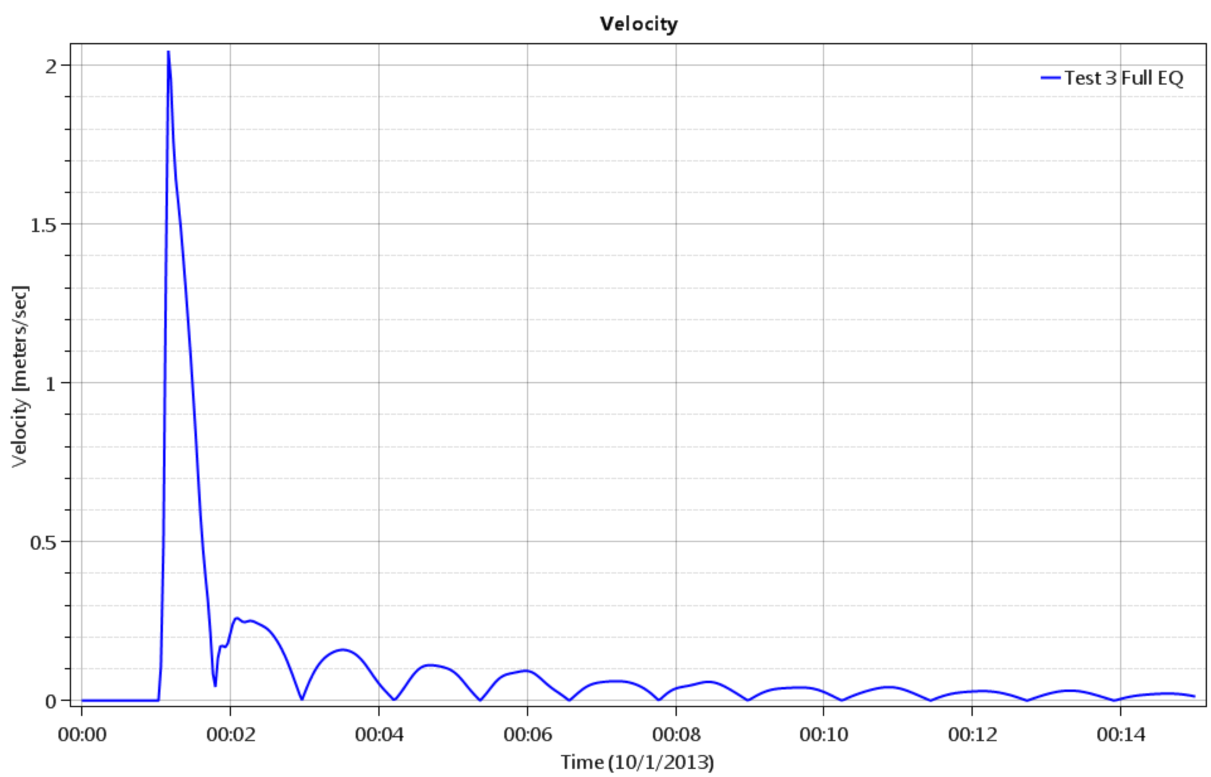


Figure 21. Test Point 1 - Velocity versus Time (minutes).

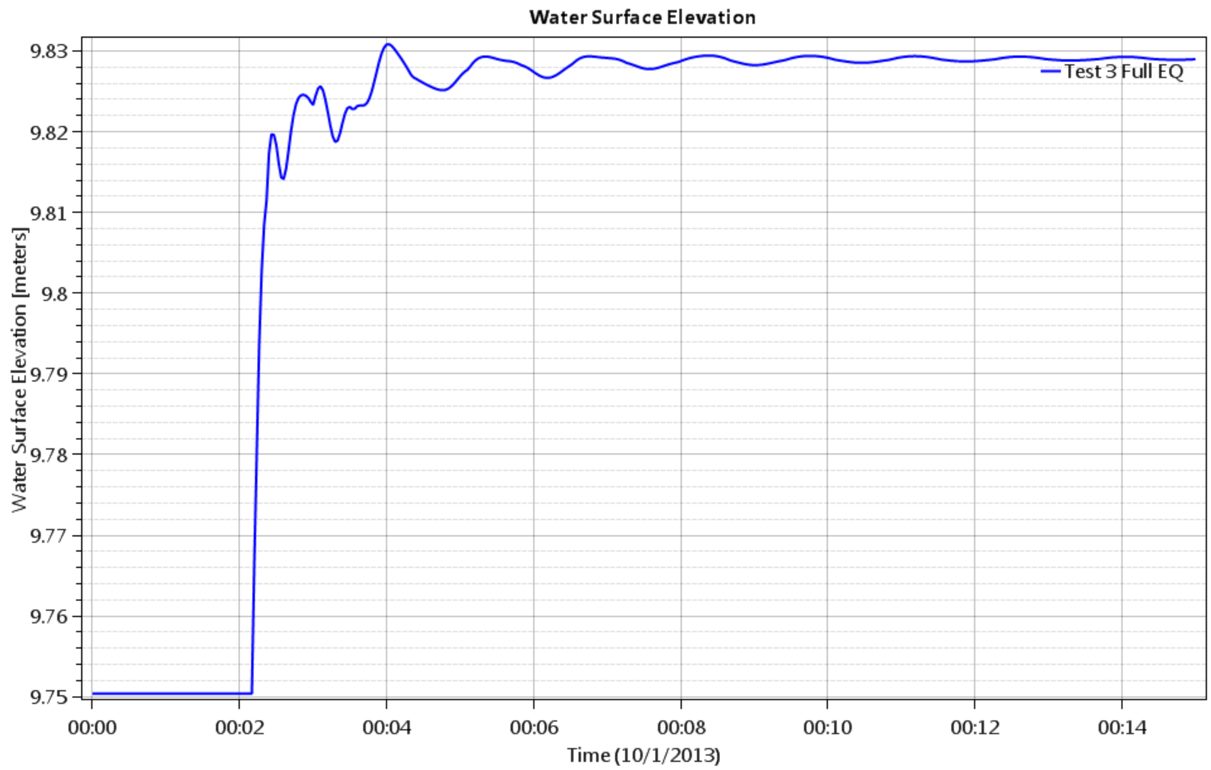


Figure 22. Test Point 2 - Water Level versus Time (minutes).

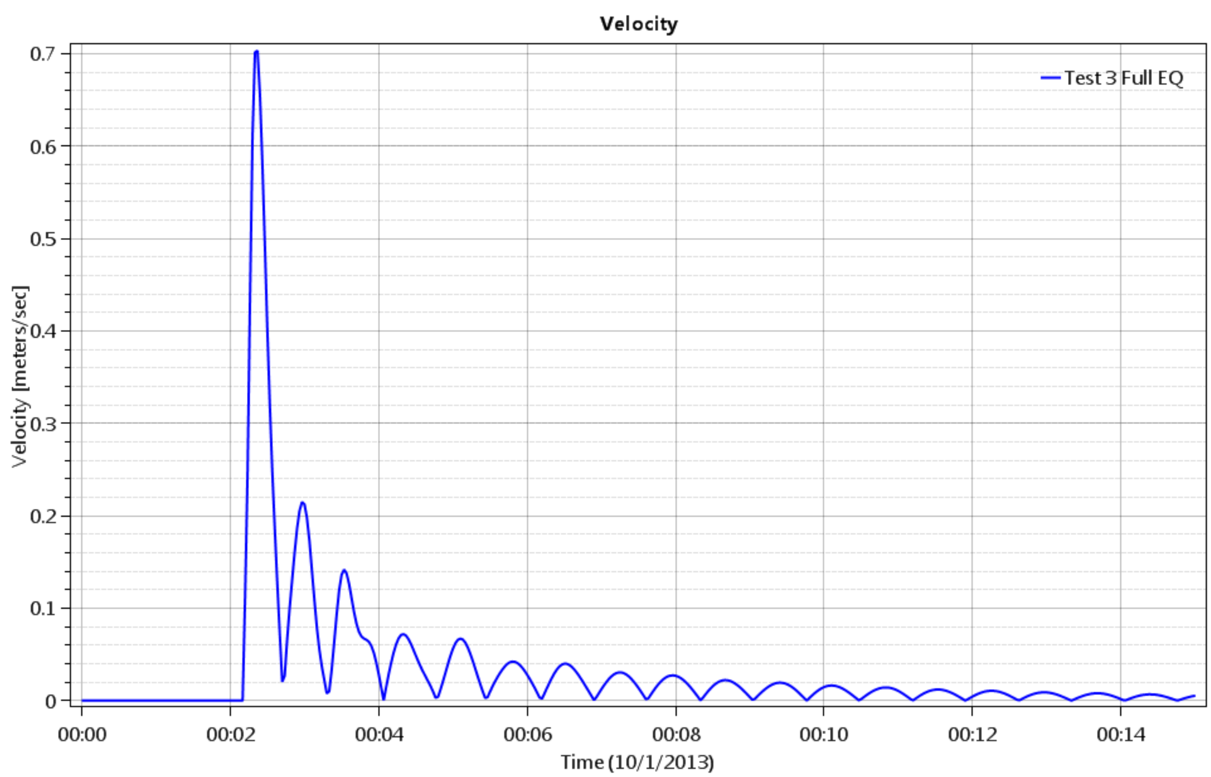


Figure 23. Test Point 2 - Velocity versus Time (minutes).

Table 5. Benchmark Test 3 Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	1 seconds
Grid resolution (or number of cells)	5 meters x 5 meters; 1,200 cells
Total computational time	Full EQ: 2 seconds

Chapter 5

Benchmark Test 4

Speed of Flood Propagation over an Extended Floodplain

5.1 Objective

The objective of Benchmark Test 4 is to assess the two-dimensional model's ability to simulate the celerity of propagation of a flood wave and predict transient velocities and depths at the leading edge of the advancing flood front. It is relevant to fluvial and coastal inundation resulting from breached embankments.

5.2 Description

The test is designed to simulate the rate of flood wave propagation over a 1,000 meter x 2,000 meter floodplain following an embankment failure (Figure 24). The floodplain surface is horizontal, at elevation zero (0) meters. 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 approximately six hours, as shown in Figure 25. The boundary condition is applied along a 20 meter line in the middle of the western side of the floodplain.

5.3 Boundary and Initial Conditions

- Flow boundary condition as shown in Figure 25.
- All other boundaries are closed.
- Initial condition: Dry bed.

5.4 Parameter Values

- Manning's n: 0.05 (uniform)
- Model grid resolution: 5 meters (or approximately 80,000 nodes in the area modeled)
- Time of end: the model is to be run until time t equals 5 hours (if an alternative end time is used, run times must be reported for t equals 5 hours).

5.5 Results

Results for this test are shown in Figures 26 - 43, and Table 6. HEC-RAS performed extremely well for both full equations and diffusion wave compared to the leading two-dimensional models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK.

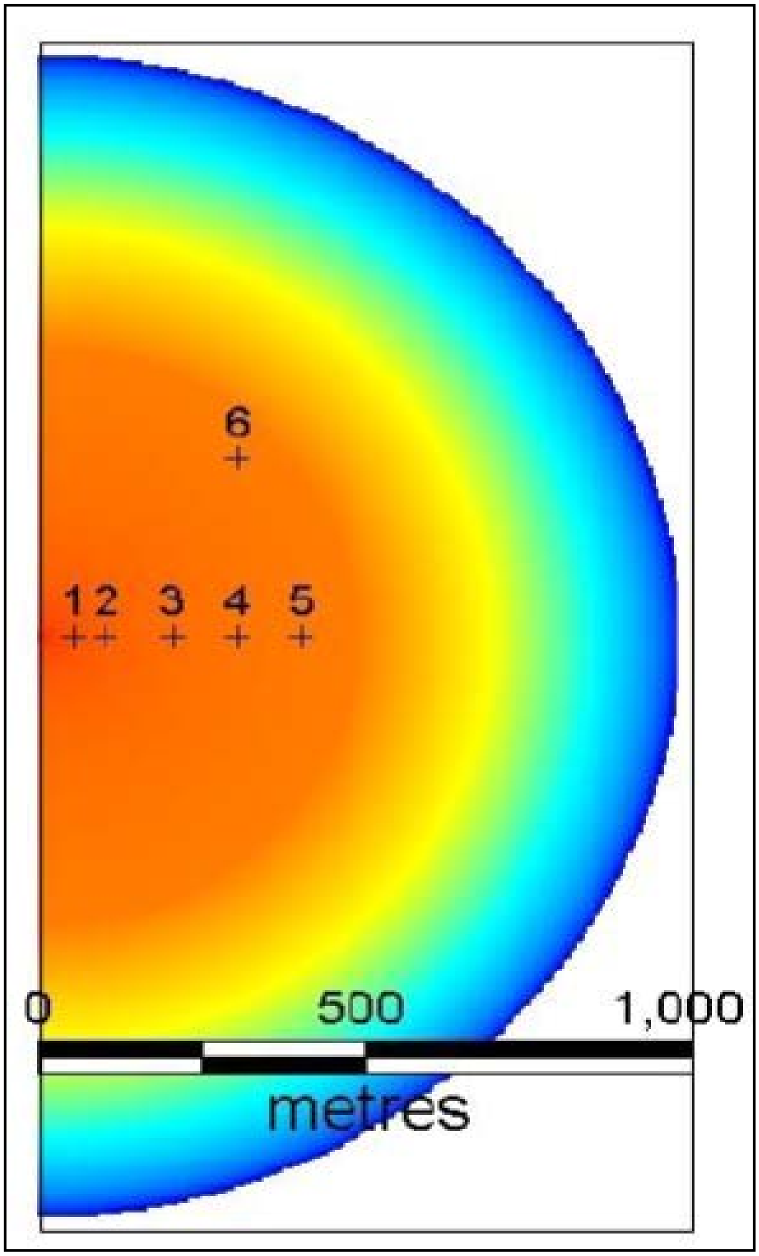


Figure 24. Modeled domain, showing the location of the 20 meter inflow hydrograph, six evaluation points.

Note: Benchmark Test 4 was run with both the Full Saint Venant equations (Full EQ) and the Diffusion Wave equations (Diff Wave). Results for both equation sets are shown in Figures 26 - 43.

Note: Benchmark Test 4 was also used to demonstration sensitivity to the computational grid resolution. Results are shown for Test Point 5 and 6, which are the two points furthest from the inflow.

Additional testing was performed with Benchmark Test 4 to demonstrate how varying the two-dimensional grid resolution has little impact on the computed results, because HEC-RAS can partially wet cells. Results from Benchmark Test 4 show that the model can get almost the same results using a ten meter grid as the originally stated five meter grid. Run times with the larger grid cell size are dramatically lower than with the smaller grid cell size. This capability provides a major advantage of the HEC-RAS two-dimensional solver over other software that does not support partial cell wetting, as well as using the detailed terrain within the cell and for the cell face properties.

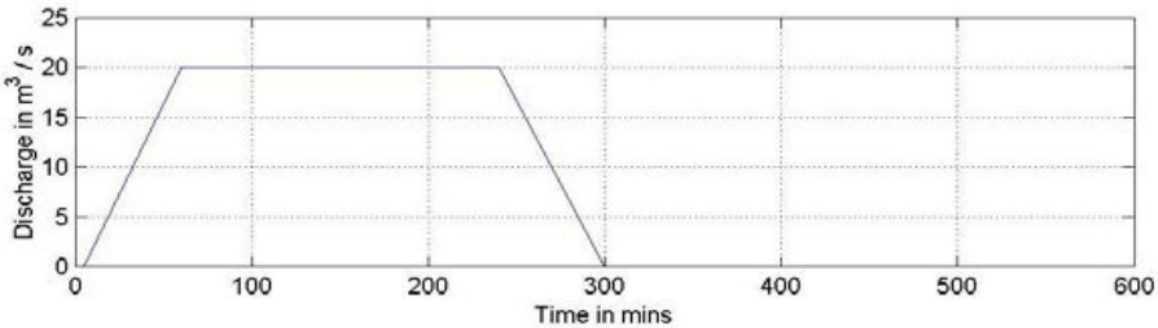


Figure 25. Hydrograph applied as inflow boundary condition.

Table 6. Benchmark Test 4 Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	30 seconds
Grid resolution (or number of cells)	5 meters x 5 meters; 79,401 cells
Total computational time	Full EQ: 56 seconds Diff Wav: 41 seconds 10 meter grid Full EQ: 13 seconds

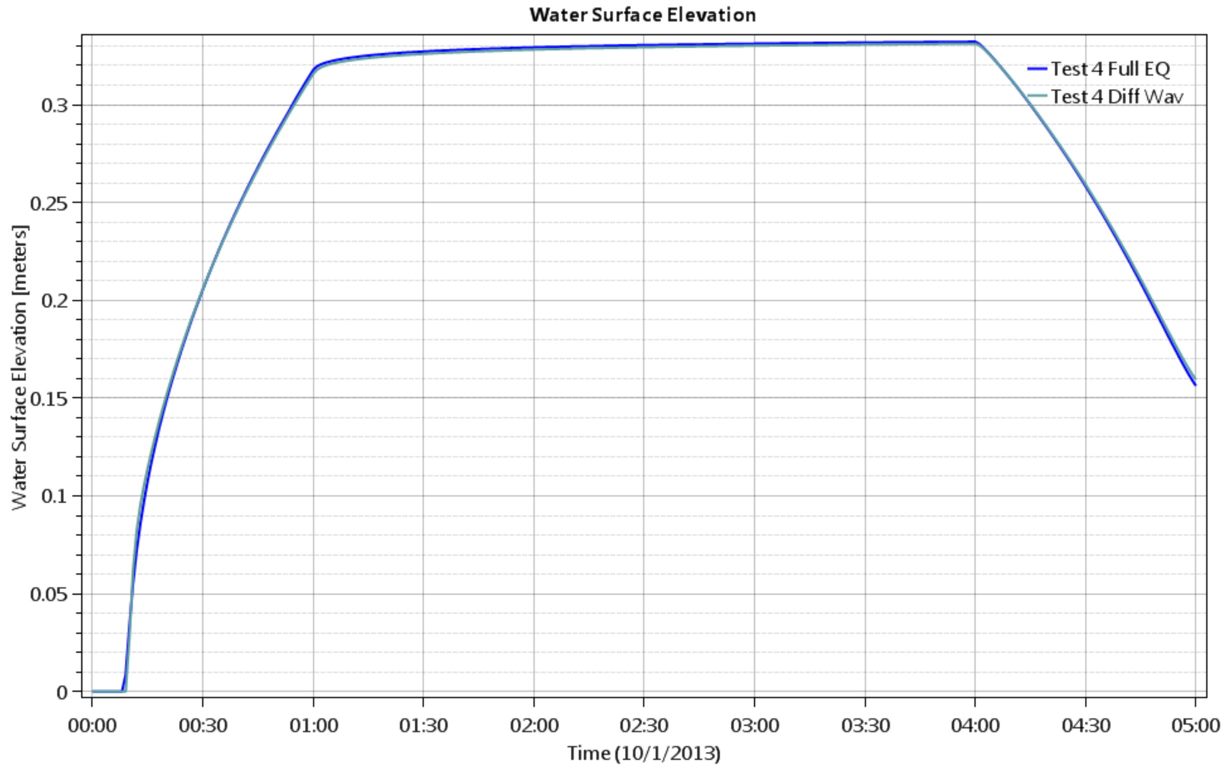


Figure 26. Test Point 1 Water Level (depth).

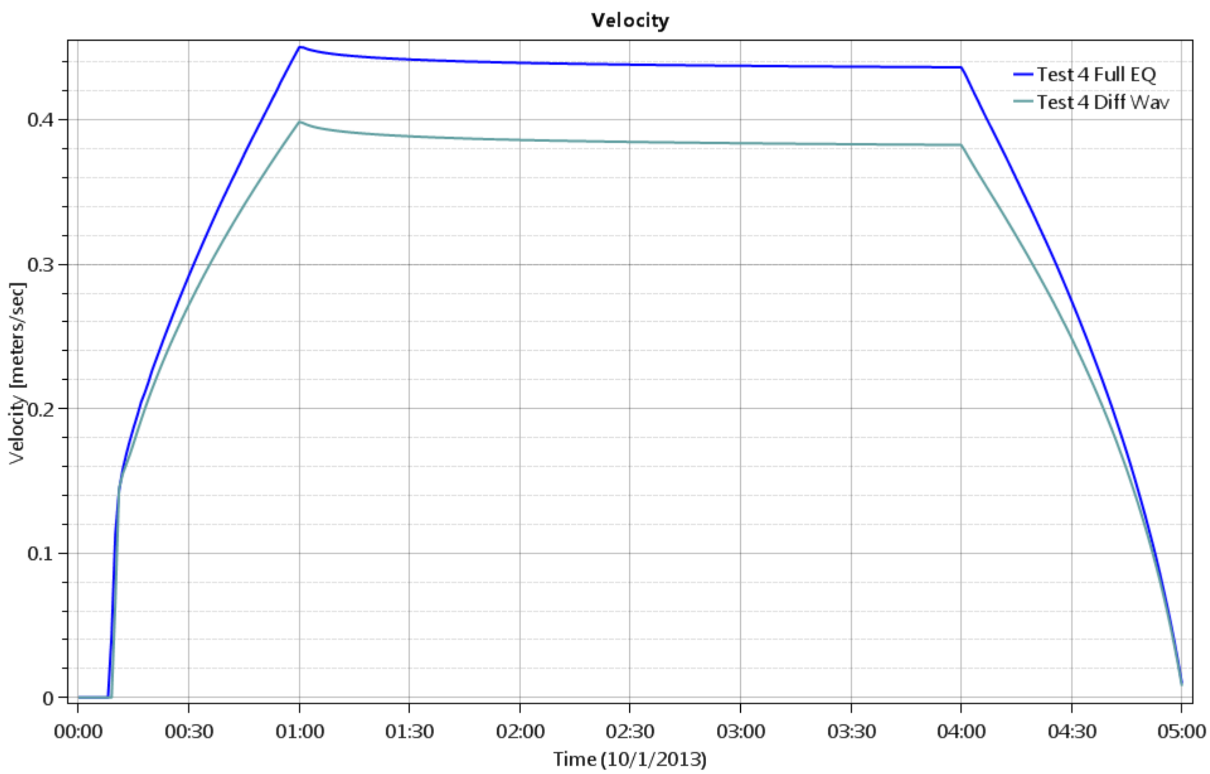


Figure 27. Test Point 1 Velocity Time Series.

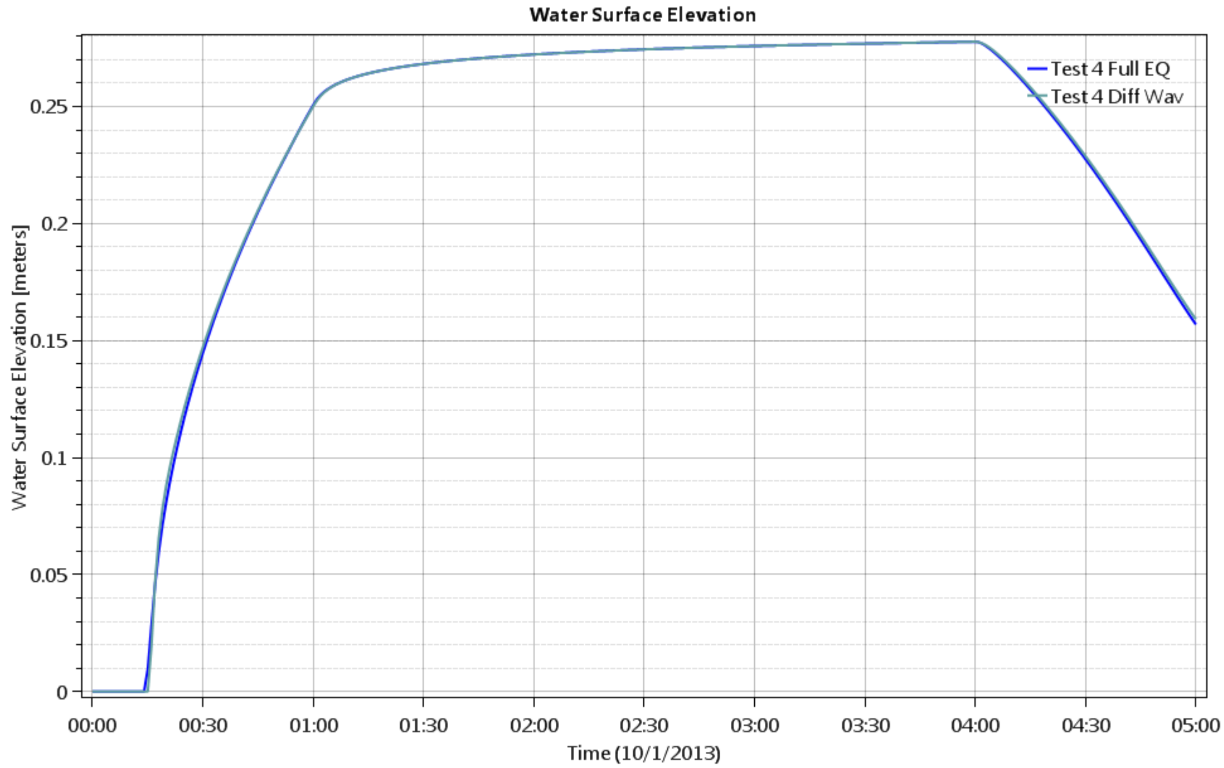


Figure 28. Test Point 2 Water Level (depth).

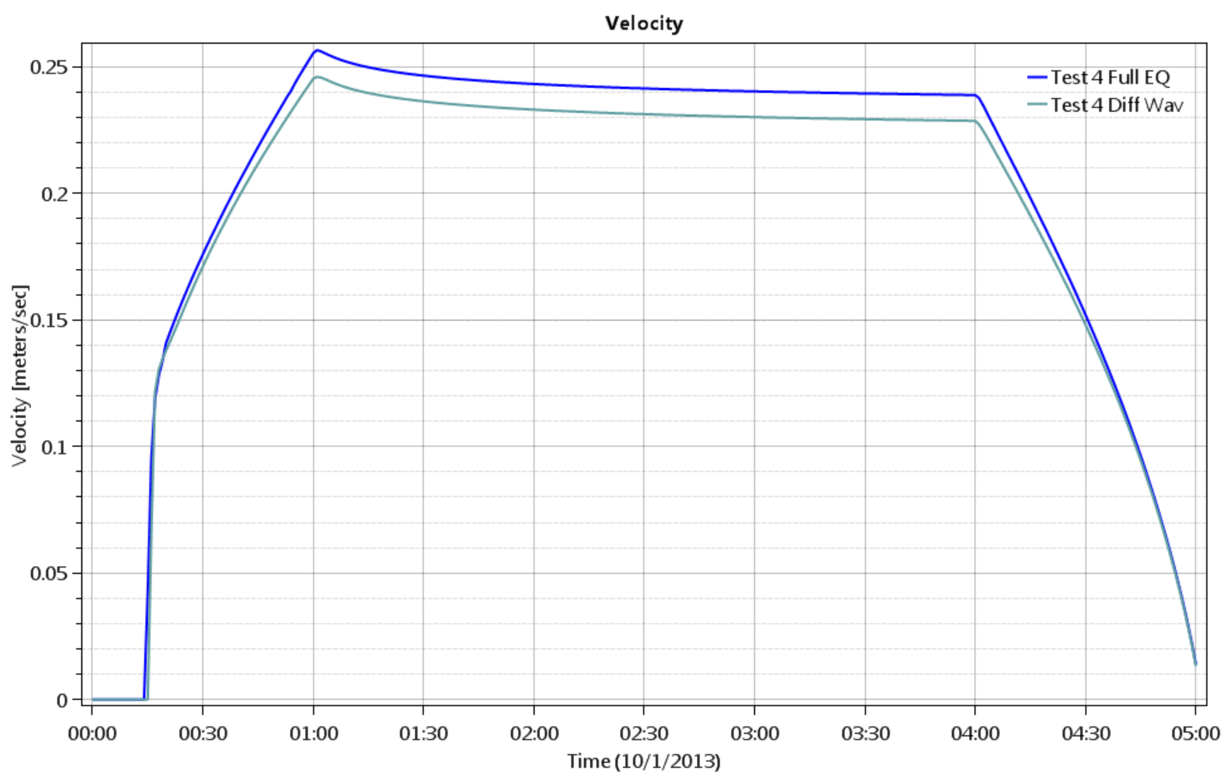


Figure 29. Test Point 2 Velocity Time Series.

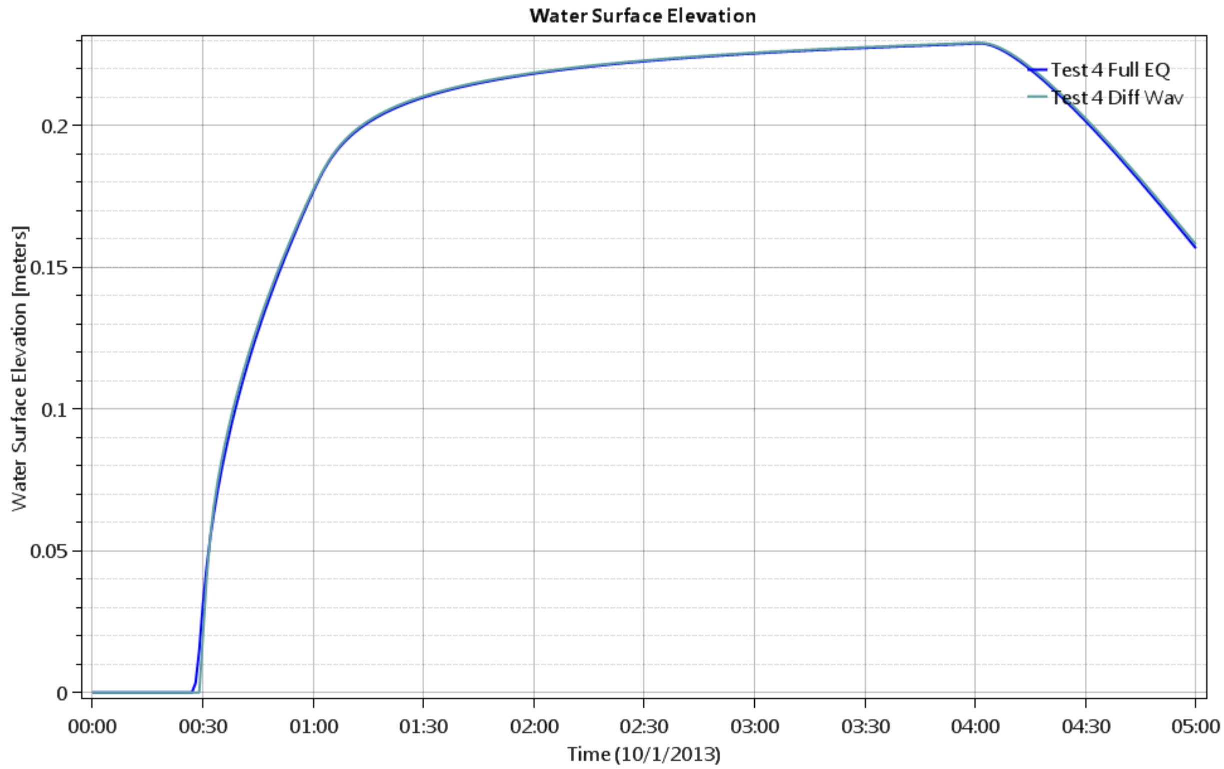


Figure 30. Test Point 3 Water Level (depth).

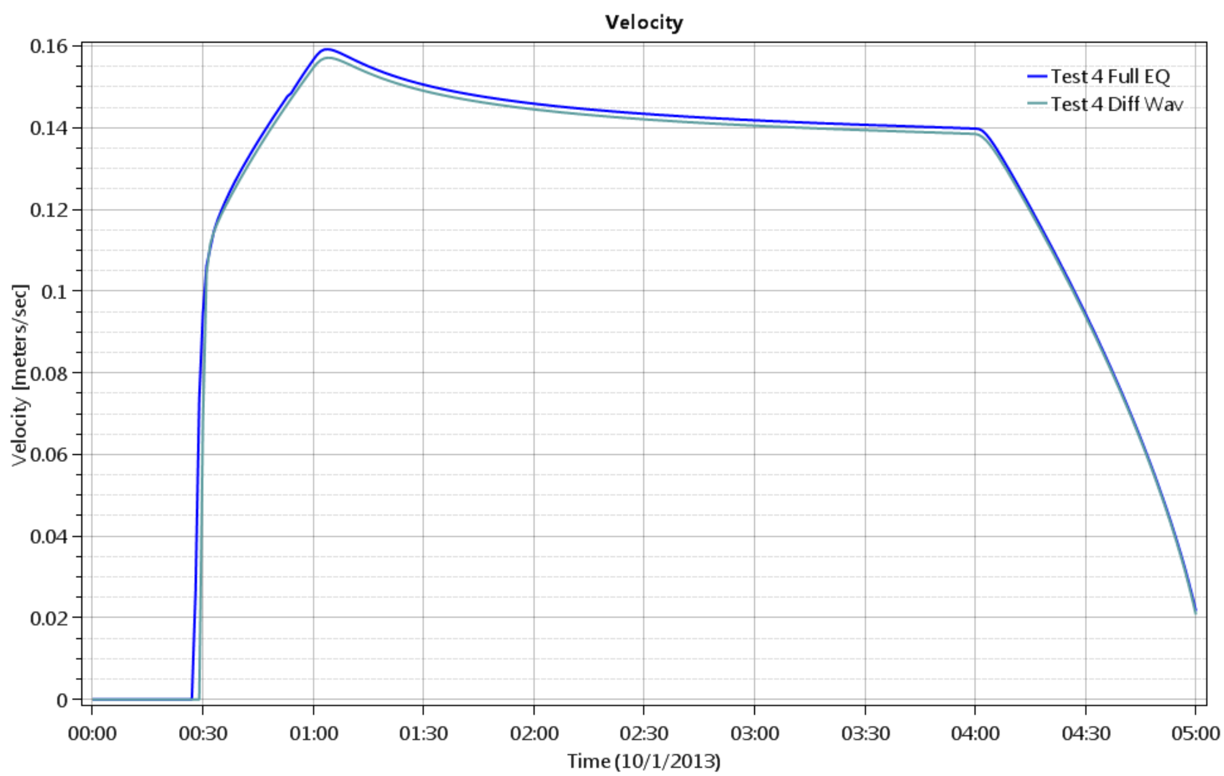


Figure 31. Test Point 3 Velocity Time Series.

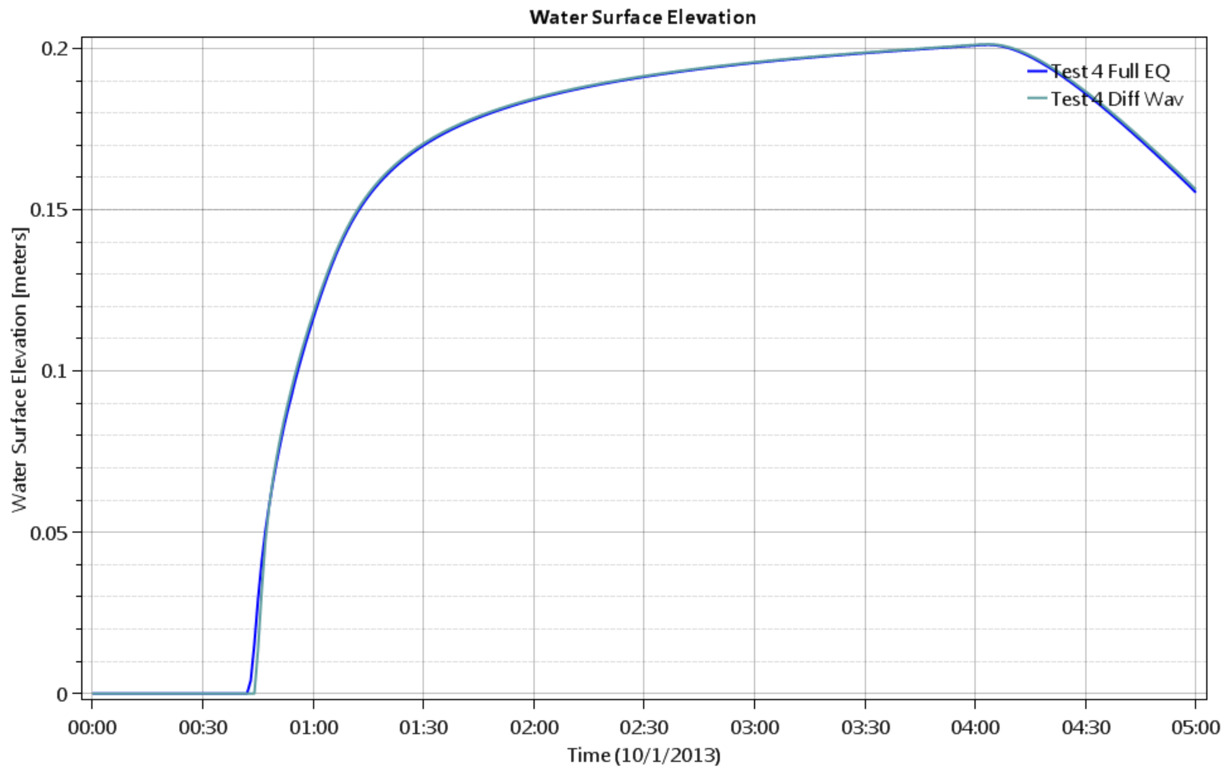


Figure 32. Test Point 4 Water Level (depth).

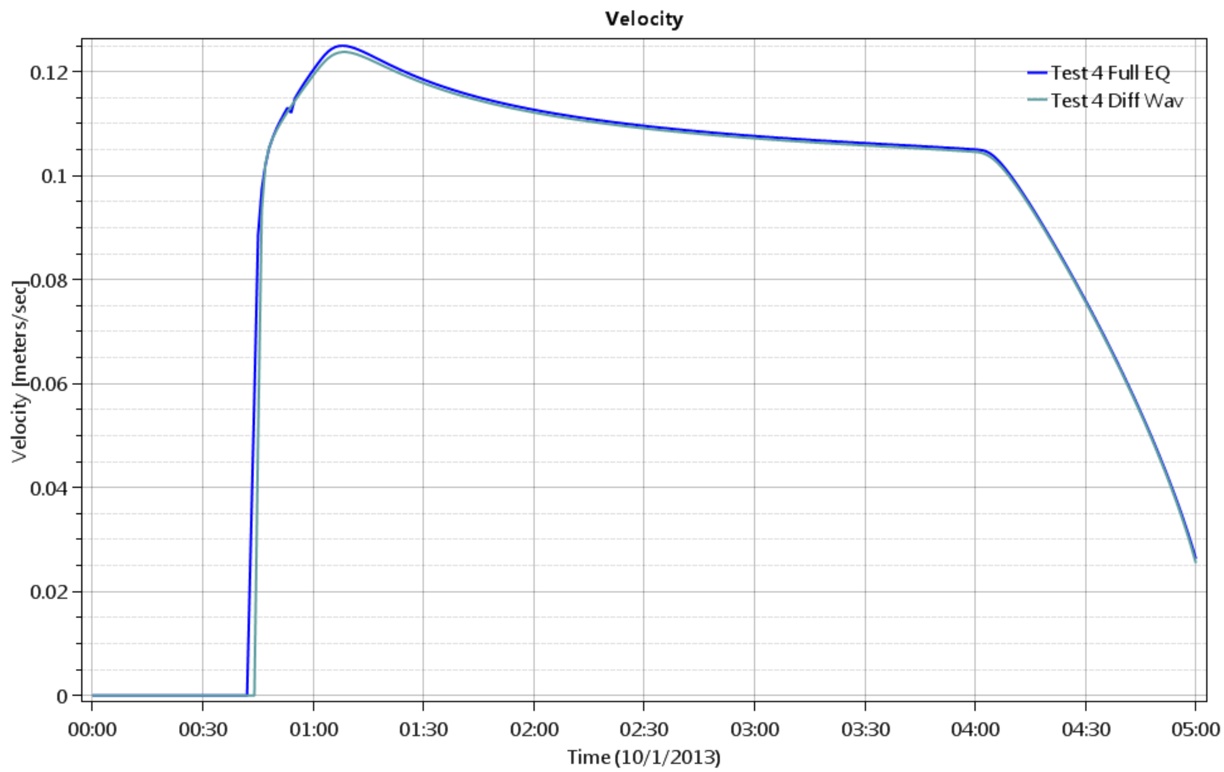


Figure 33. Test Point 4 Velocity Time Series.

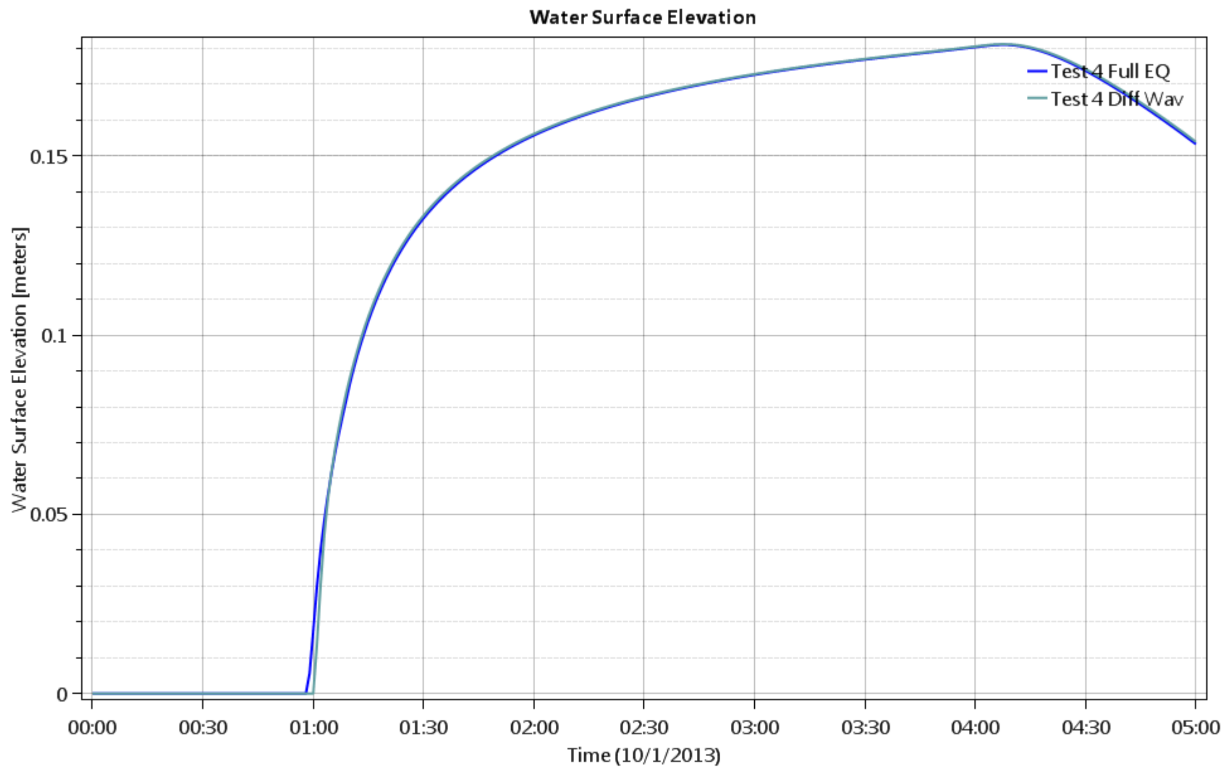


Figure 34. Test Point 5 Water Level (depth).

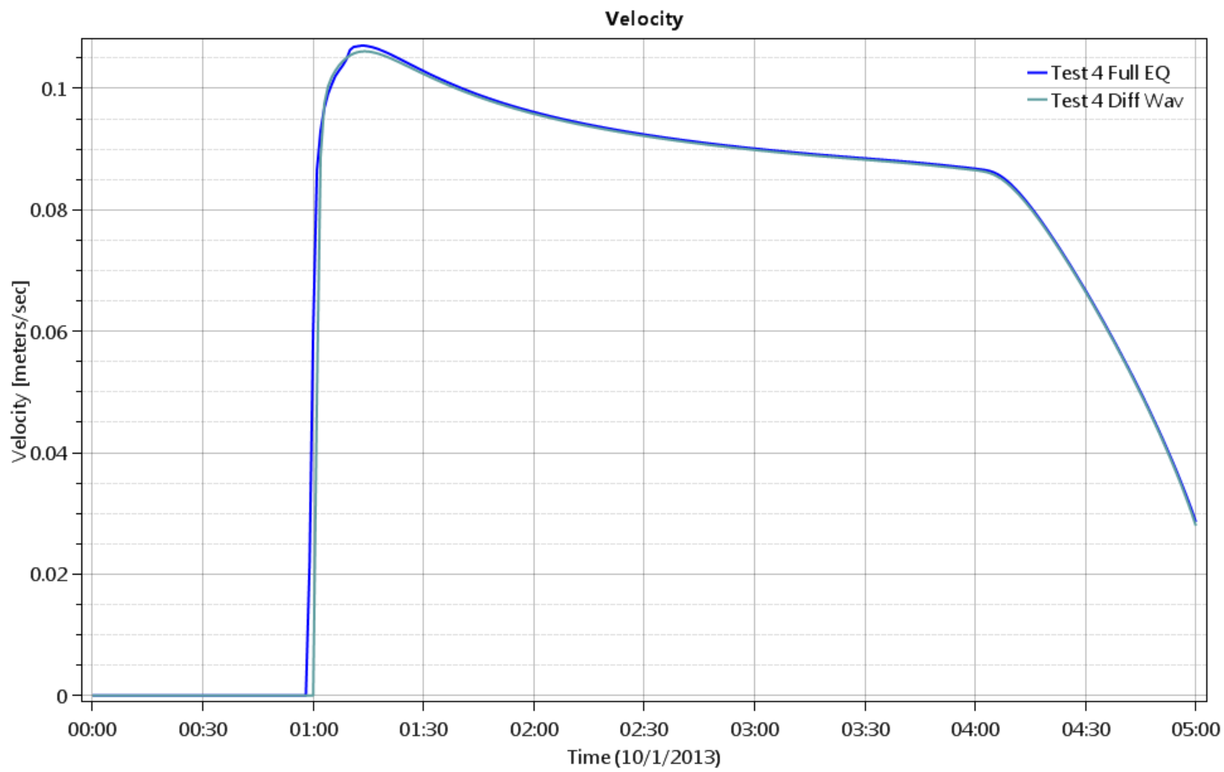


Figure 35. Test Point 5 Velocity Time Series.

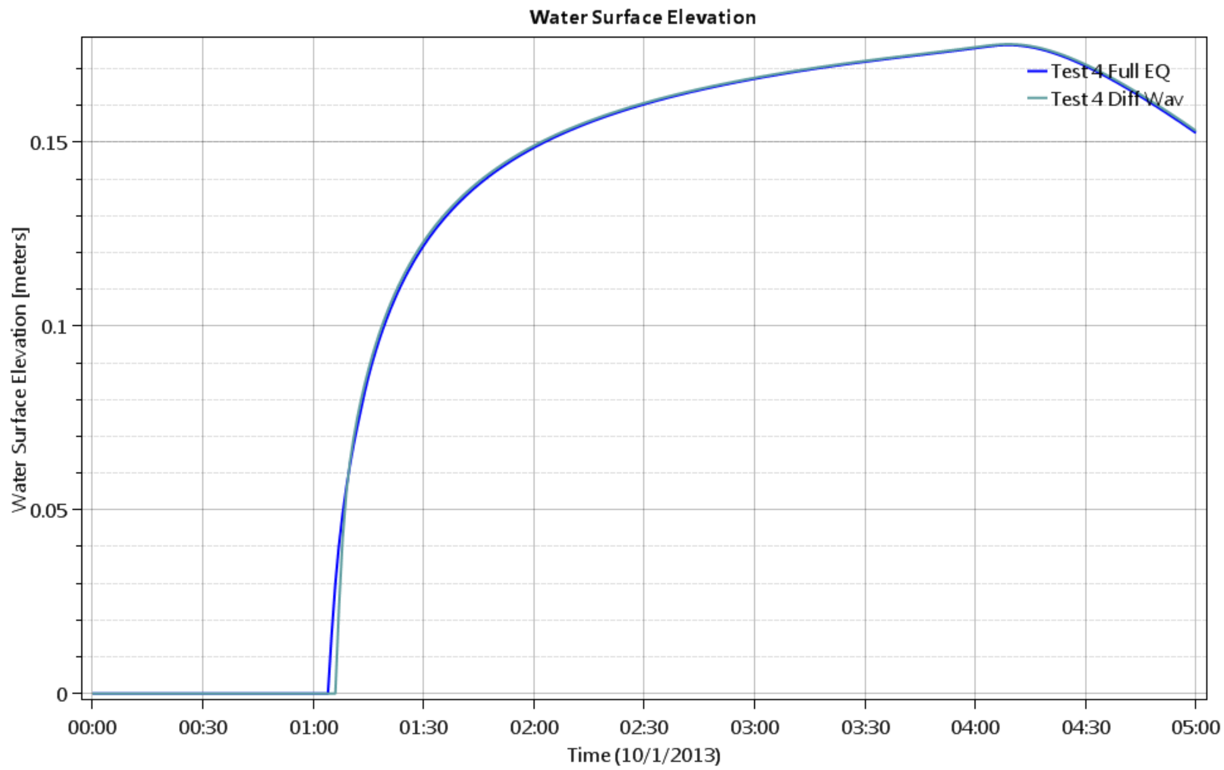


Figure 36. Test Point 6 Water Level (depth).

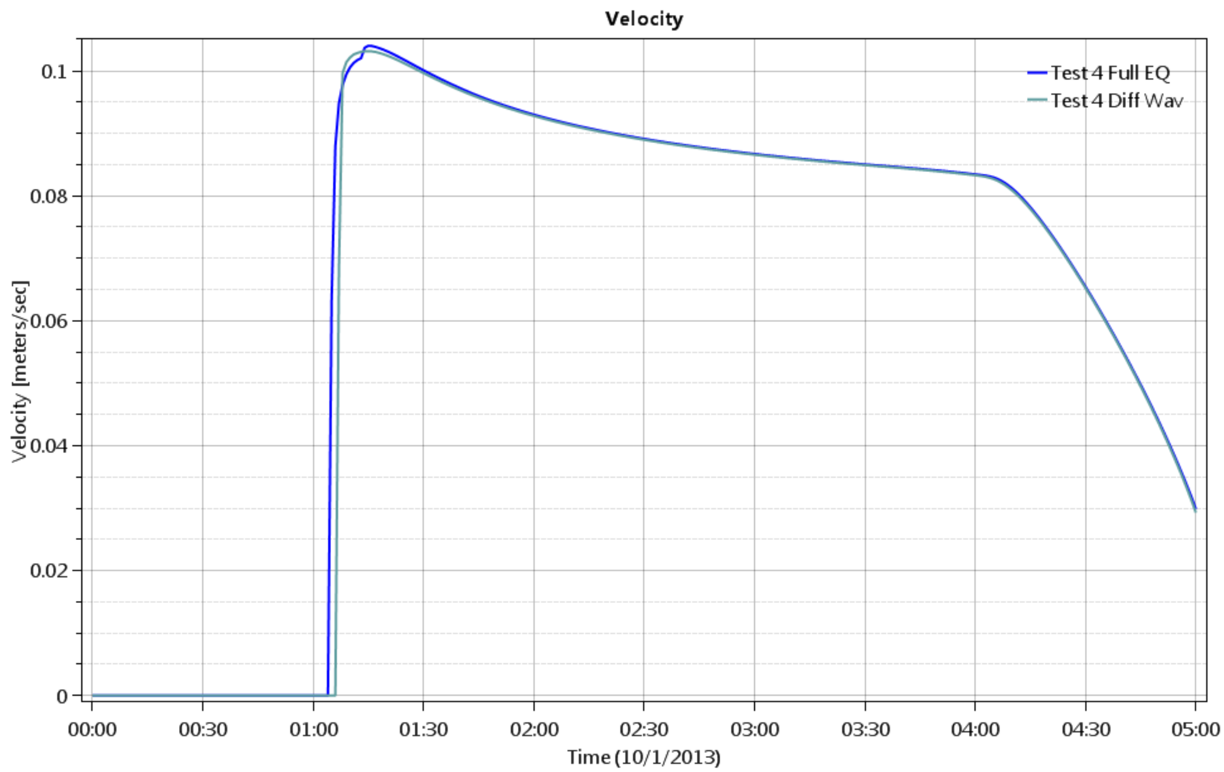


Figure 37. Test Point 6 Velocity Time Series.

5.5.1 Cross Section Plots at Time 1HOUR, from Inflow through Point 5

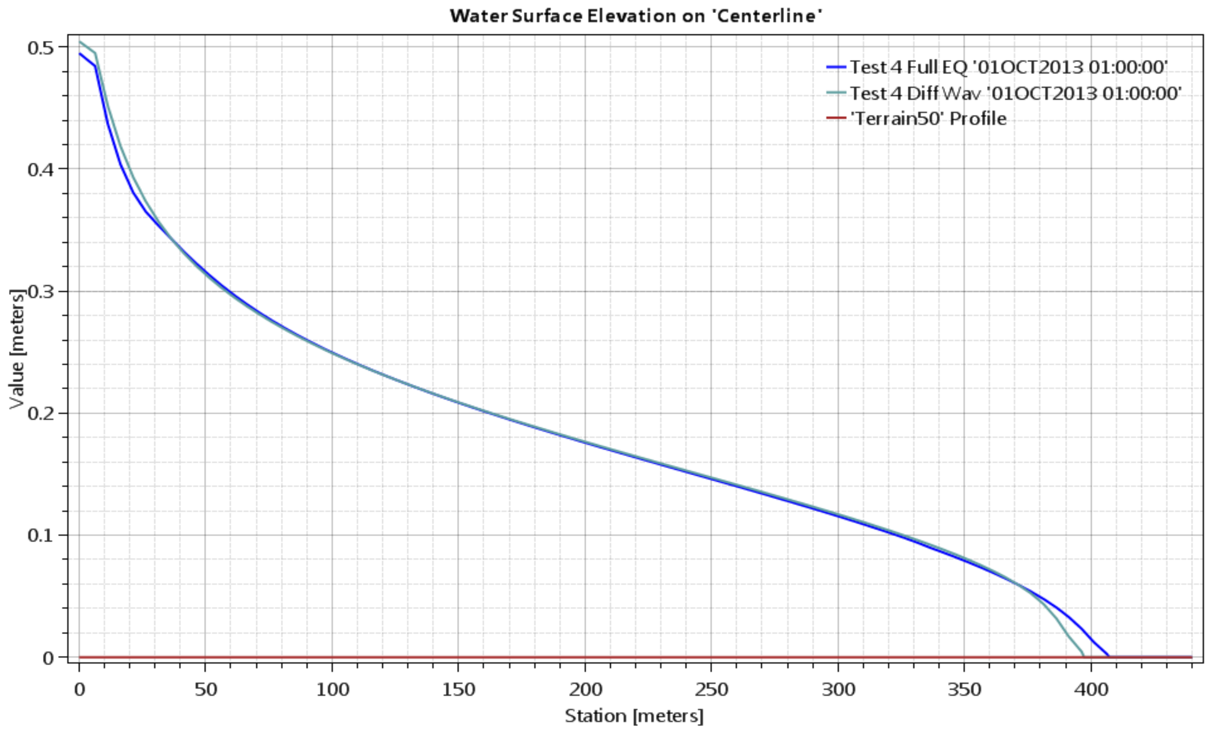


Figure 38. Depth versus Distance at Time 1HOUR.

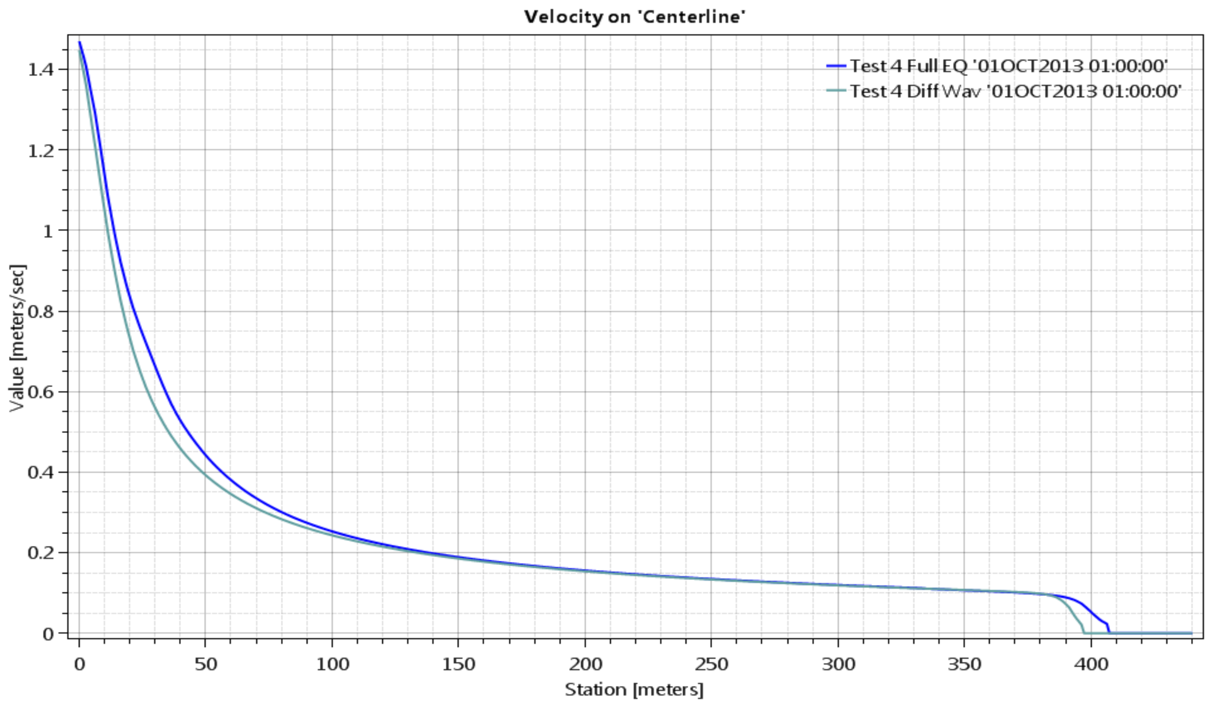


Figure 39. Velocity versus Distance at Time 1HOUR.

5.5.2 Sensitivity to Grid Resolution - Grid Sizes of 5 and 10 meters, Full Saint Venant Equations

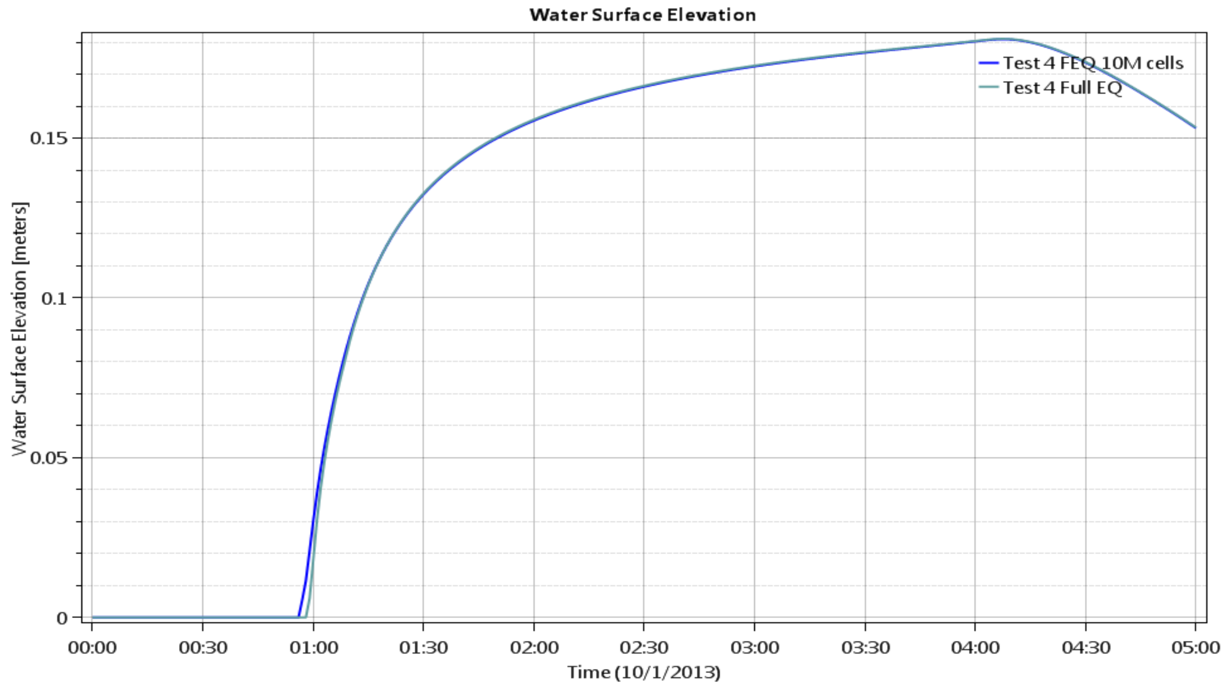


Figure 40. Test Point 5 water level vs time for 5 and 10 m Grids

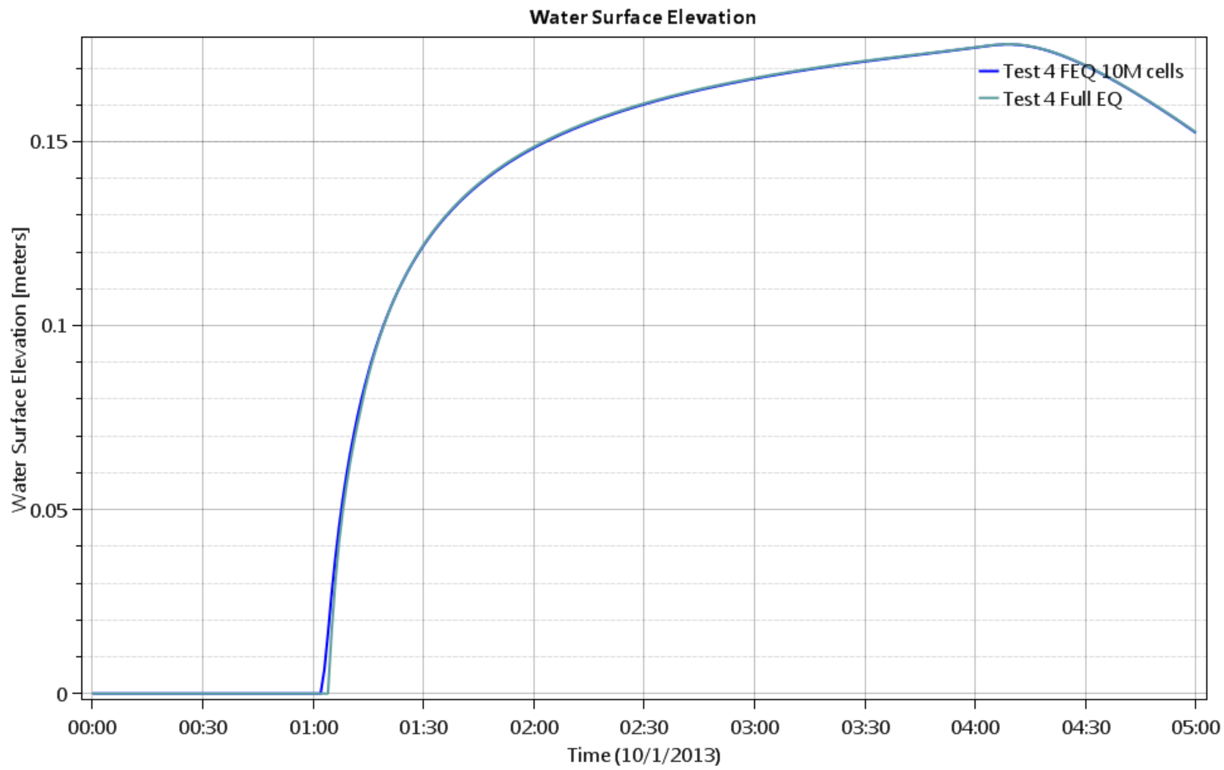


Figure 41. Test Point 6 water level vs time for 5 and 10 m Grids

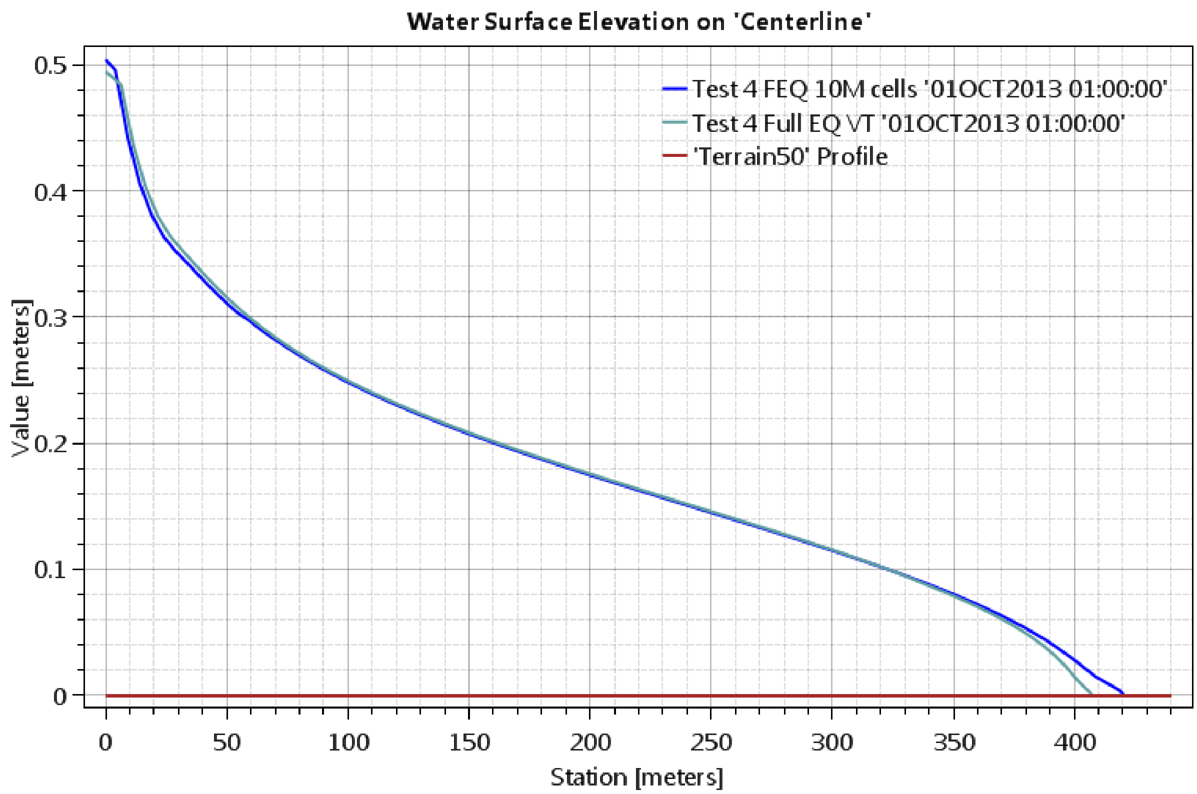


Figure 42. Depth versus Distance at Time 1HOUR.

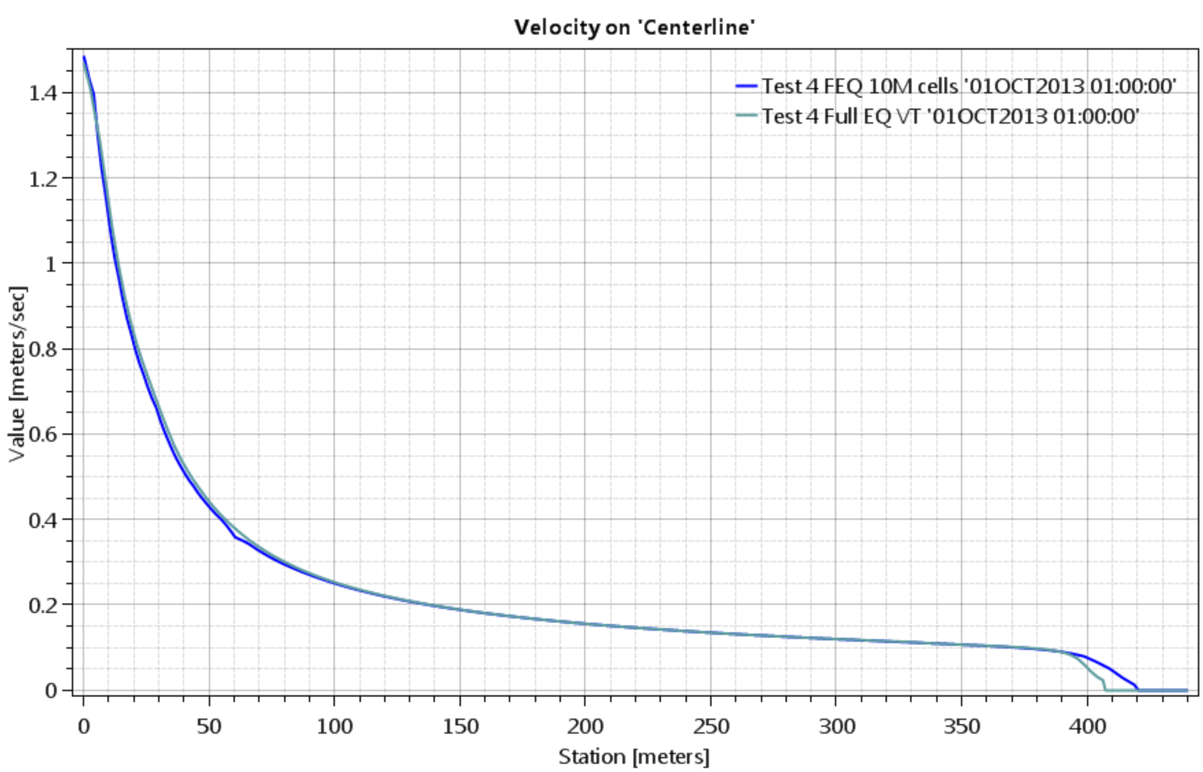


Figure 43. Velocity versus Distance at Time 1HOUR.

Chapter 6

Benchmark Test 5

Valley Flooding

6.1 Objective

Benchmark Test 5 tests a two-dimensional model's capability to simulate major flood inundation and predict flood hazard arising from dam failure (peak water levels, velocities, travel times).

6.2 Description

Benchmark Test 5 is designed to simulate flood wave propagation down a river valley following the failure of a dam. The valley DEM (Figure 44) is approximately 0.8 km by approximately 17 km and the valley slopes downstream on a slope of approximately 0.01 in its upper region, easing to approximately 0.001 in its lower region. The inflow hydrograph (Figure 45) applied as a boundary condition along an approximately 260 meter long line at the upstream end is designed to account for a typical failure of a small embankment dam and to ensure that both super-critical and sub-critical flows will occur in different parts of the flow field.

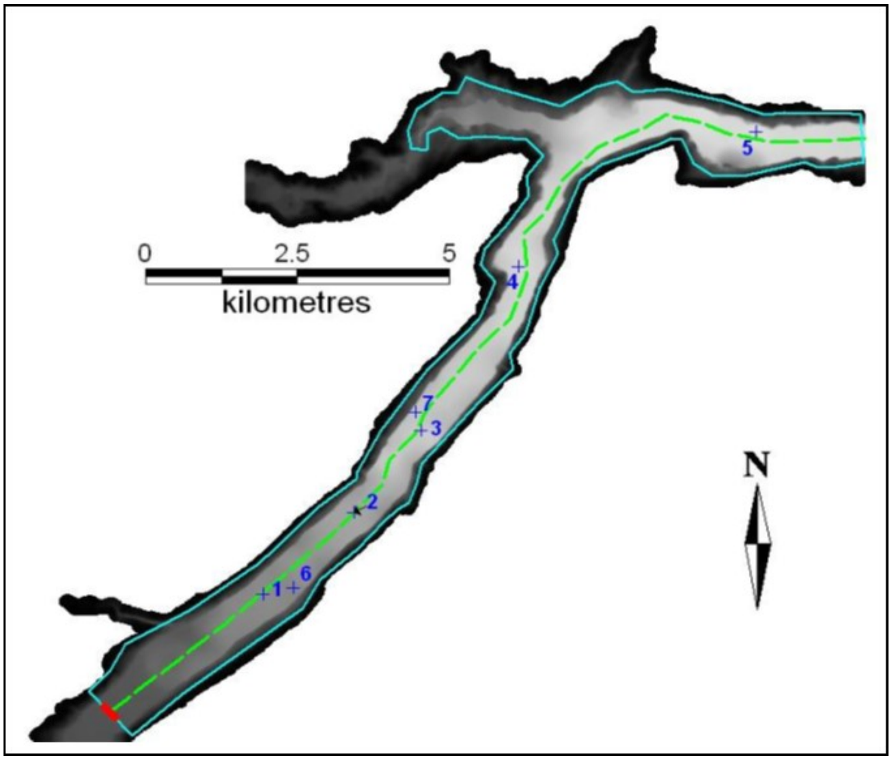


Figure 44. DEM used, with cross-section along the center line, and location of the output points. The red line indicates the location of the boundary condition and the blue polygon is the modeled area.

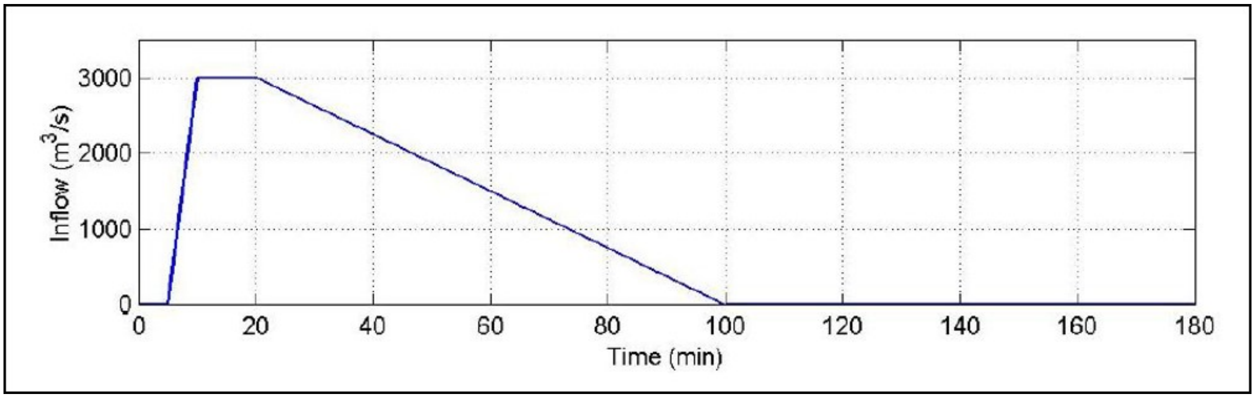


Figure 45. Inflow Hydrograph.

6.3 Boundary and Initial Conditions

- Initial boundary condition along the dashed red line in Figure 44.
- All other boundaries are closed.
- Initial condition: Dry bed.

6.4 Parameter Values

- Manning's n: 0.04 (uniform)
- Model grid resolution: 50 meters (or approximately 7,600 nodes in the 19.02 km^2 area modeled)
- Time of end: the model is to be run until T equals 30 hours (if an alternative is used, run times must be reported for T equals 30 hours).

6.5 Results

Results for water surface elevations and velocities are shown for the seven evaluation points in Figure 44. HEC-RAS performed extremely well compared to the leading 2D models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK. While the results for the full equations runs were a little better than the diffusion wave results, even the diffusion wave results were good compared to the other leading models used in this study.

Note: Benchmark Test 5 was run with both the Full Saint Venant equations (Full EQ) and the Diffusion Wave equations (Diff Wave). Results for both equation sets are shown in Figures 46 - 79.

Note: Benchmark Test 5 was also used to demonstration sensitivity to the computational interval and sensitivity to grid resolution. Results are shown for Test Points 1-5, which is the upstream to the very downstream end of the system. Both time step sensitivity and grid resolution tests were performed with the full Saint Venant equations. The time step sensitivity test demonstrates that the HEC-RAS two-dimensional code can be used for a wide range of time steps, down to very low Courant numbers, and still get the same answers. The time step tests demonstrate that the HEC-RAS two-dimensional code converges to an answer as the time step is reduced. The grid

resolution tests show that, because of the use of the subgrid bathymetry, HEC-RAS can get almost the same results as the originally stated problem (50 meter grid), with a grid resolution twice as large (100 meter grid). Run times with the larger grid cell size are dramatically lower than with the smaller grid cell size. This capability provides a major advantage of the HEC-RAS two-dimensional capability over other software that does not support using the detailed terrain within the cell and for the cell face properties.

Table 7. Benchmark Test 5 Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	10 seconds
Grid resolution (or number of cells)	50 meters x 50 meters; 7,460 cells 100 meters x 100 meters; 1,809 cells
Total computational time	Full EQ: 48 seconds Diff Wave: 30 seconds 100 meter grid Full EQ: 7 seconds 100 meter grid Diff Wave: 7 seconds

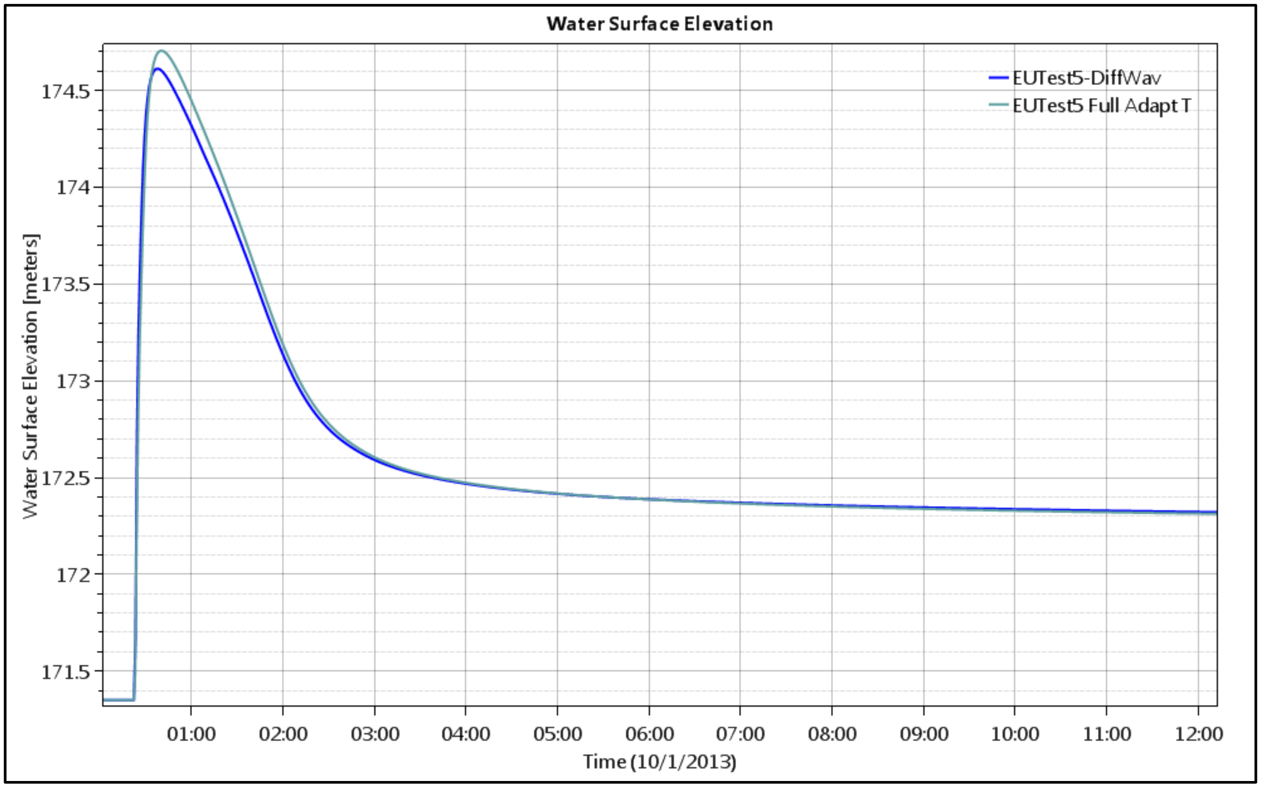


Figure 46. Test Point 1 - Water Level (depth) for Full Equations and Diffusion Wave.

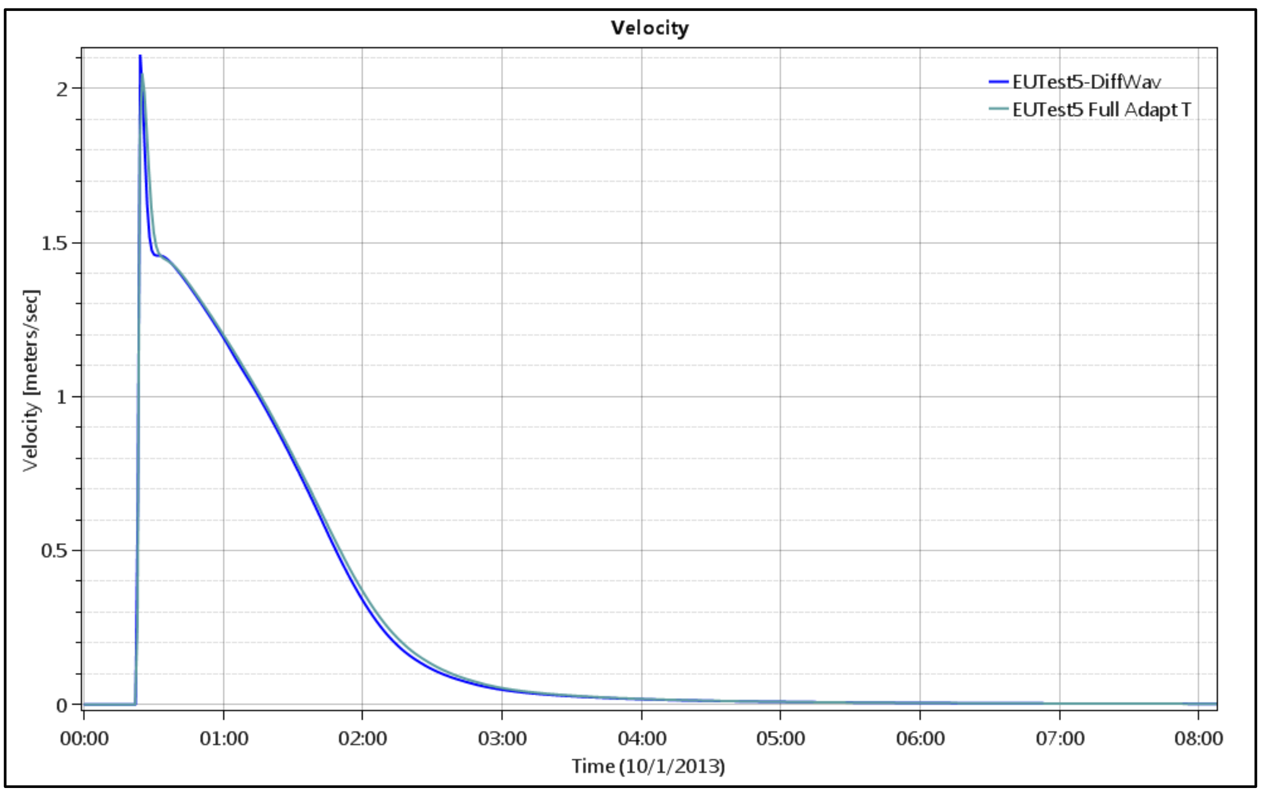


Figure 47. Test Point 1 - Velocity Time Series for Full Equations and Diffusion Wave.

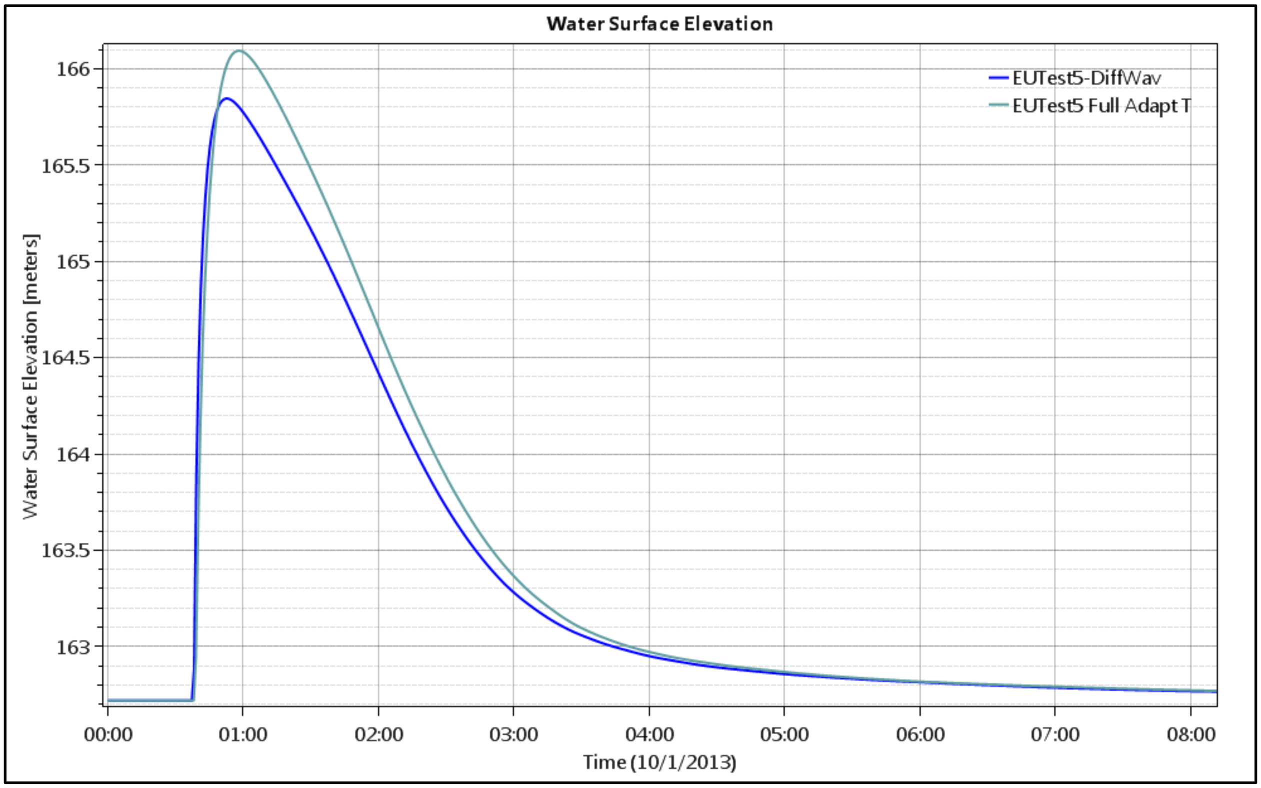


Figure 48. Test Point 2 - Water Level (depth) for Full Equations and Diffusion Wave.

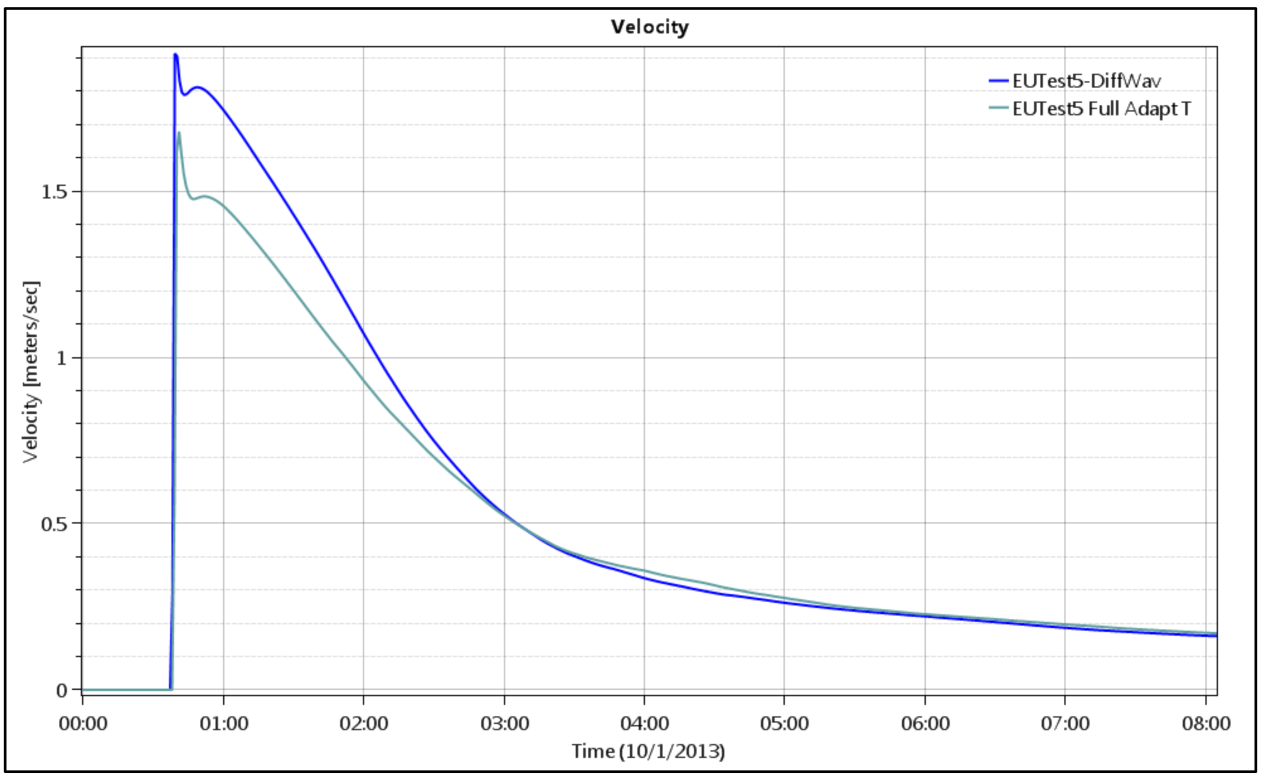


Figure 49. Test Point 2 - Velocity Time Series for Full Equations and Diffusion Wave.

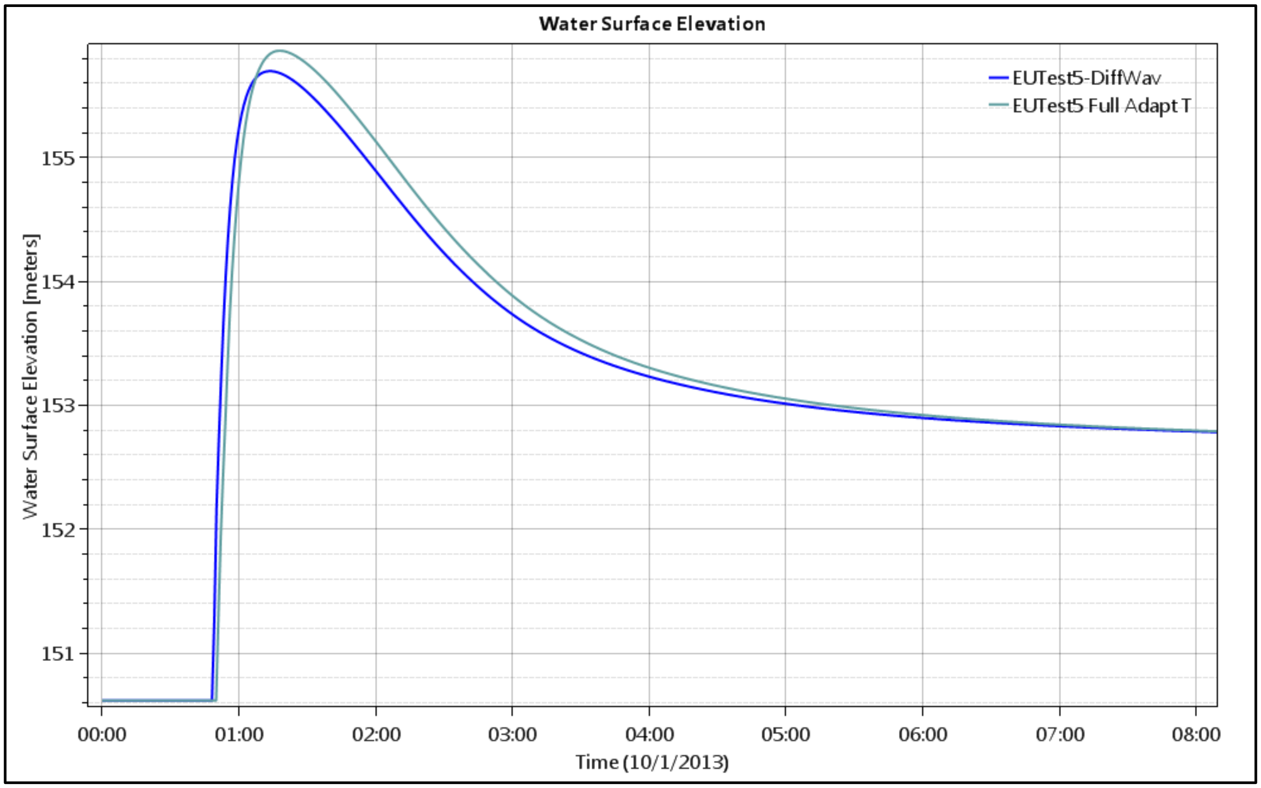


Figure 50. Test Point 3 - Water Level (depth) for Full Equations and Diffusion Wave.

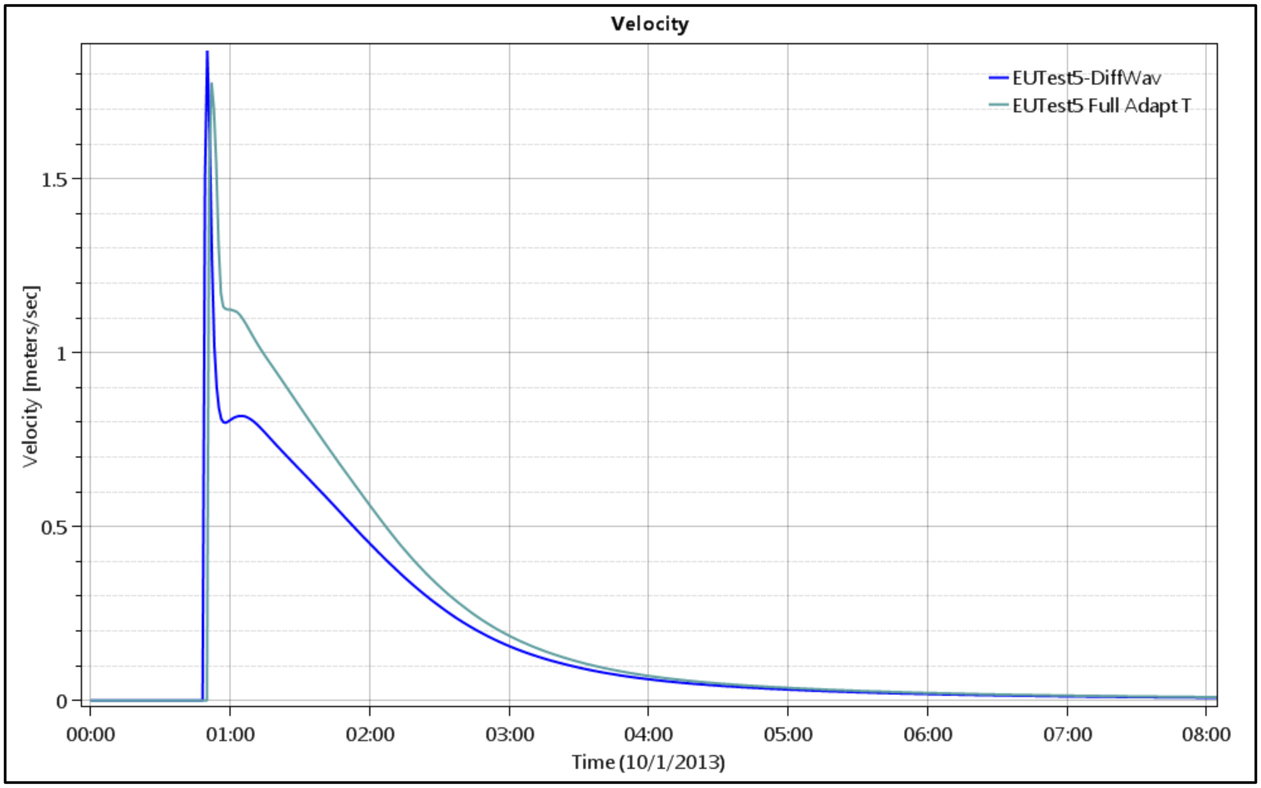


Figure 51. Test Point 3 - Velocity Time Series for Full Equations and Diffusion Wave.

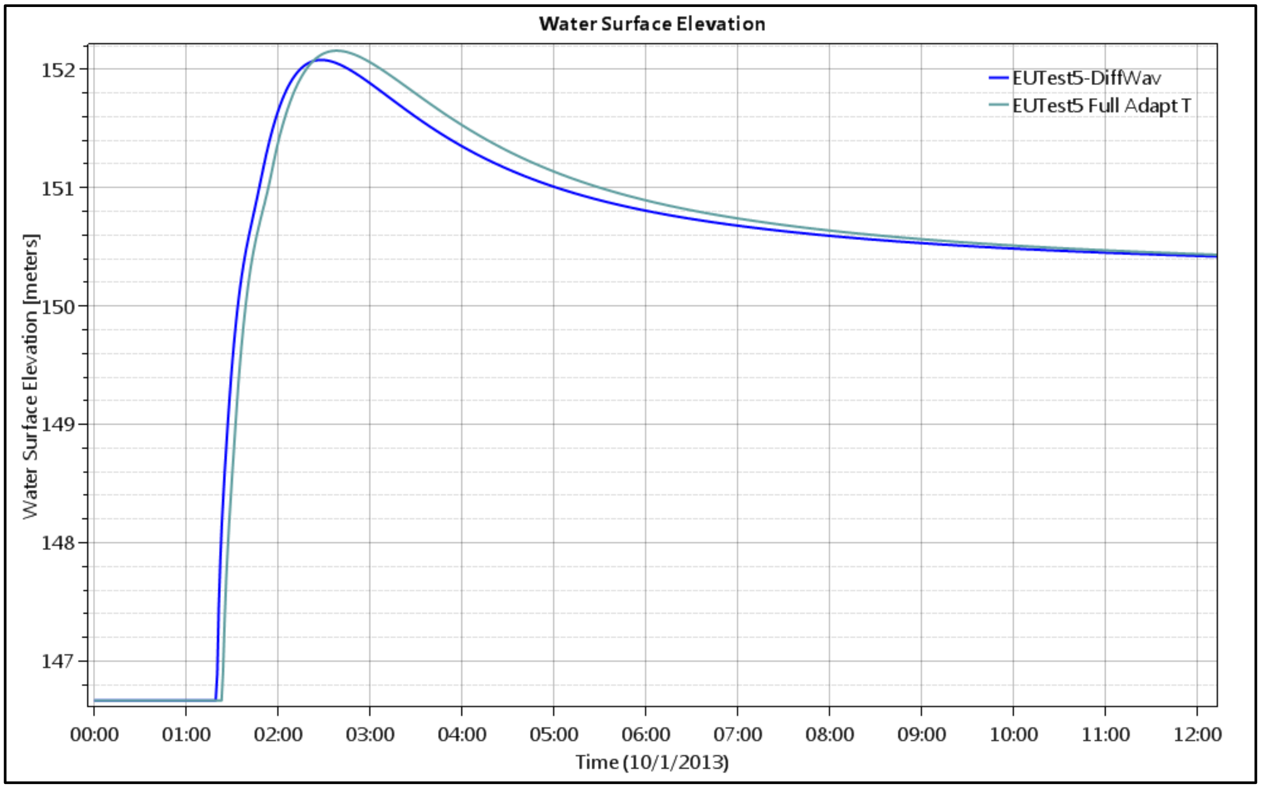


Figure 52. Test Point 4 - Water Level (depth) for Full Equations and Diffusion Wave.

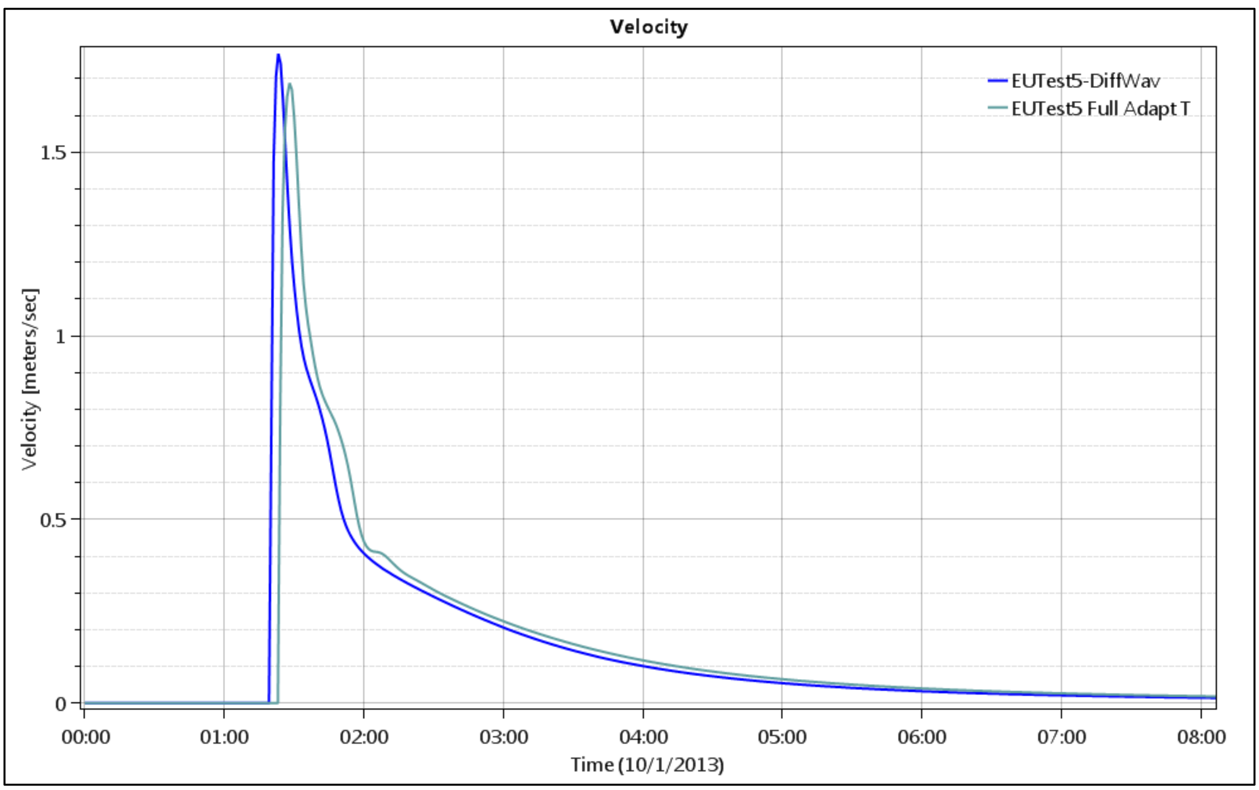


Figure 53. Test Point 4 - Velocity time series for Full Equations and Diffusion Wave.

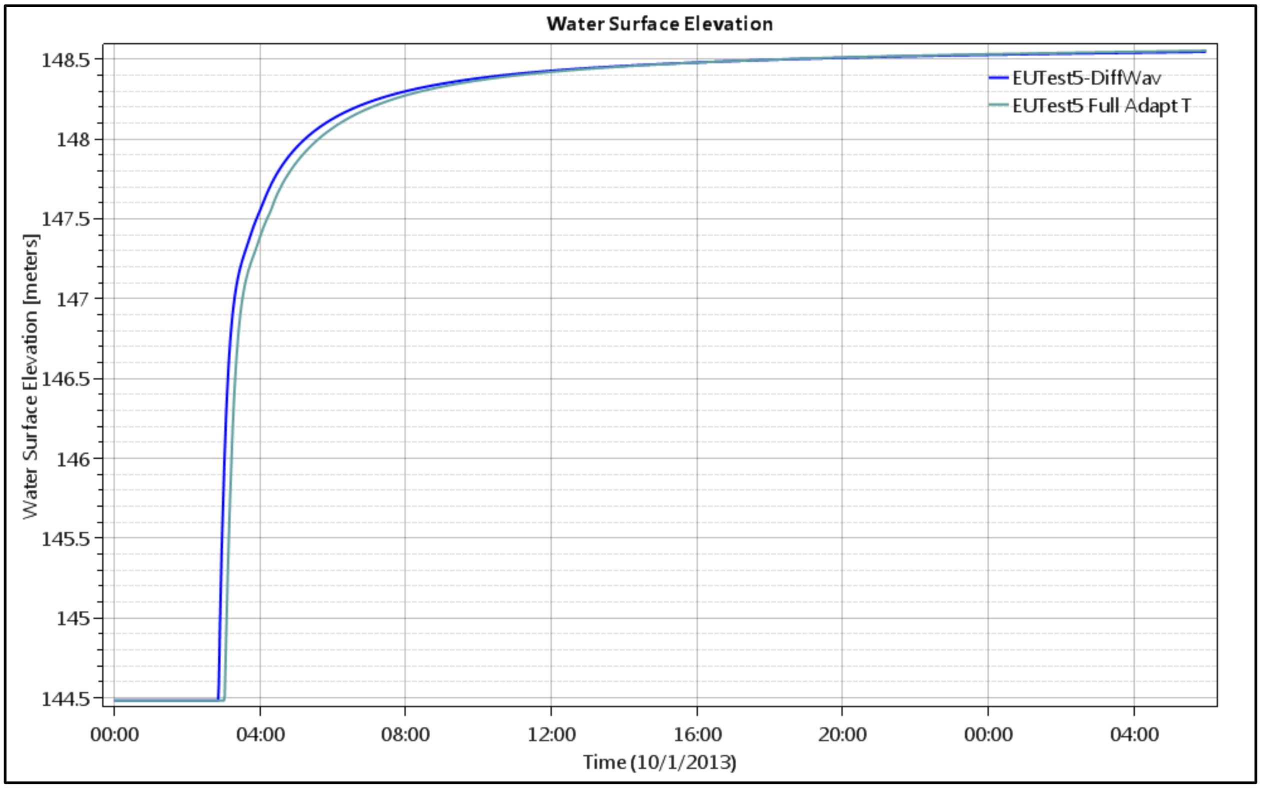


Figure 54. Test Point 5 - Water Level (depth) for Full Equations and Diffusion Wave.

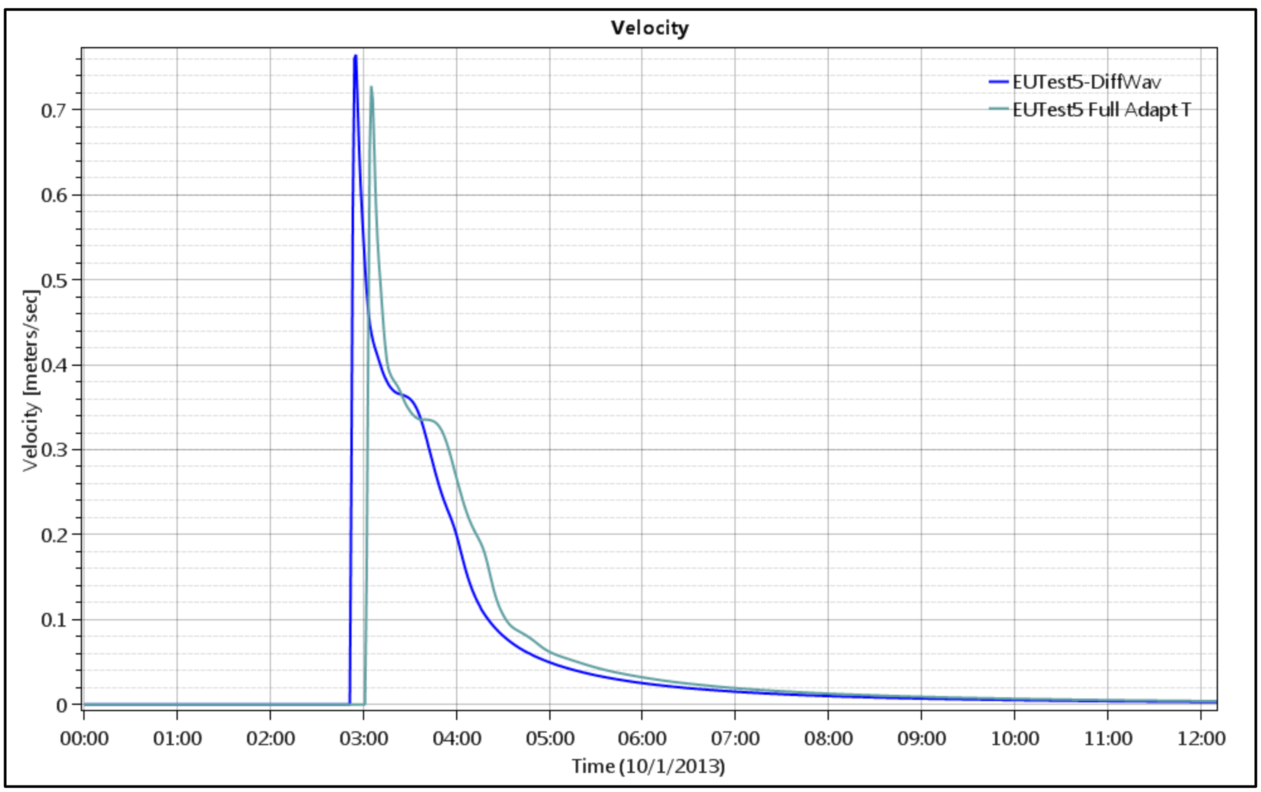


Figure 55. Test Point 5 - Velocity Time Series for Full Equations and Diffusion Wave.

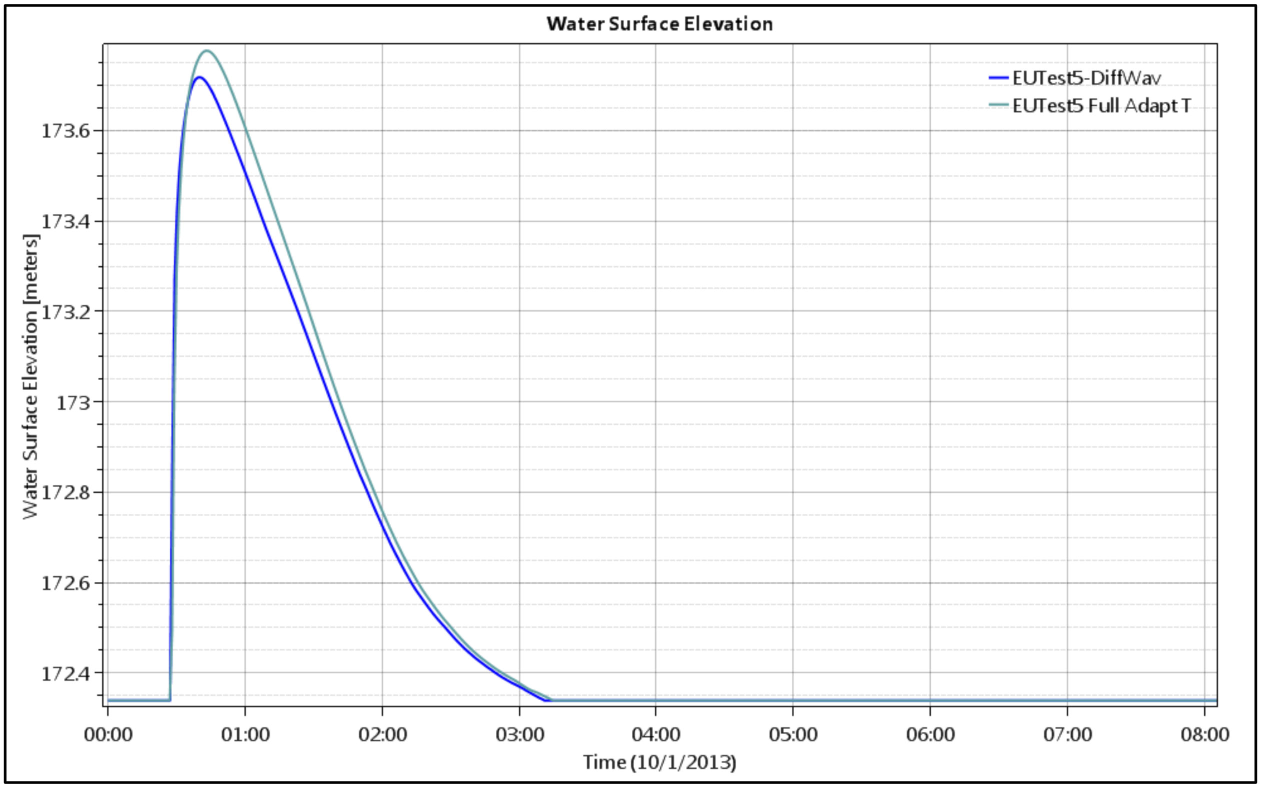


Figure 56. Test Point 6 - Water Level (depth) for Full Equations and Diffusion Wave.

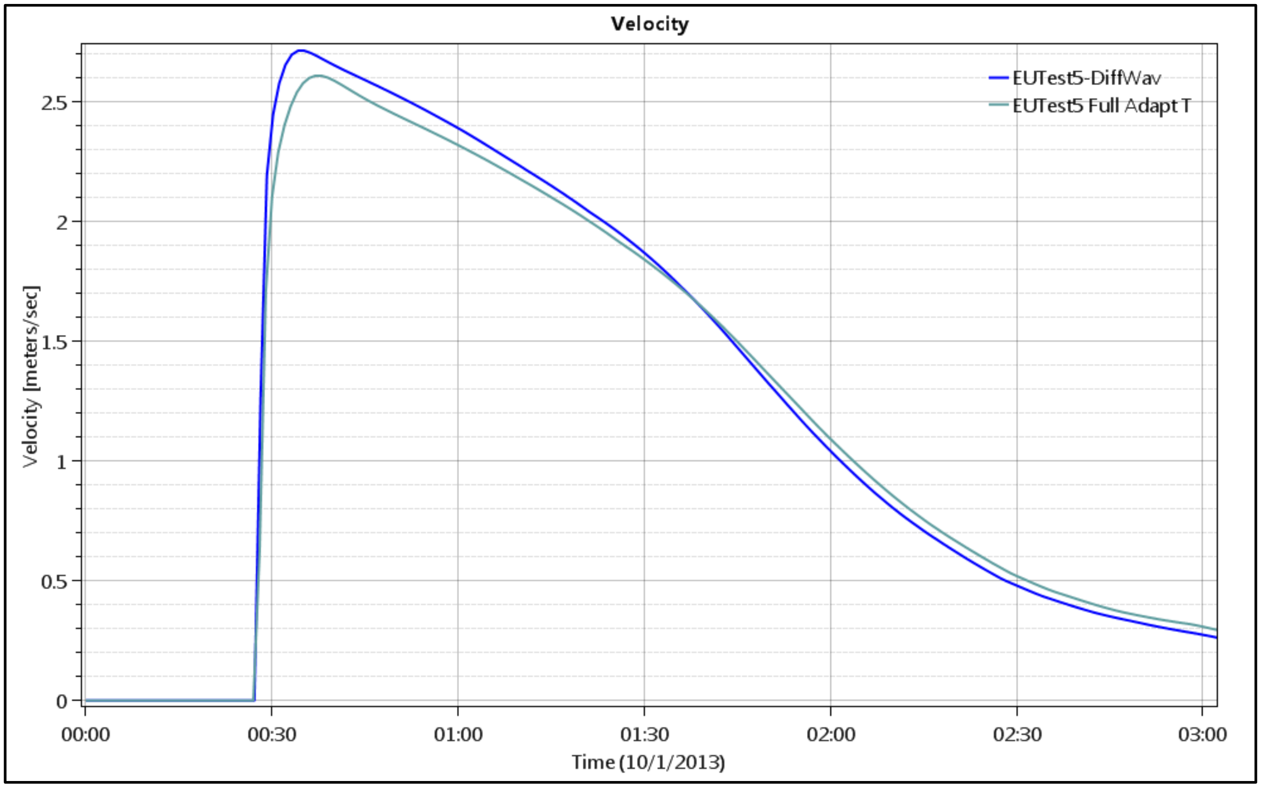


Figure 57. Test Point 6 - Velocity Time Series for Full Equations and Diffusion Wave.

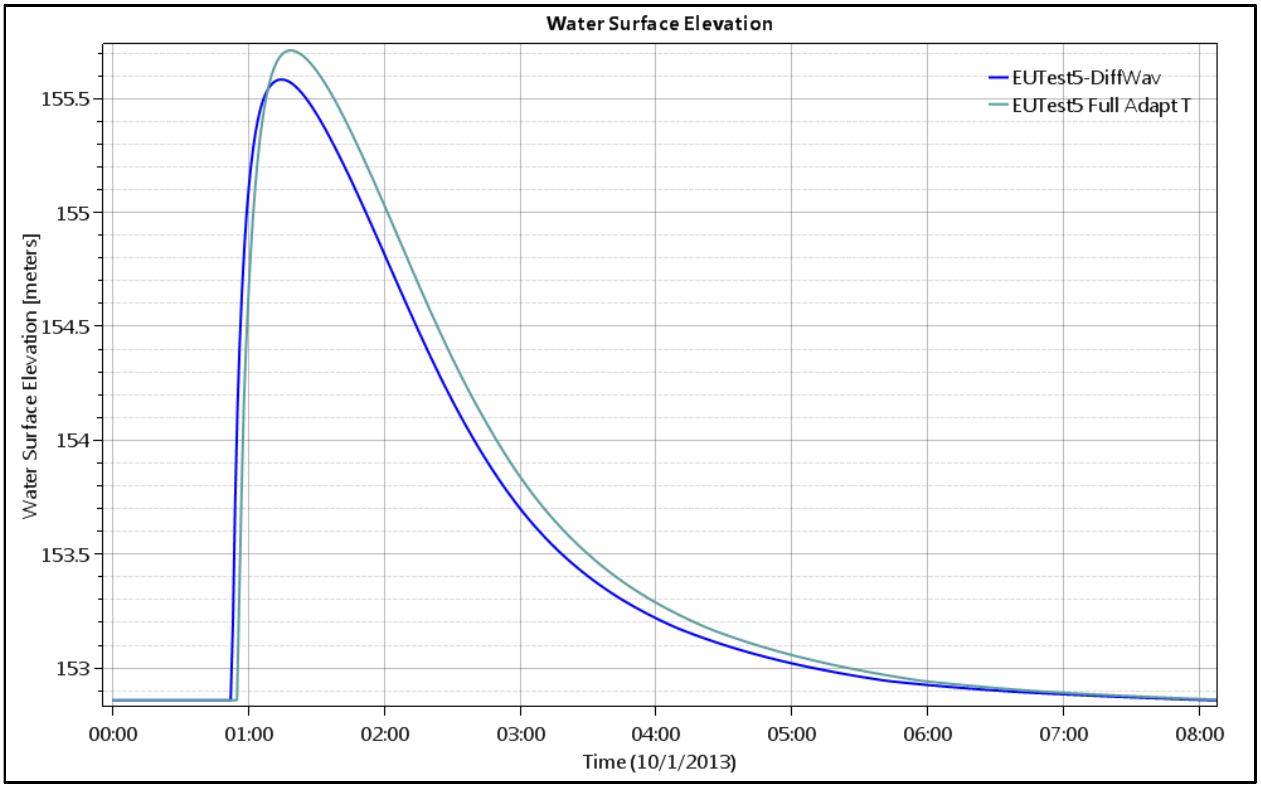


Figure 58. Test Point 7 - Water Level (depth) for Full Equations and Diffusion Wave.

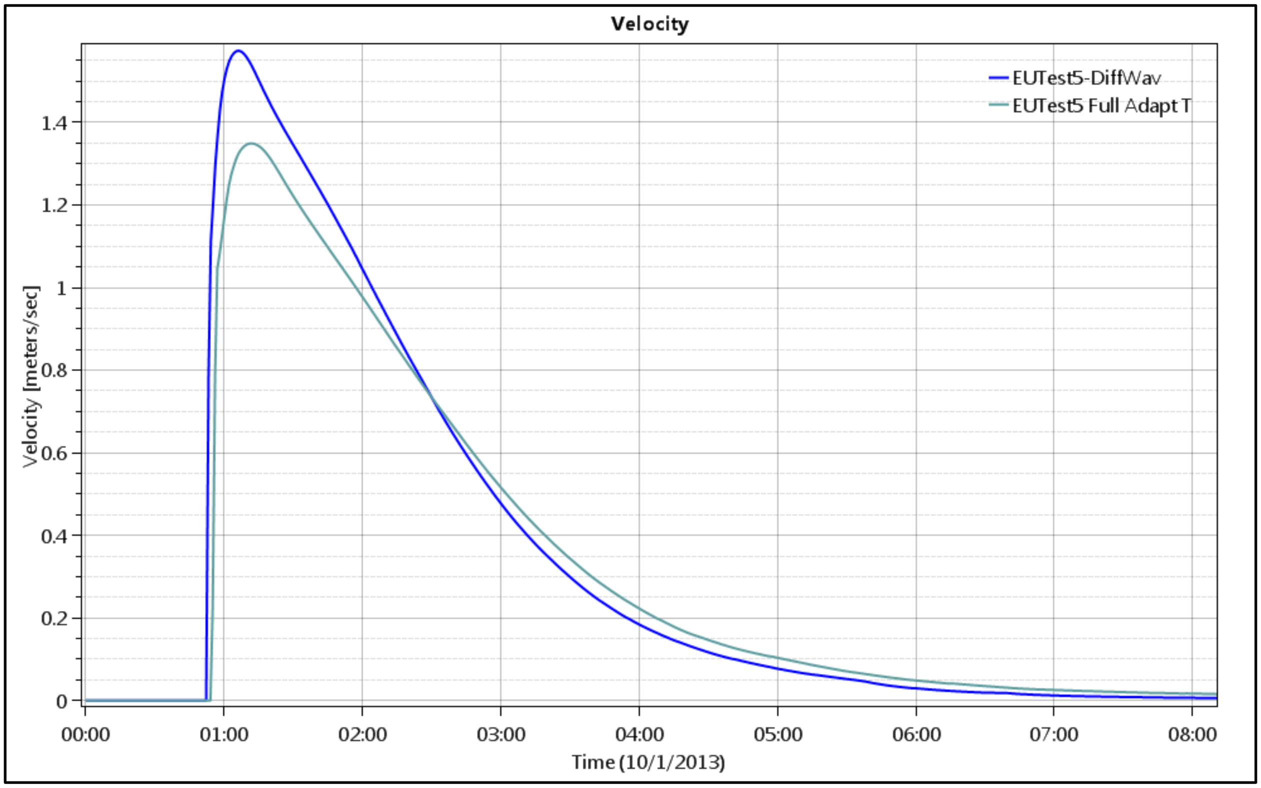


Figure 59. Test Point 7 - Velocity Time Series for Full Equations and Diffusion Wave.

6.5.1 Sensitivity to Computation Interval, ΔT = 1, 2, 5, 10 seconds – Full Saint Venant Equations

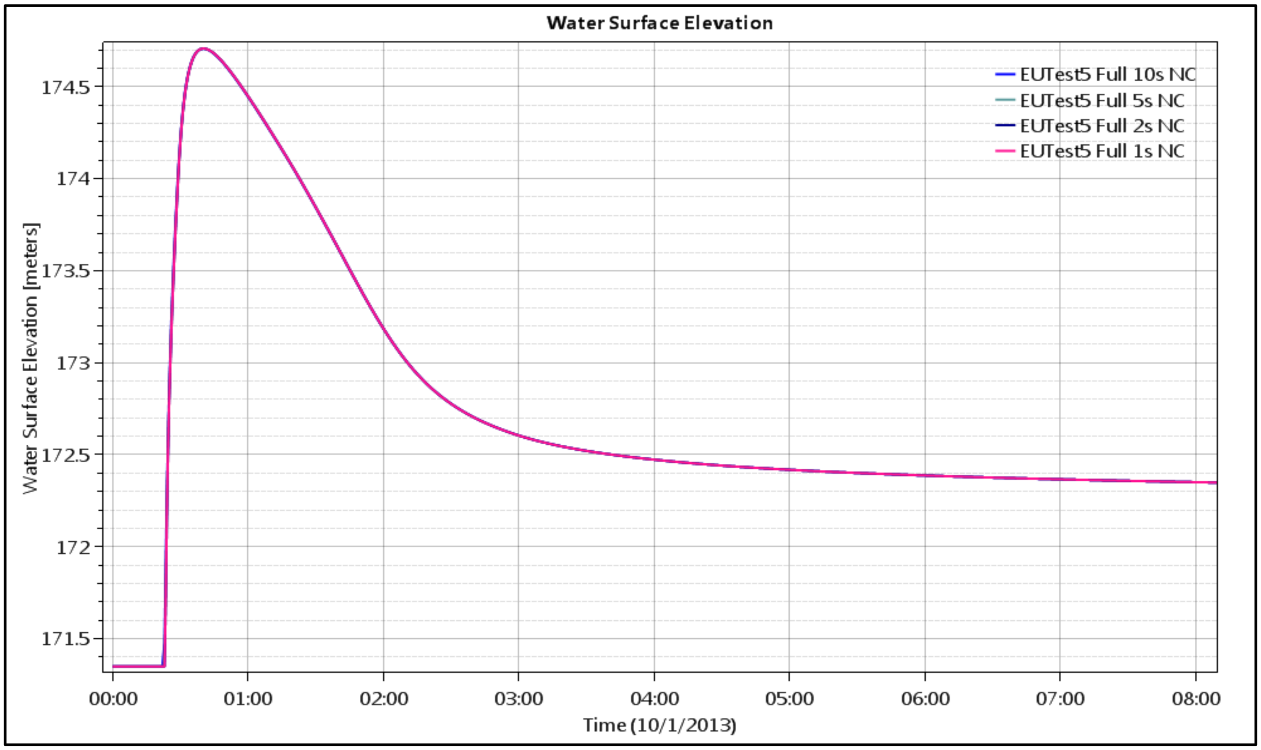


Figure 60. Test Point 1 - Water Level (depth), ΔT = 1, 2, 5, 10 seconds.

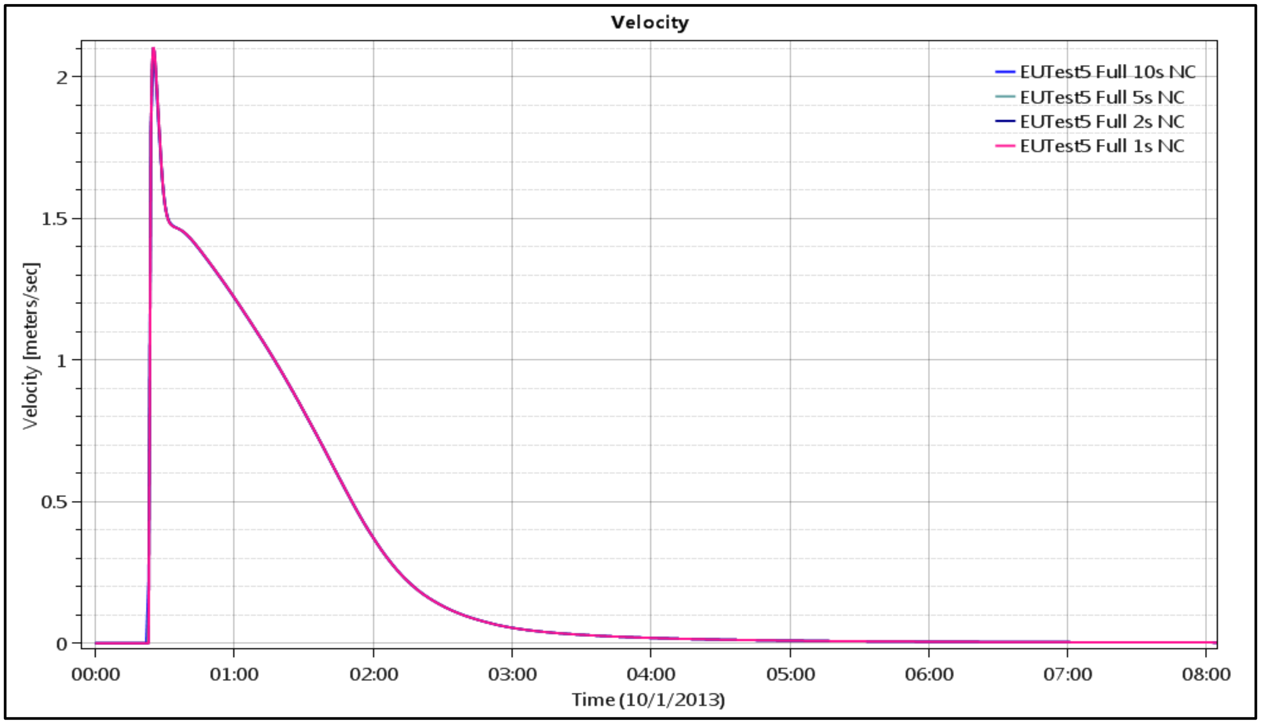


Figure 61. Test Point 1 - Velocity Time Series, ΔT = 1, 2, 5, 10 seconds.

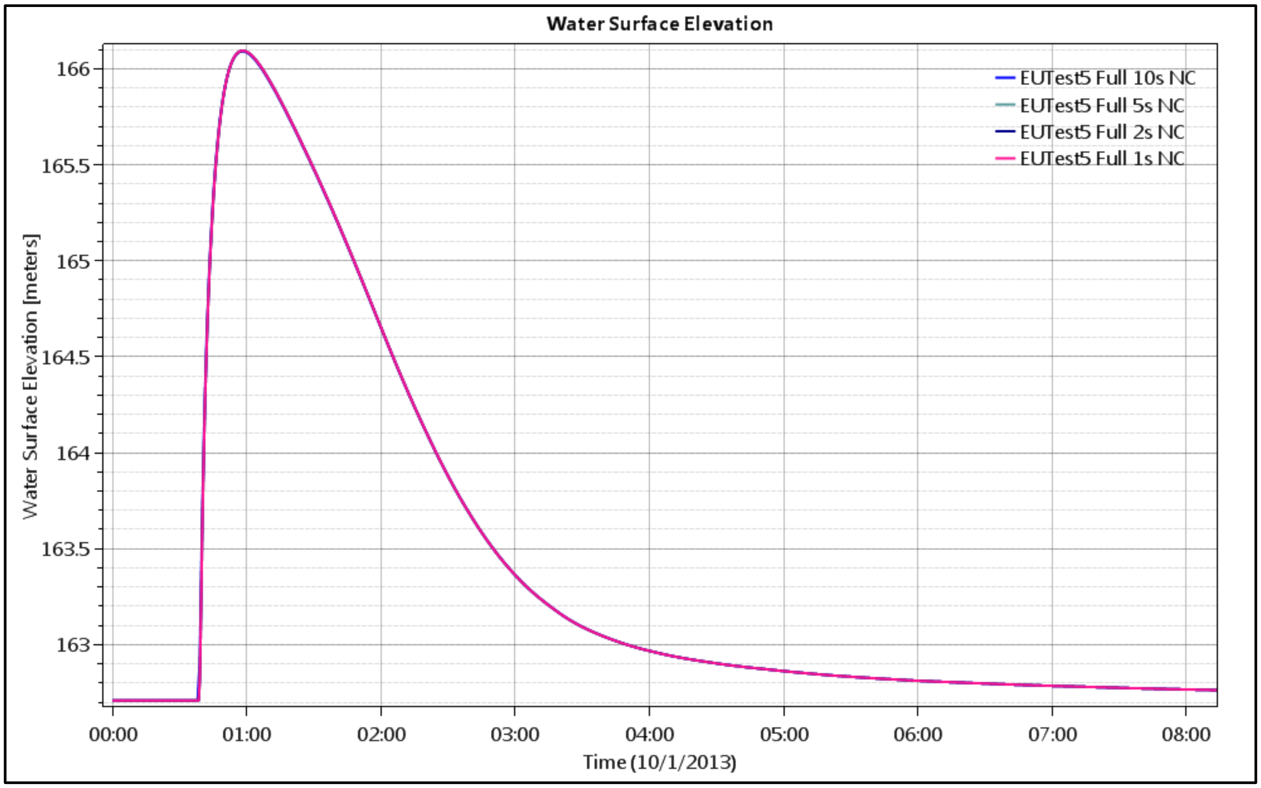


Figure 62. Test Point 2 - Water Level (depth), ΔT = 1, 2, 5, 10 seconds.

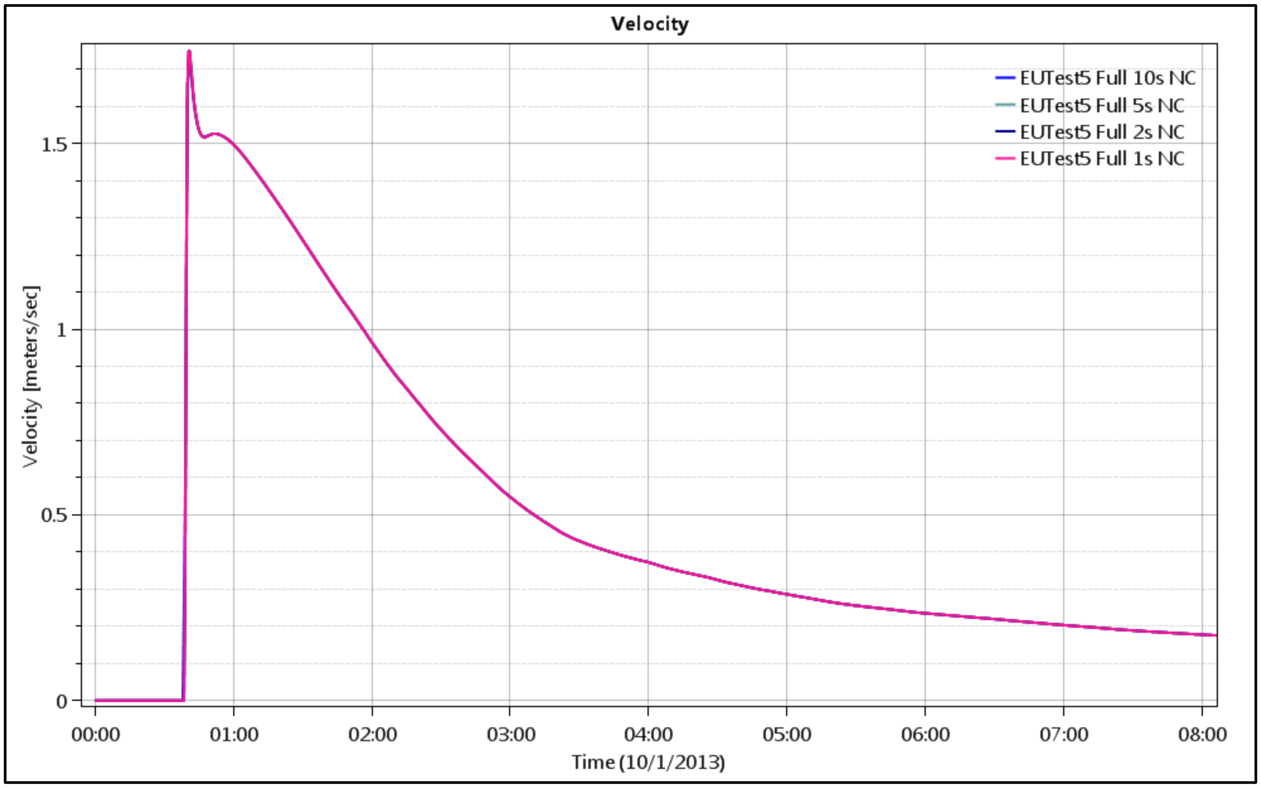


Figure 63. Test Point 2 - Velocity Time Series, ΔT = 1, 2, 5, 10 seconds.

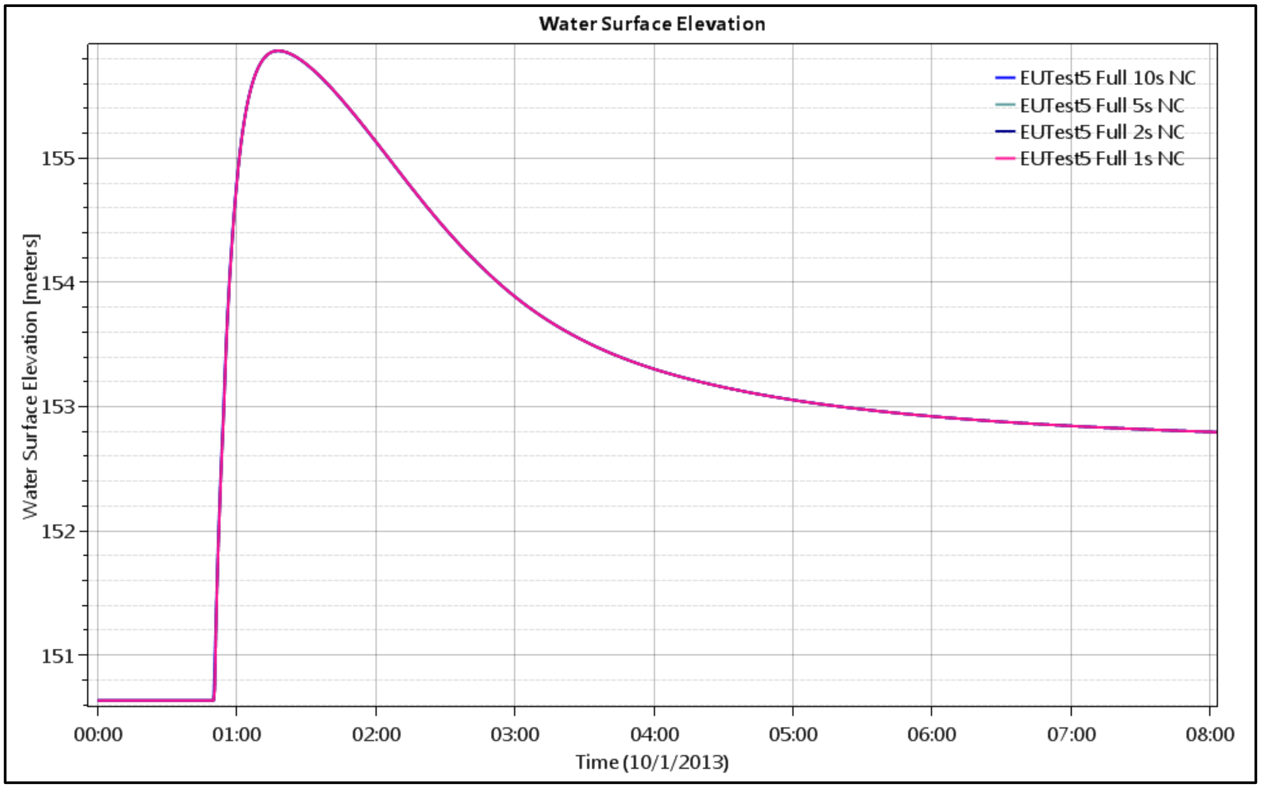


Figure 64. Test Point 3 - Water Level (depth), ΔT = 1, 2, 5, 10 seconds.

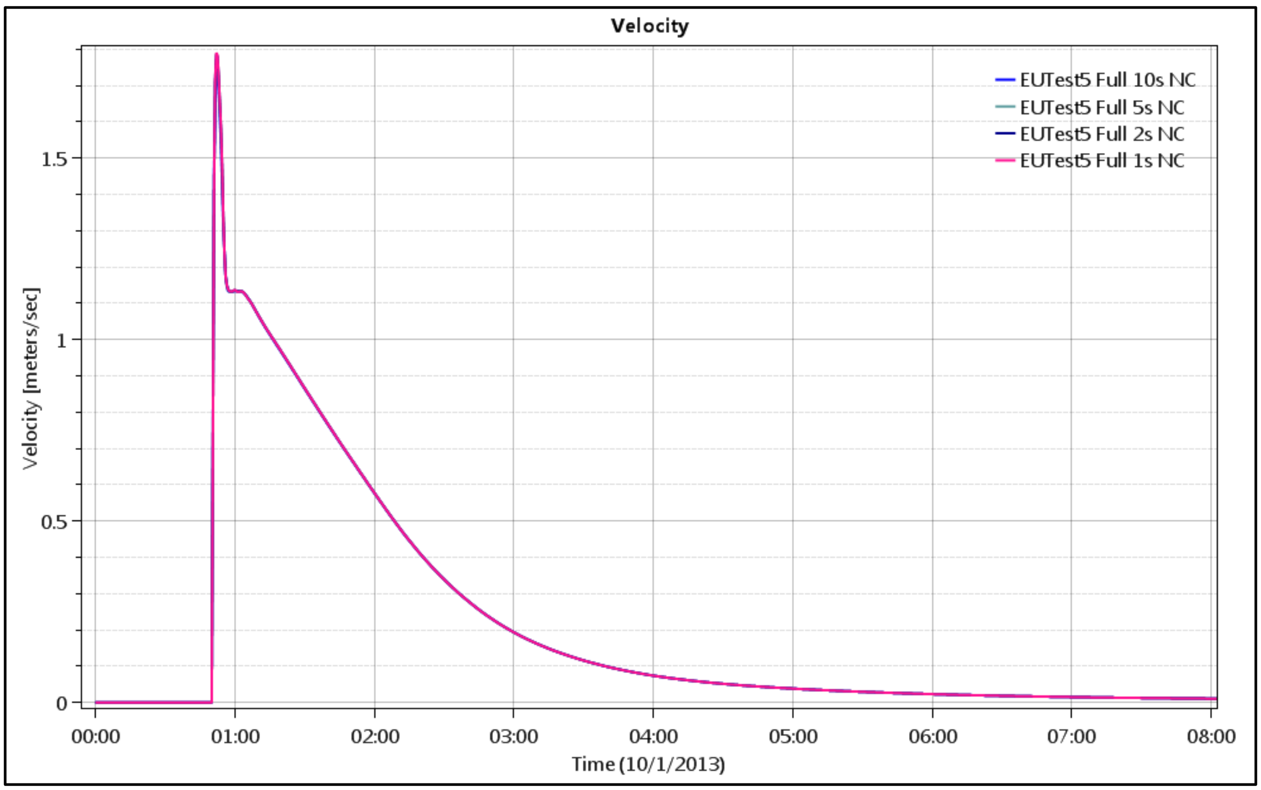


Figure 65. Test Point 3 - Velocity Time Series, ΔT = 1, 2, 5, 10 seconds.

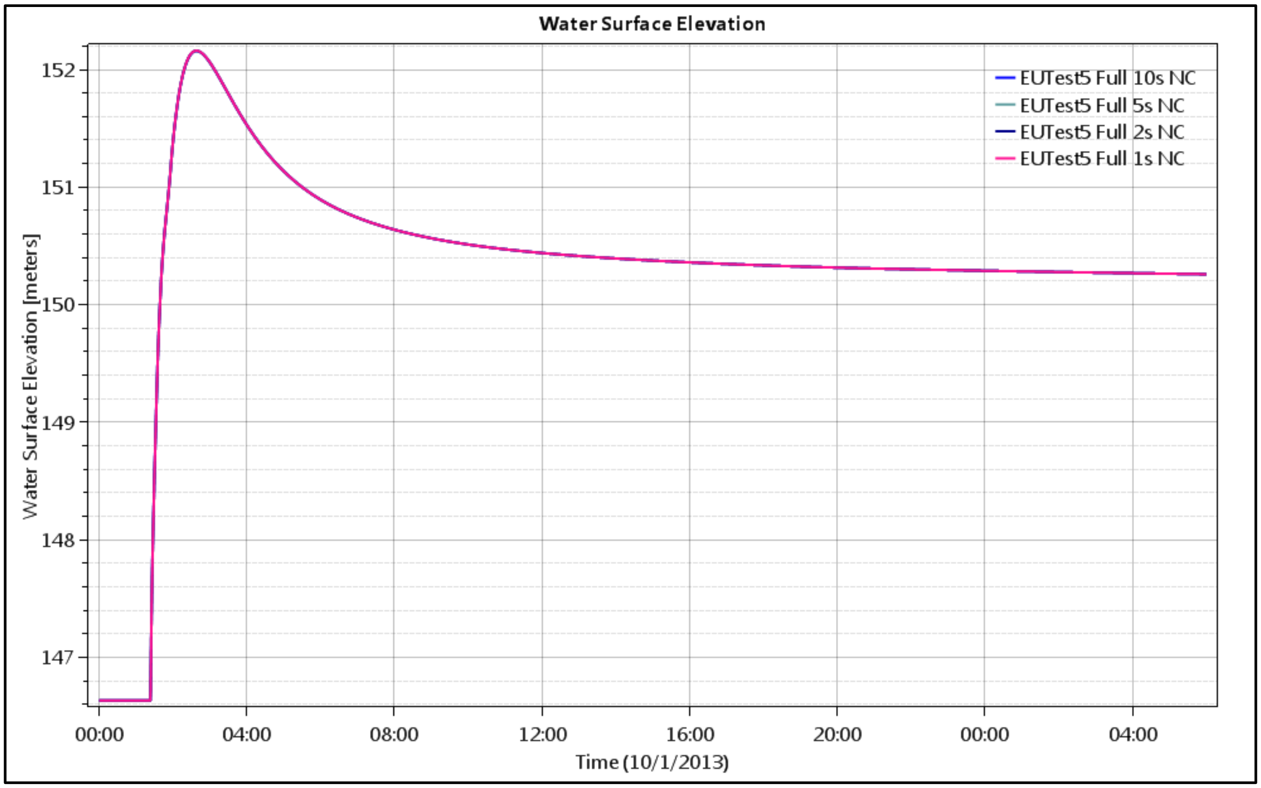


Figure 66. Test Point 4 - Water Level (depth), ΔT = 1, 2, 5, 10 seconds.

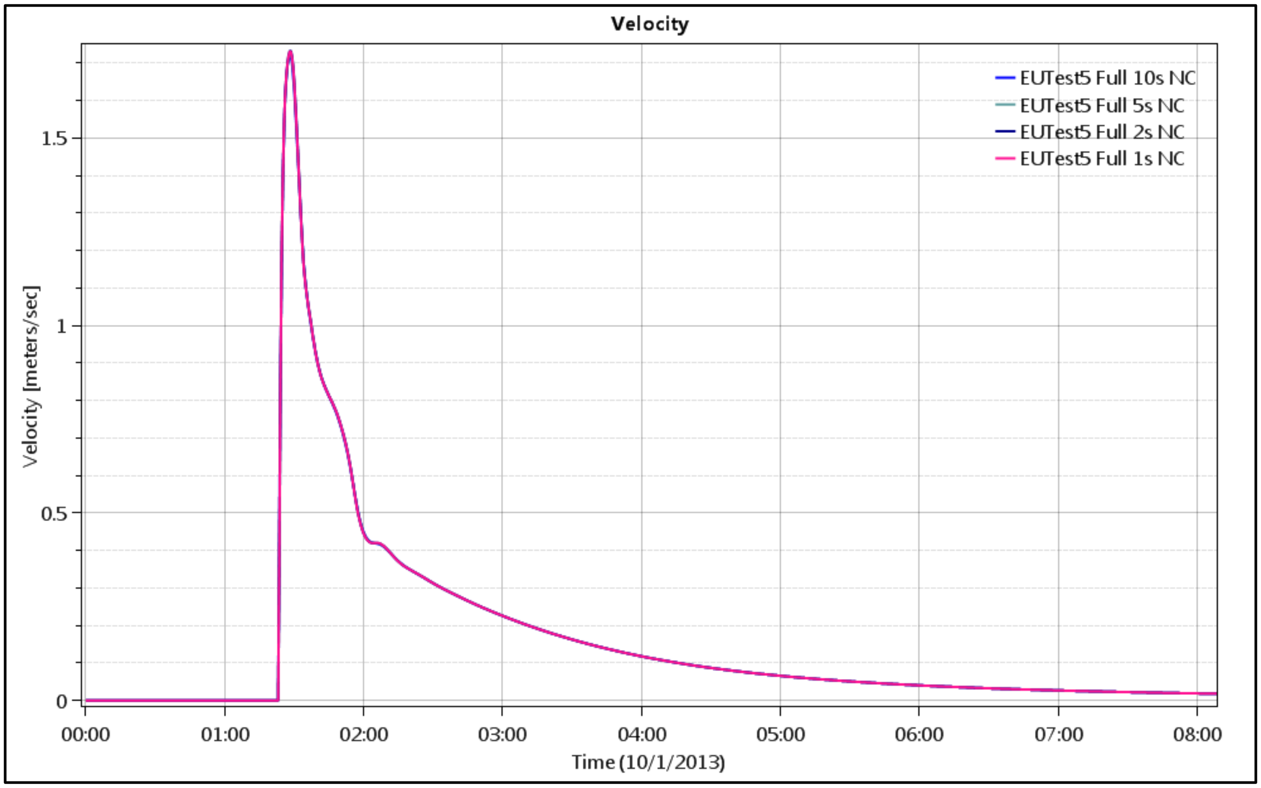


Figure 67. Test Point 4 - Velocity Time Series, ΔT = 1, 2, 5, 10 seconds.

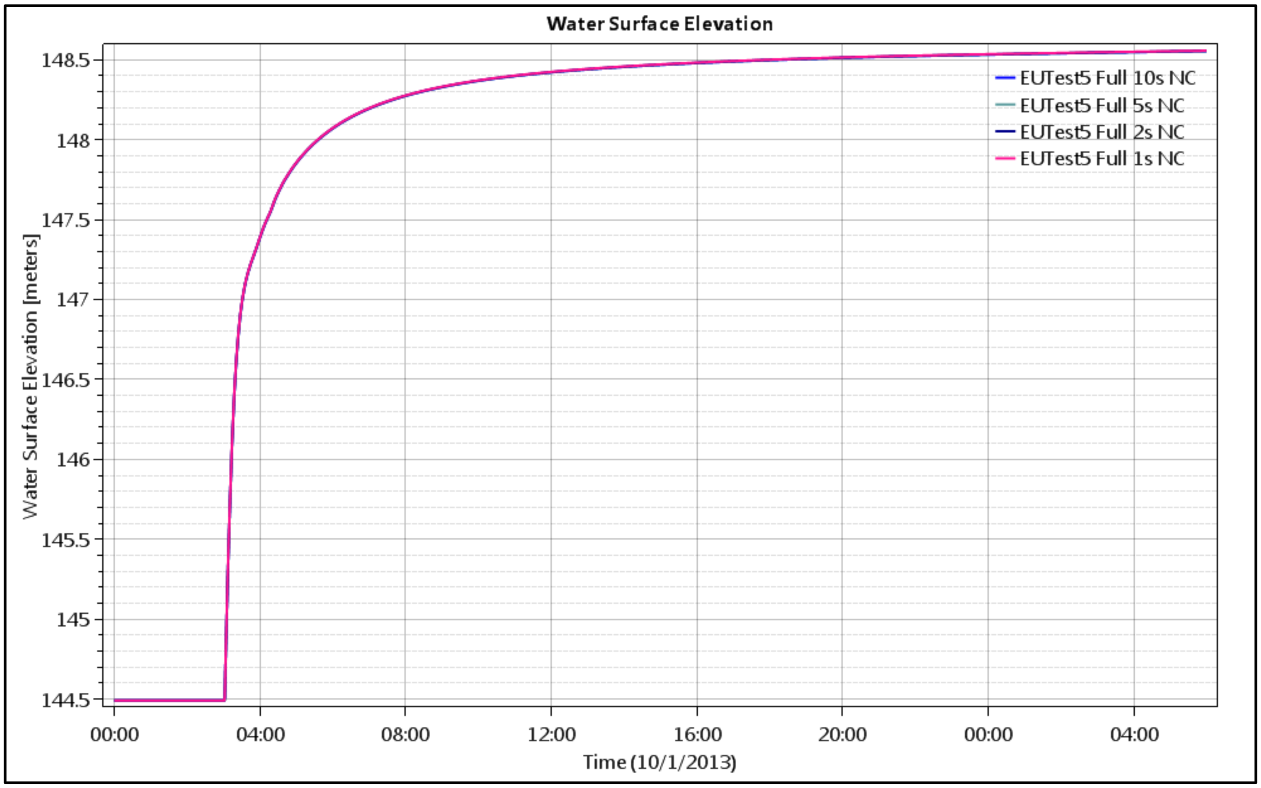


Figure 68. Test Point 5 - Water Level (depth), ΔT = 1, 2, 5, 10 seconds.

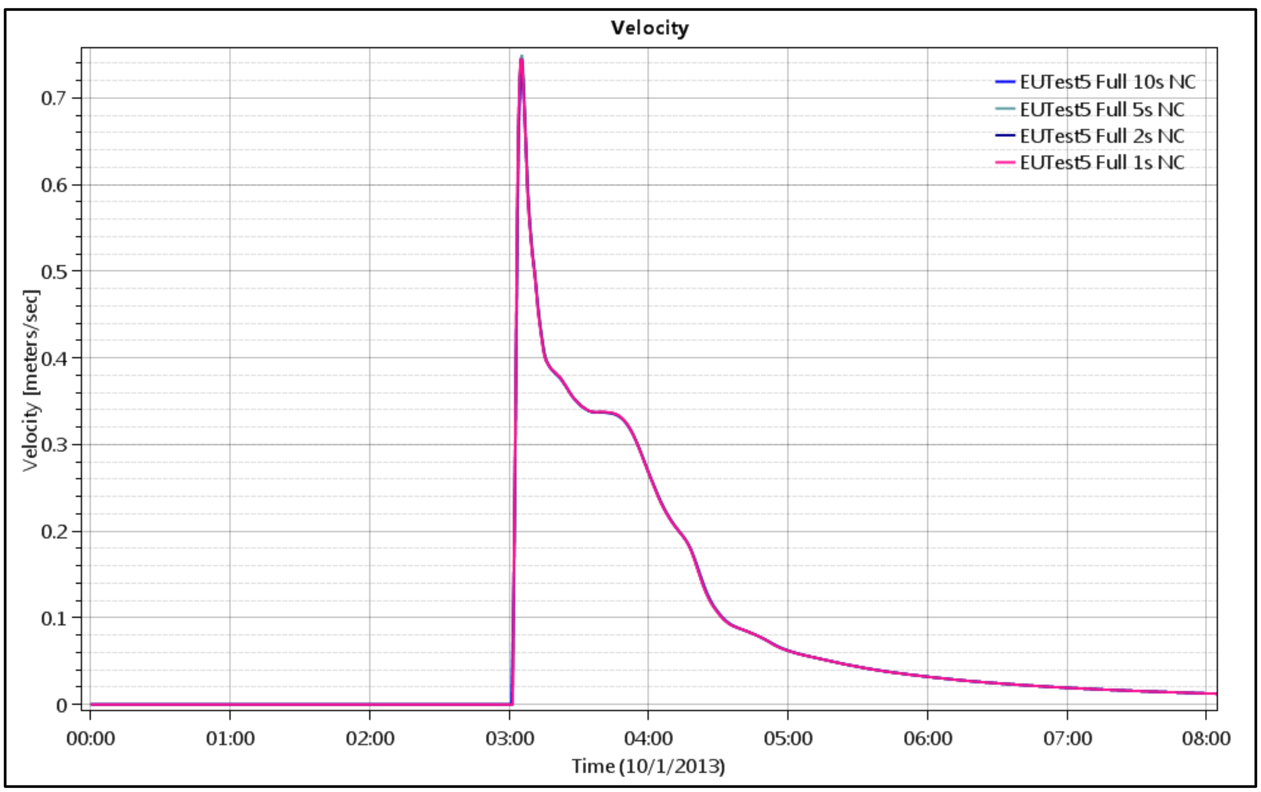


Figure 69. Test Point 5 - Velocity Time Series, ΔT = 1, 2, 5, 10 seconds.

6.5.2 Sensitivity to Grid Resolution, 50 and 100 Meter Grids – Full Saint Venant Equations

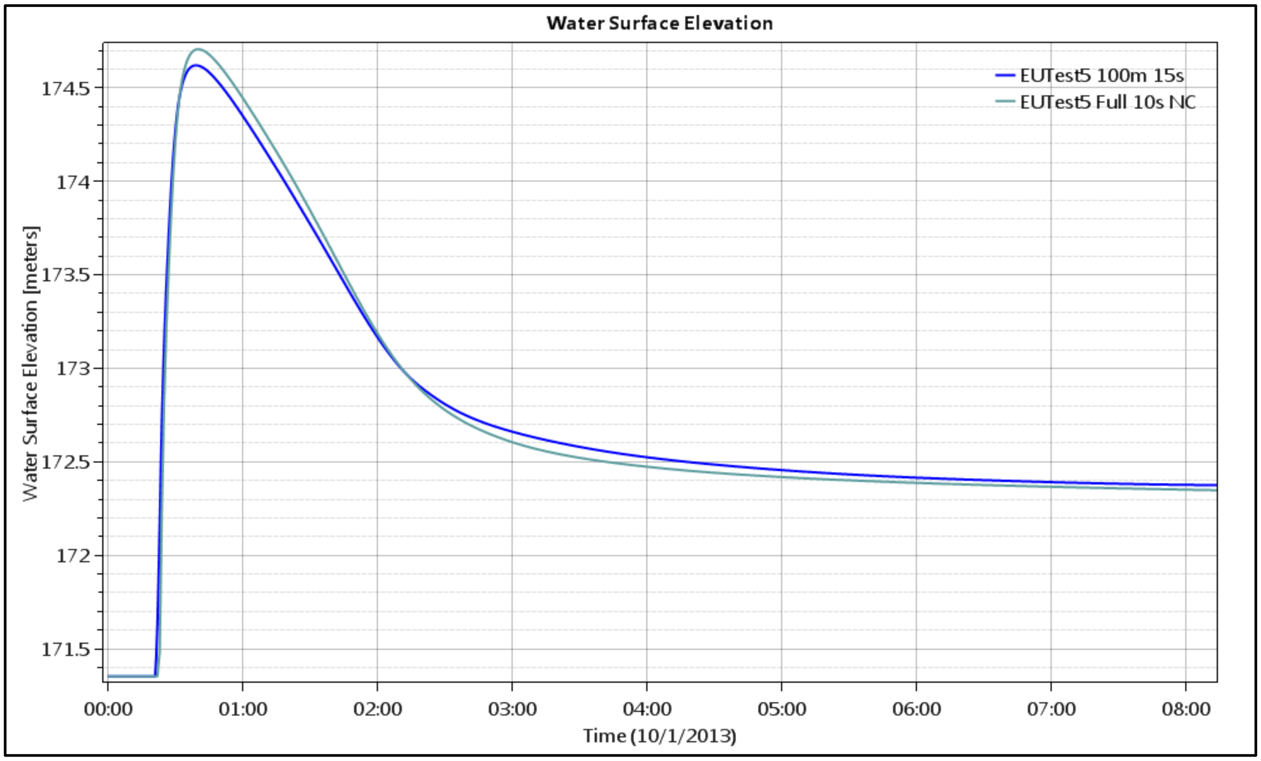


Figure 70. Test Point 1 - Water Level (depth), 50 and 100 meter grids.

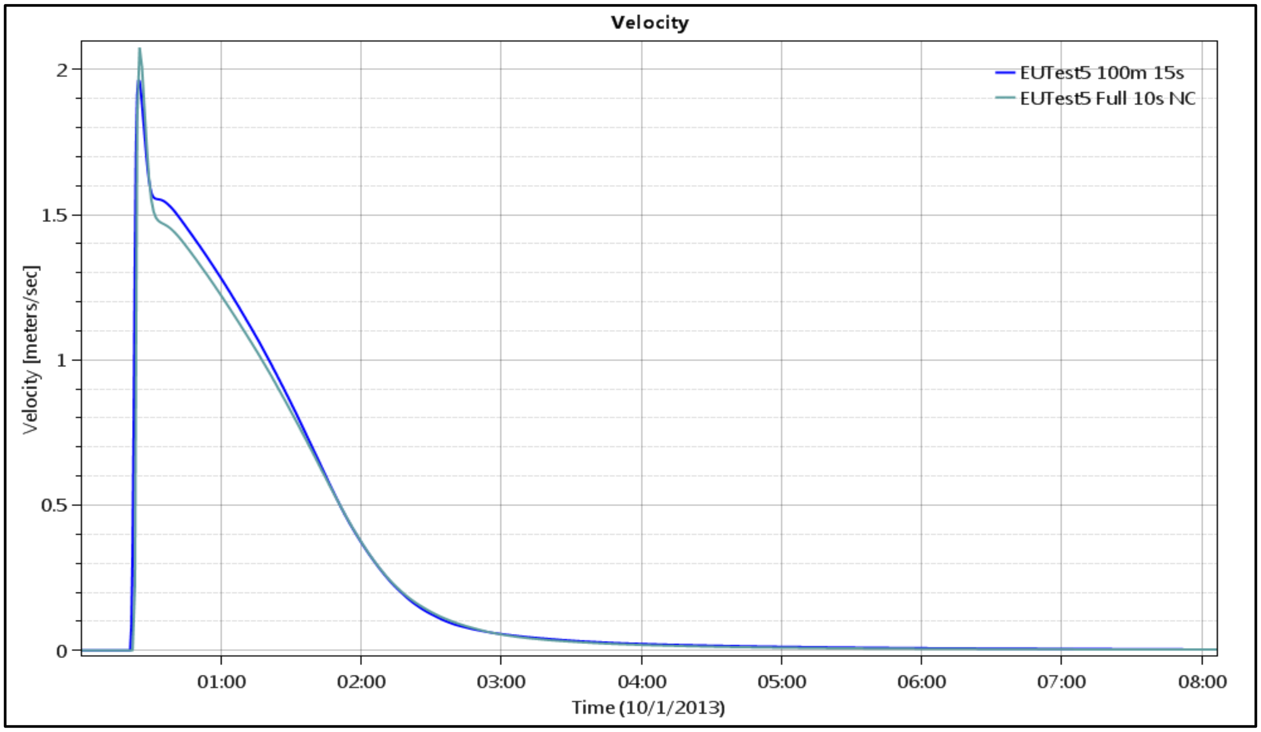


Figure 71. Test Point 1 - Velocity Time Series, 50 and 100 meter grids.

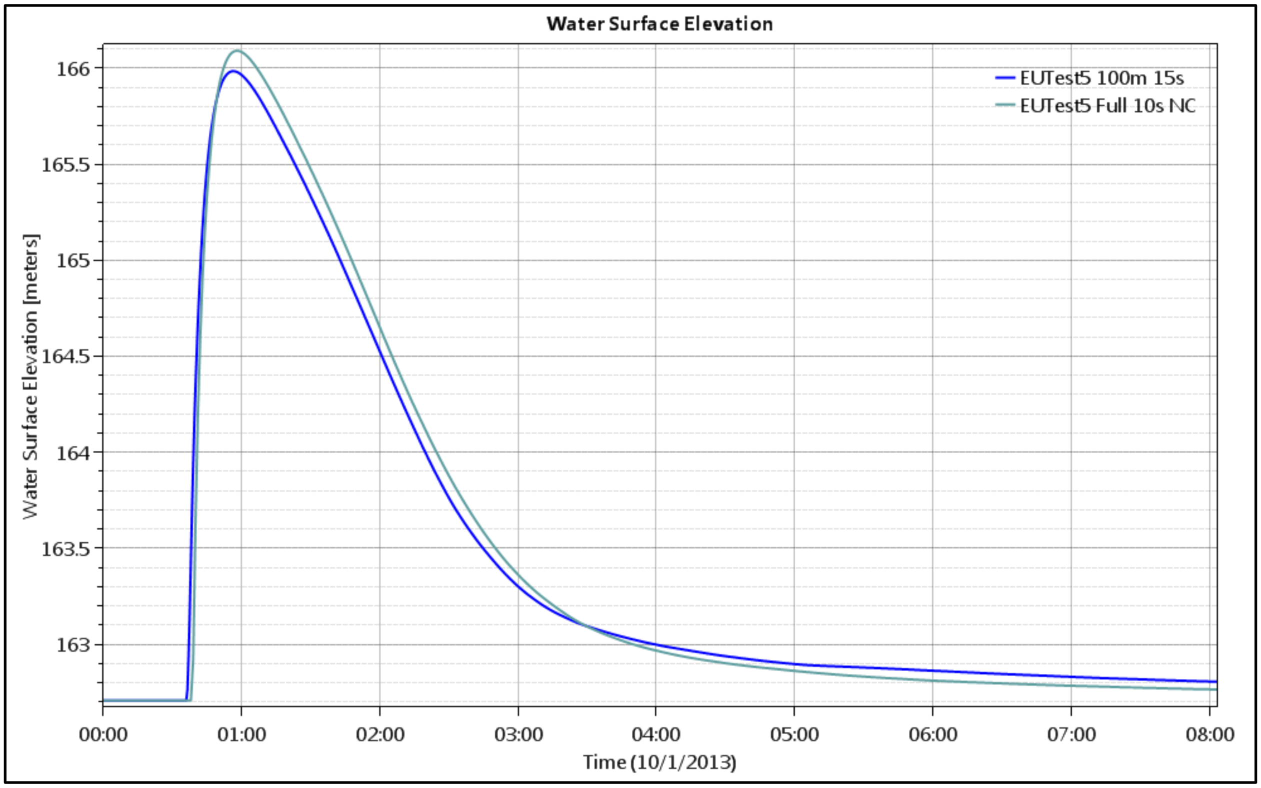


Figure 72. Test Point 2 - Water Level (depth), 50 and 100 meter grids.

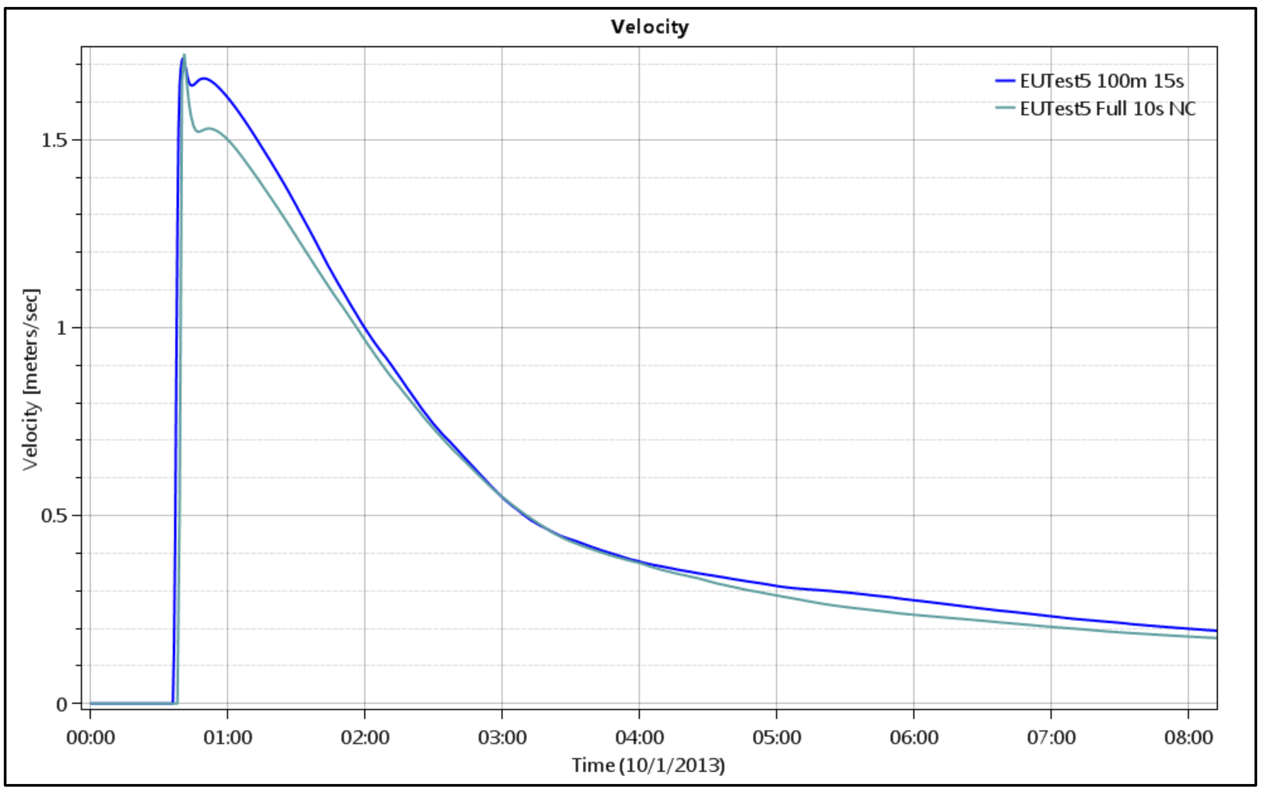


Figure 73. Test Point 2 - Velocity Time Series, 50 and 100 meter grids.

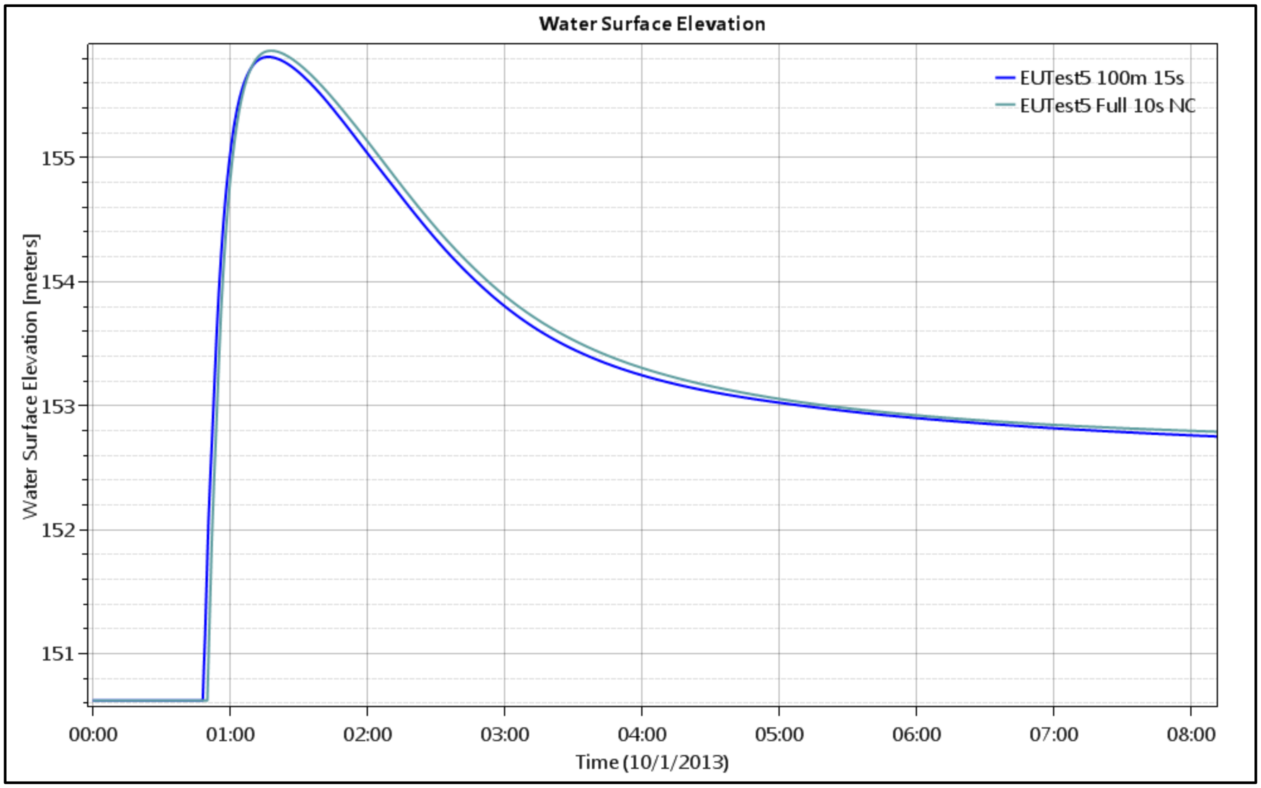


Figure 74. Test Point 3 - Water Level (depth), 50 and 100 meter grids.

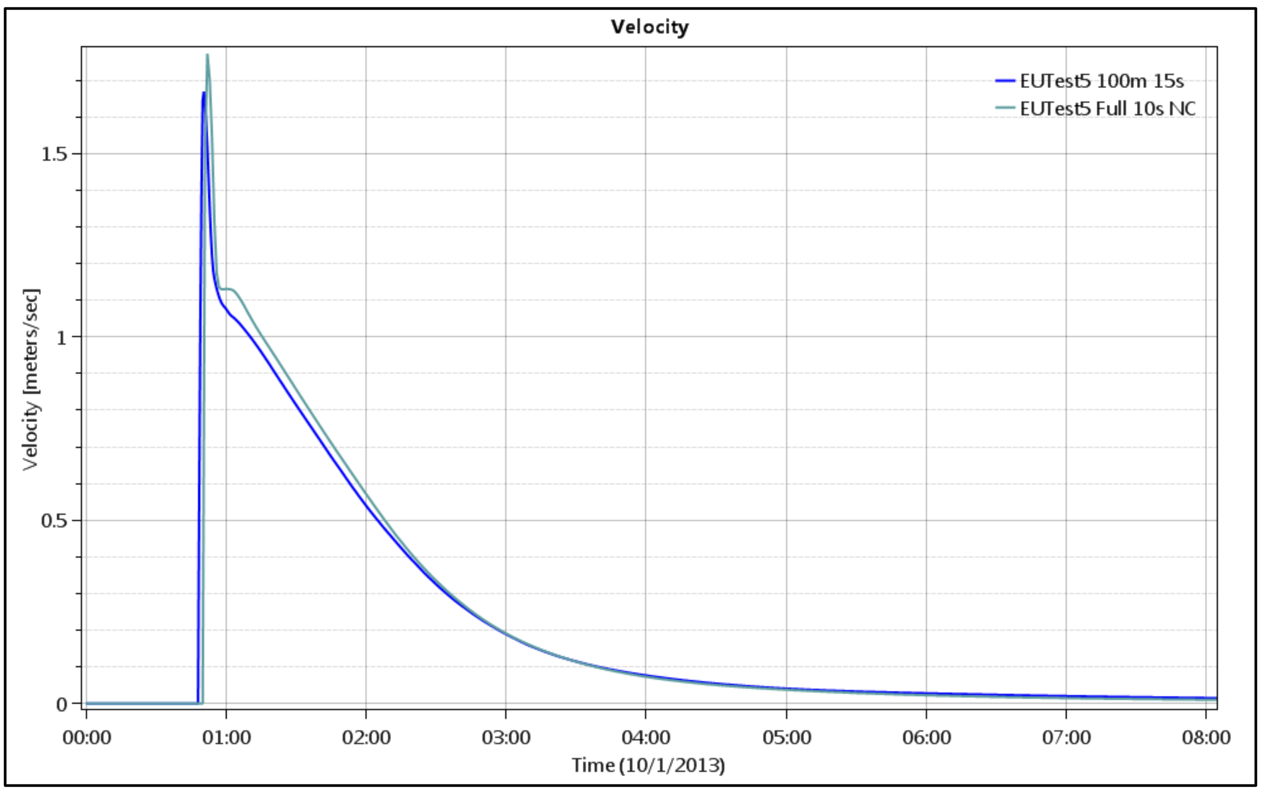


Figure 75. Test Point 3 - Velocity Time Series, 50 and 100 meter grids.

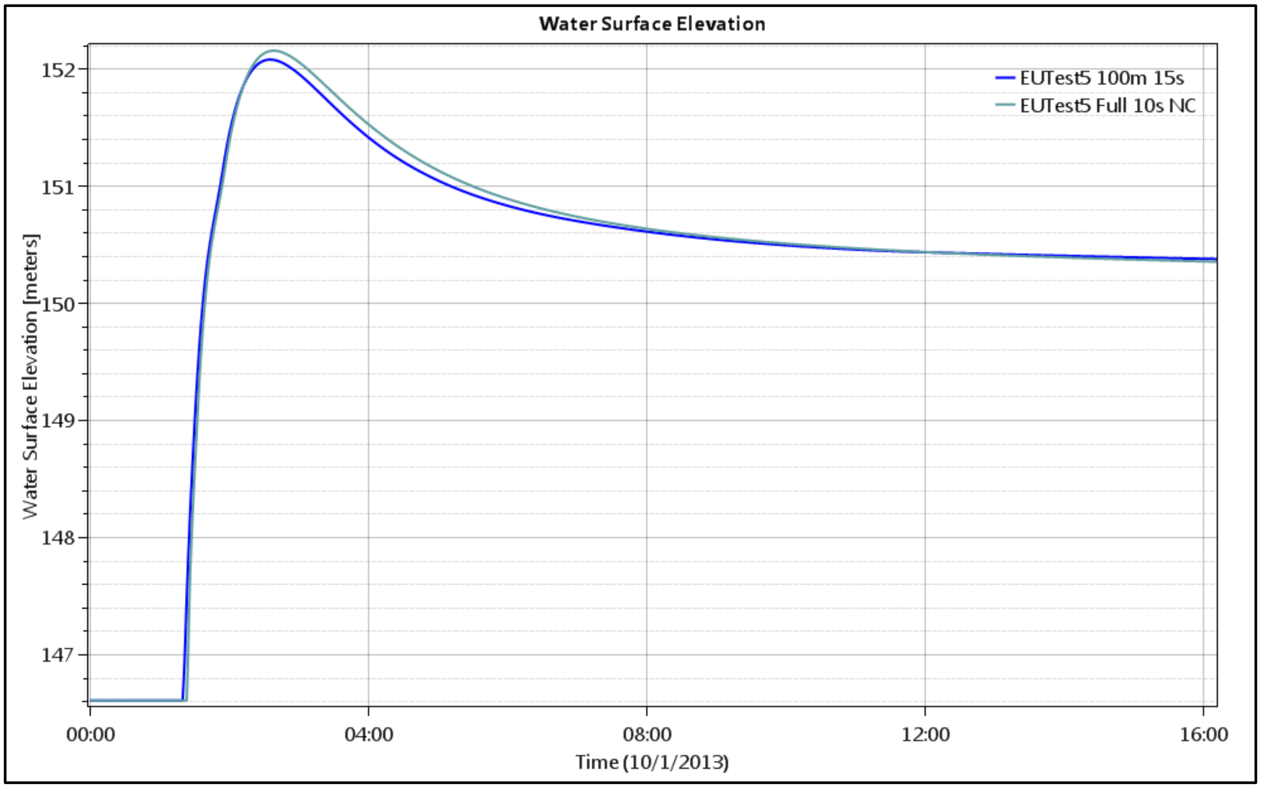


Figure 76. Test Point 4 - Water Level (depth), 50 and 100 meter grids.

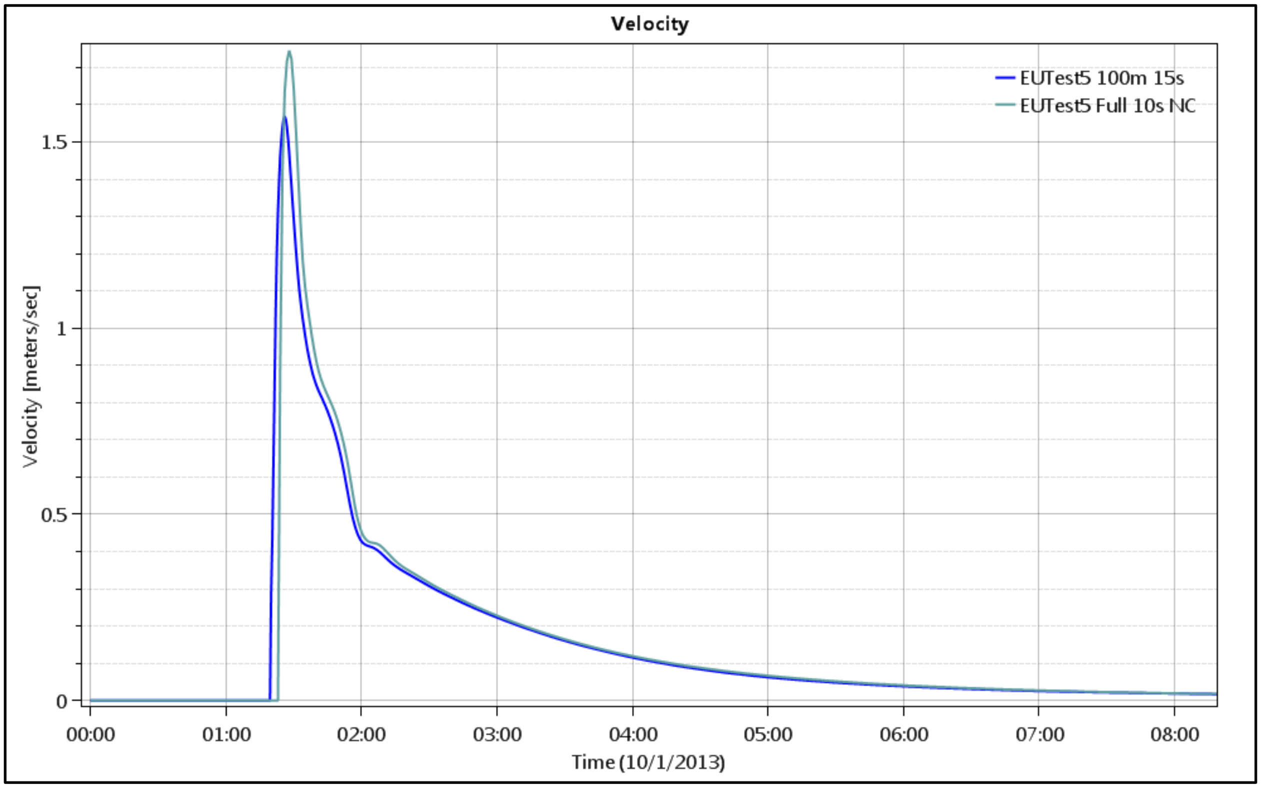


Figure 77. Test Point 4 - Velocity Time Series, 50 and 100 meter grids.

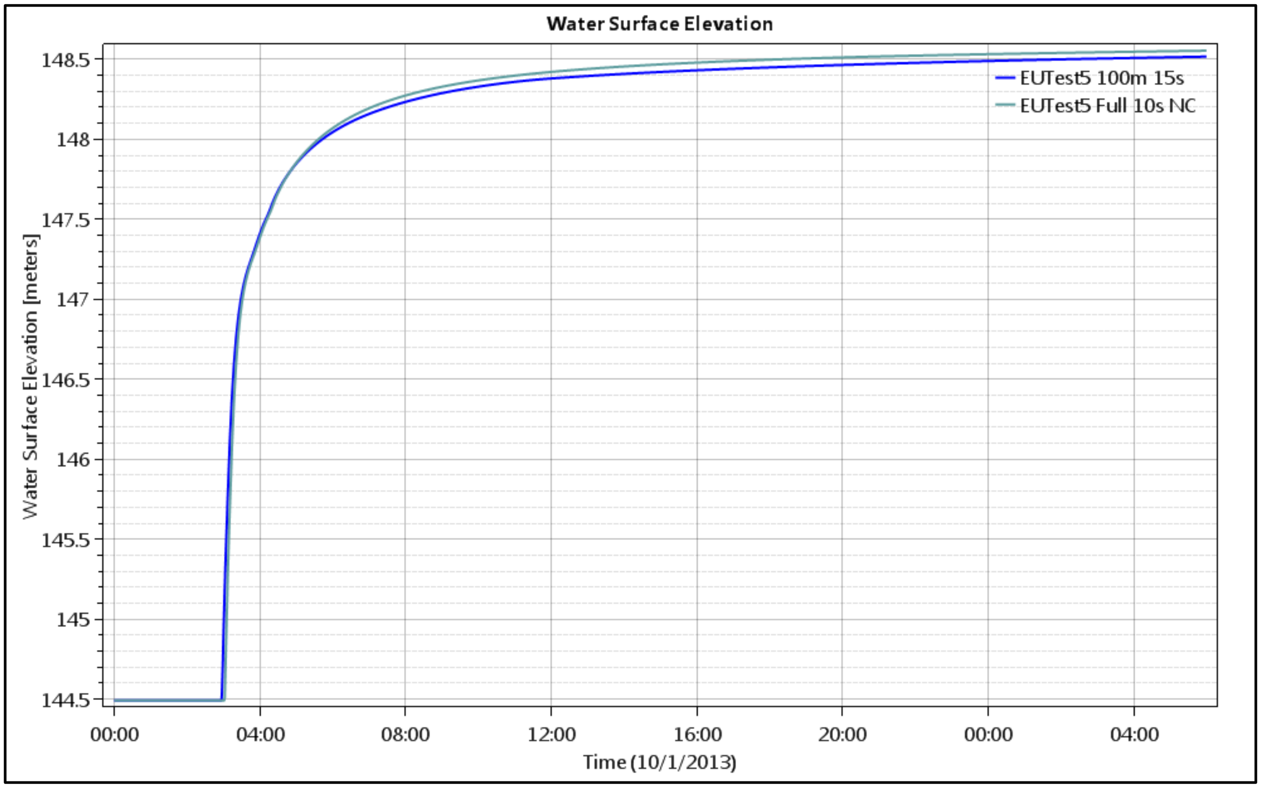


Figure 78. Test Point 5 - Water Level (depth), 50 and 100 meter grids.

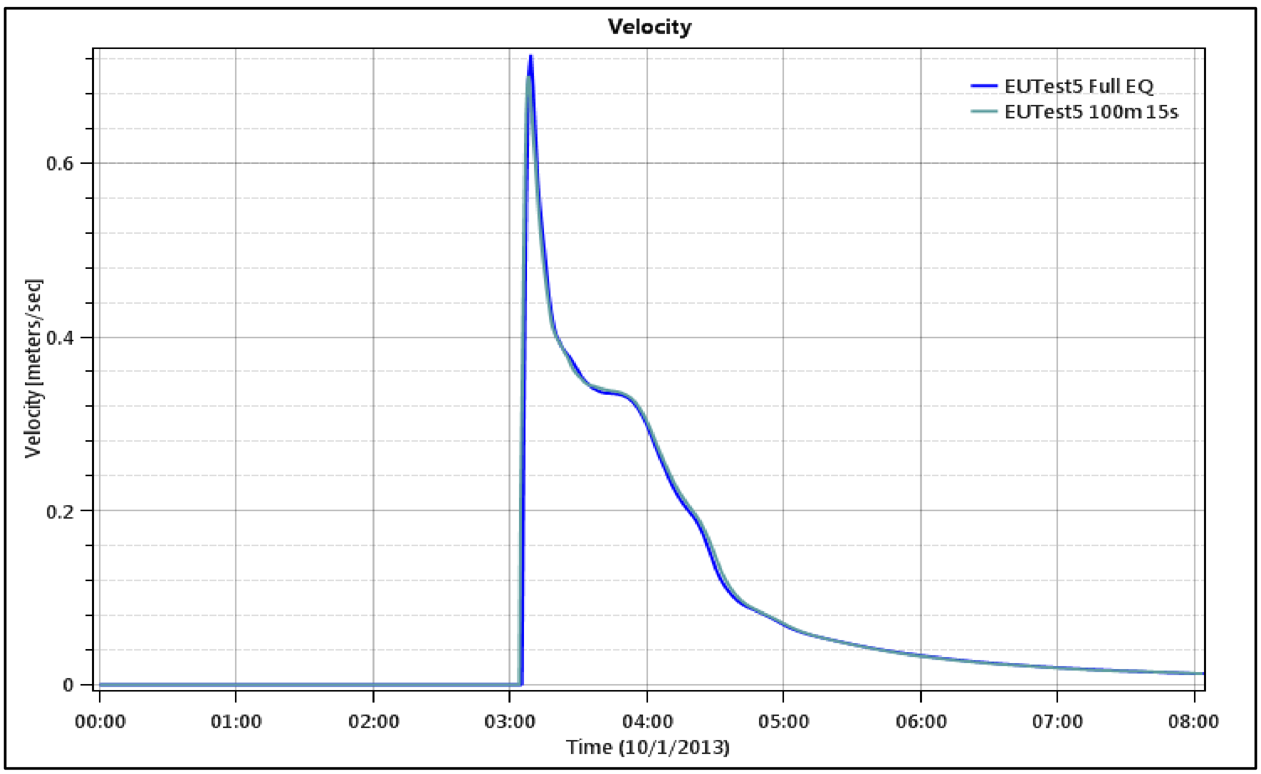


Figure 79. Test Point 5 - Velocity Time Series, 50 and 100 meter grids.

Chapter 7

Benchmark Tests 6A & 6B

Dam Break

7.1 Objective

Benchmark Test 6B tests the capability of each two-dimensional model to correctly simulate hydraulic jumps and wake zones behind buildings using high-resolution modeling. This test depicts an instantaneous dam break upstream of a building.

7.2 Description

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

Test 6A is the original test proposed in Soares-Frazao and Zech 2002, where the physical dimensions are those of the laboratory model. The test involves a simple topography, a dam with a one meter wide opening, and an idealized representation of a single building downstream of the dam (Figure 80). An initial condition is applied, consisting of a uniform depth of 0.4 meters upstream from the dam, and 0.02 meters downstream from the dam. The flow is contained by vertical walls at all boundaries of the DEM.

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

7.3 Boundary and Initial Conditions

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

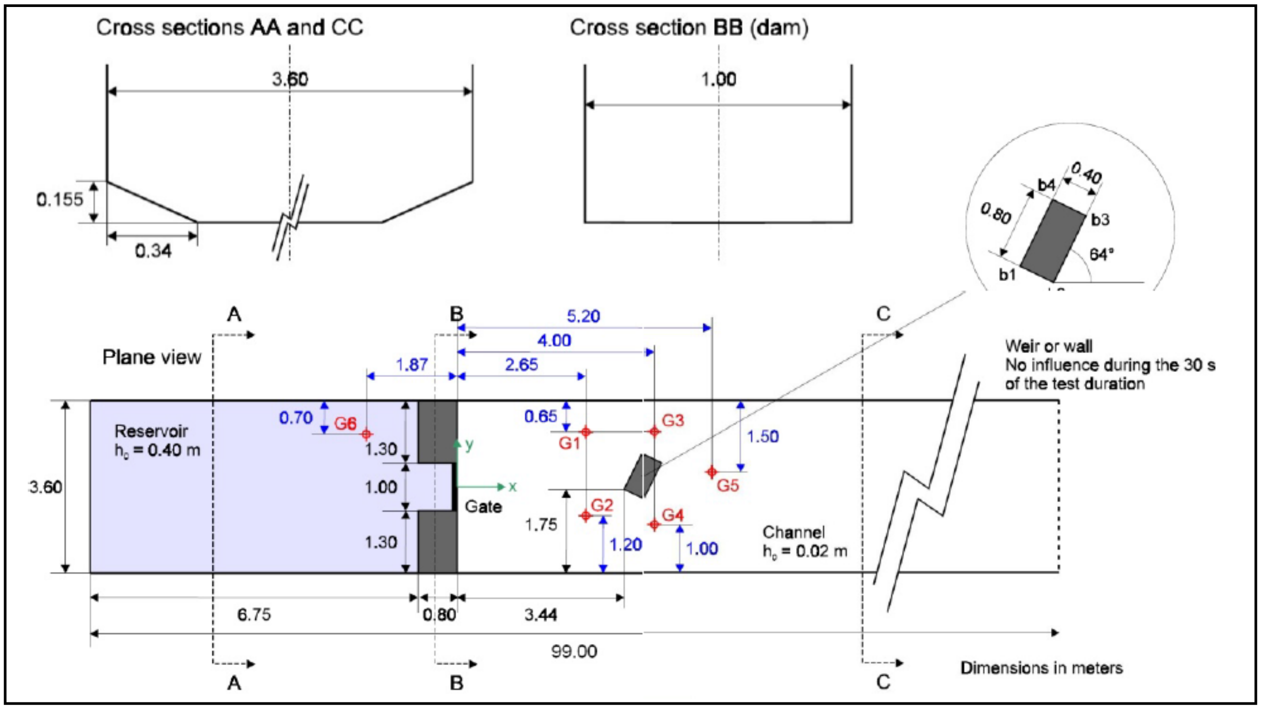


Figure 80. Setup for Test 6A (adapted from Soares-Frazao and Zech, 2002).

7.4 Parameter Values

- No preferred value of eddy viscosity is specified
- In Test 6A:
  - Manning's n: 0.01 (uniform)
  - Model grid resolution: 0.1 meter or approximately 36,000 nodes in area bounded by vertical scale
  - Time of end: the model is to be run until time t equals 2 minutes (if an alternative end time is used, run times must be reported for t equals 2 minutes)
- In Test 6B:
  - Manning's n: 0.05 (uniform)
  - Model grid resolution: 2 meters or approximately 36,000 nodes in area bounded by vertical scale

7.5 Results

Results for this test are shown in Figures 81 – 98. HEC-RAS performed extremely well compared to the leading 2D models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK.

Note: HEC-RAS was run for both Test 6A and 6B. The results presented here are for test 6B. The measured lab data for test 6A was very noisy. None of the models applied to this data set were able to replicate the lab results. Below is a quote about the Test 6A results from the Joint Defra / Environment Agency research report:

"The UCL measurements exhibit high frequency oscillations (that were either physical or due to measurement errors) of amplitude typically ~0.01m (water levels) and ~0.2m/s or more (velocities). As expected, none of the model predictions replicated this, which will in part be caused by the discretised nature of numerical modelling (0.1m space resolution and 0.1s time resolution in the output)."

Table 8. Benchmark Test 6B Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	1 seconds
Grid resolution (or number of cells)	2 meters x 2 meters; 36,492 cells
Total computational time	Full EQ: 1 minute 18 seconds

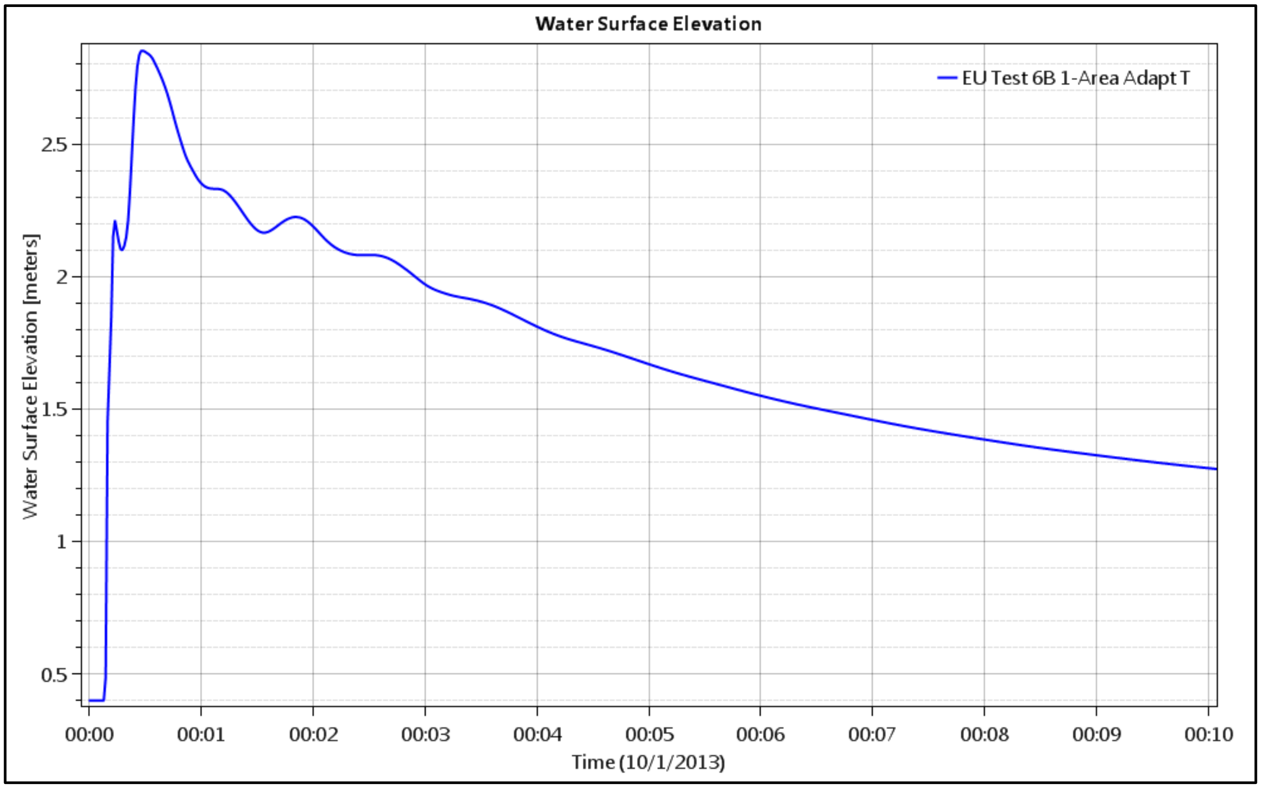


Figure 81. Test Point 1 - Water Level (depth).

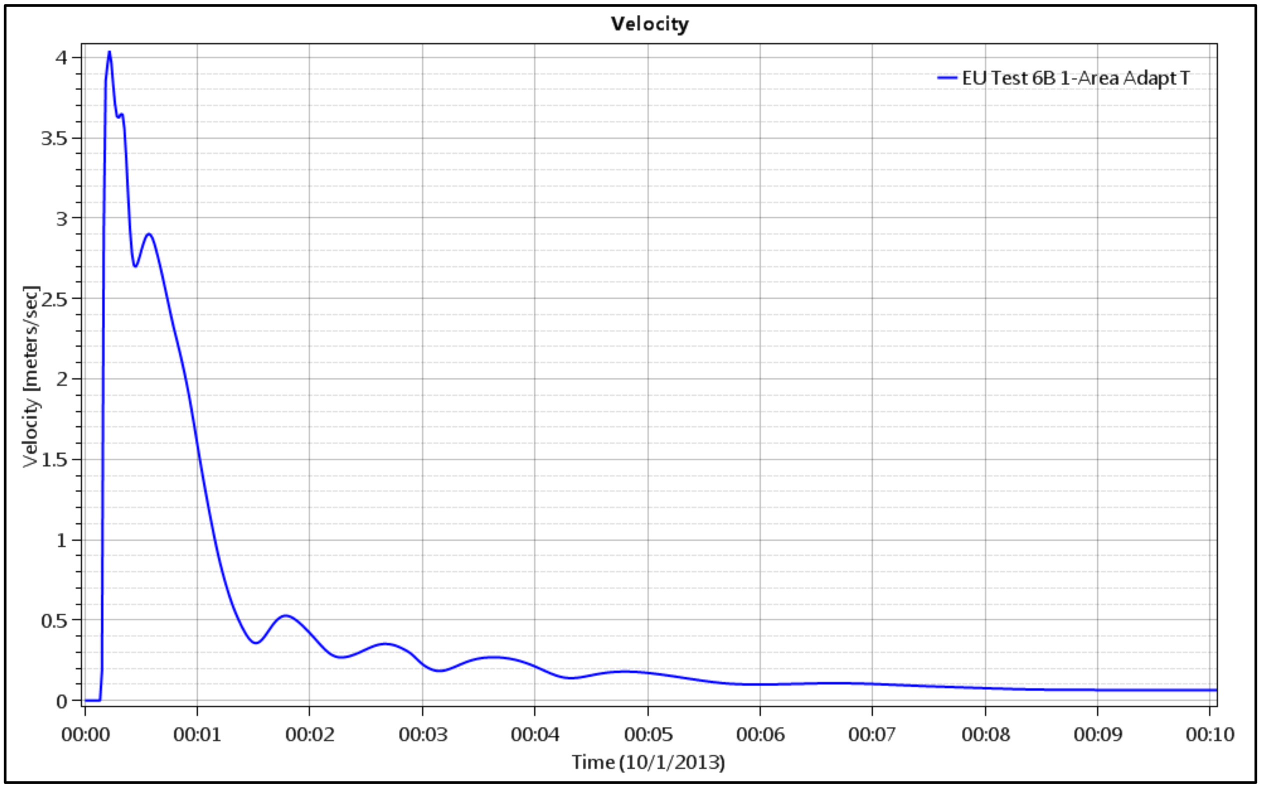


Figure 82. Test Point 1 - Velocity Time Series.

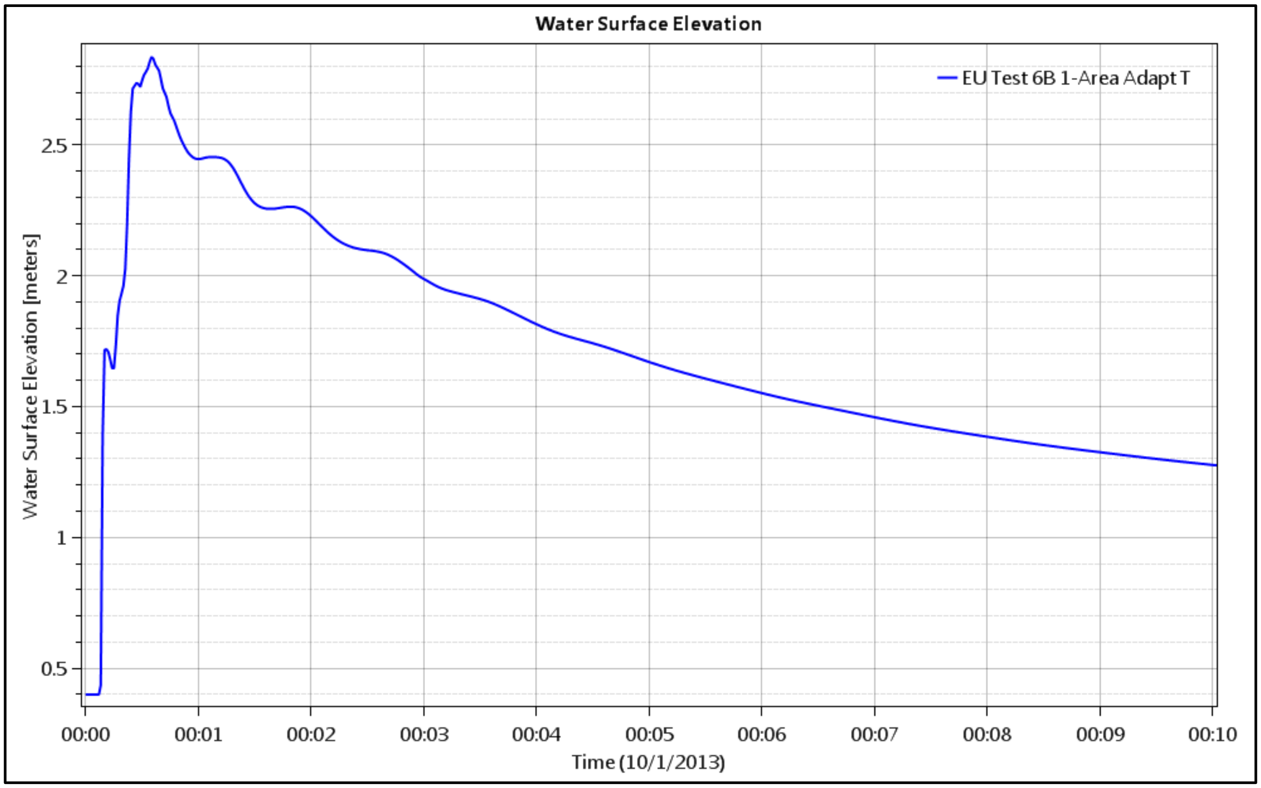


Figure 83. Test Point 2 - Water Level (depth).

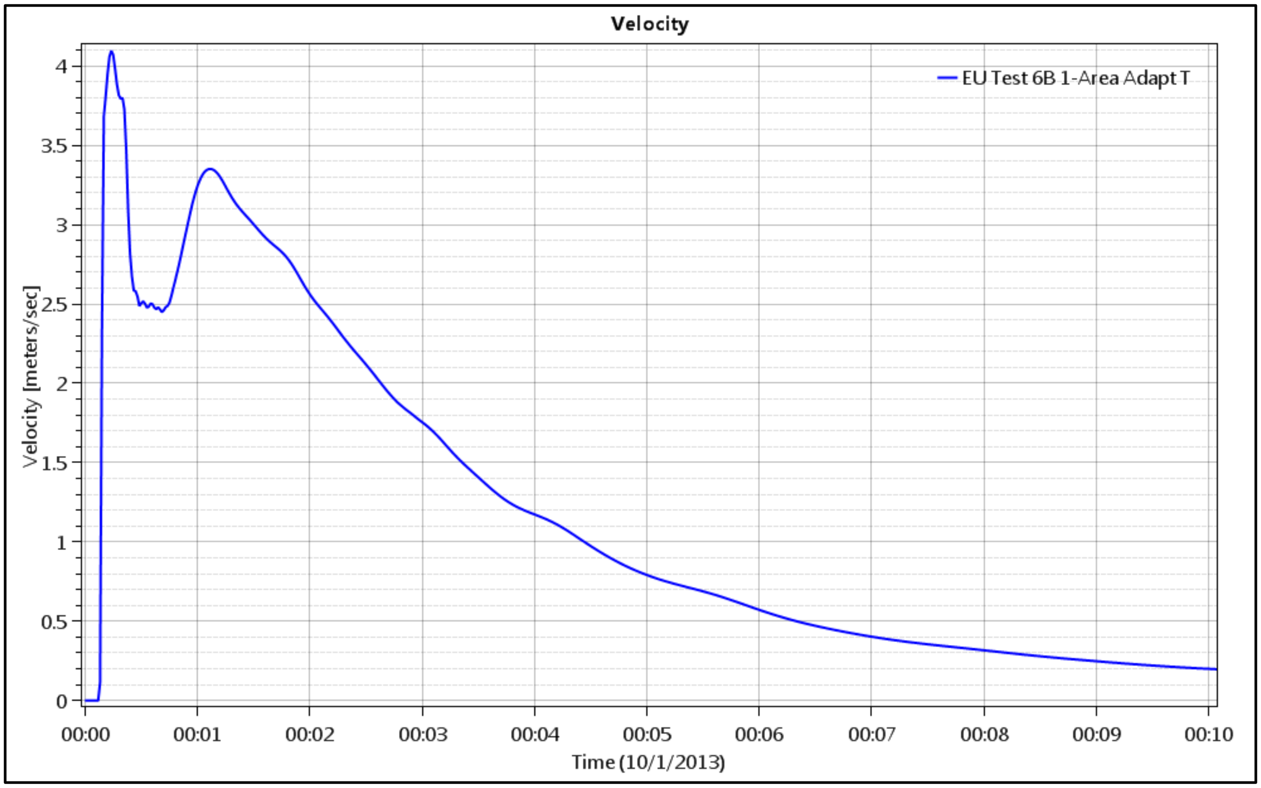


Figure 84. Test Point 2 - Velocity Time Series.

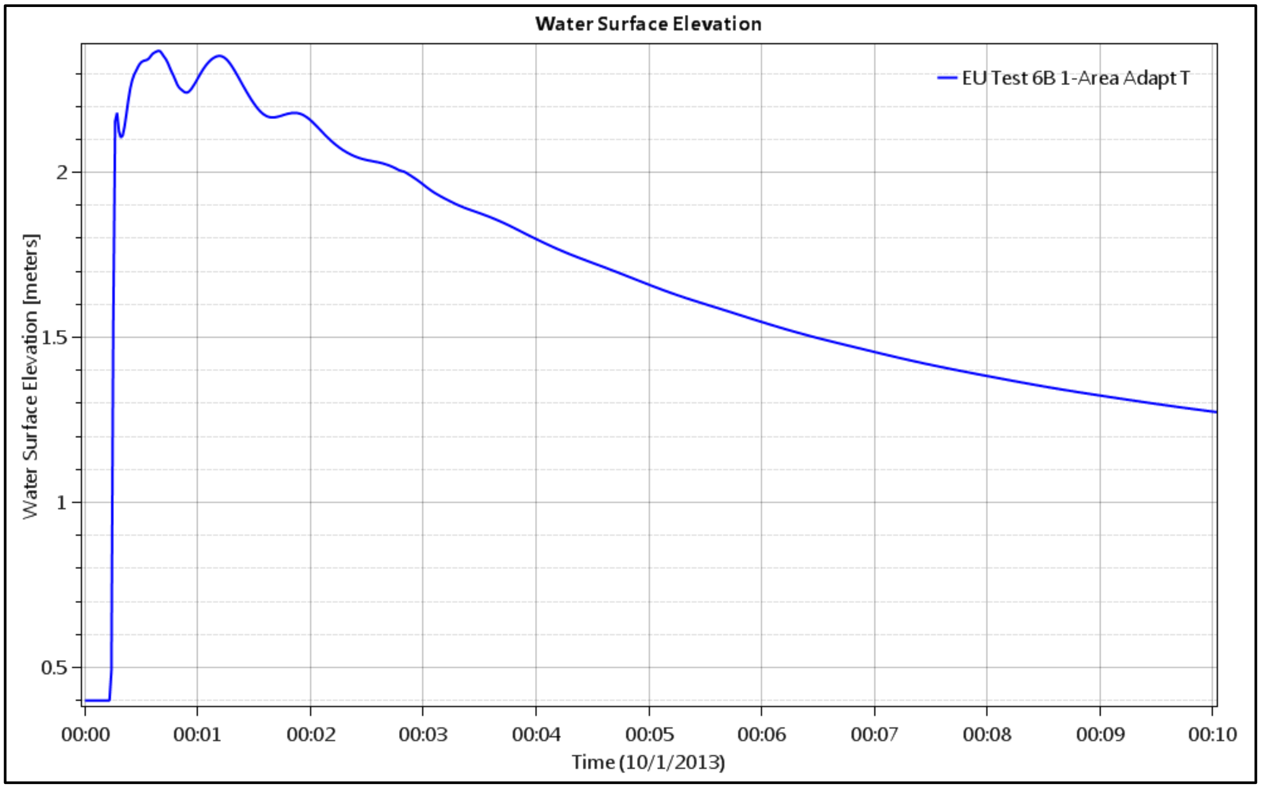


Figure 85. Test Point 3 - Water Level (Depth).

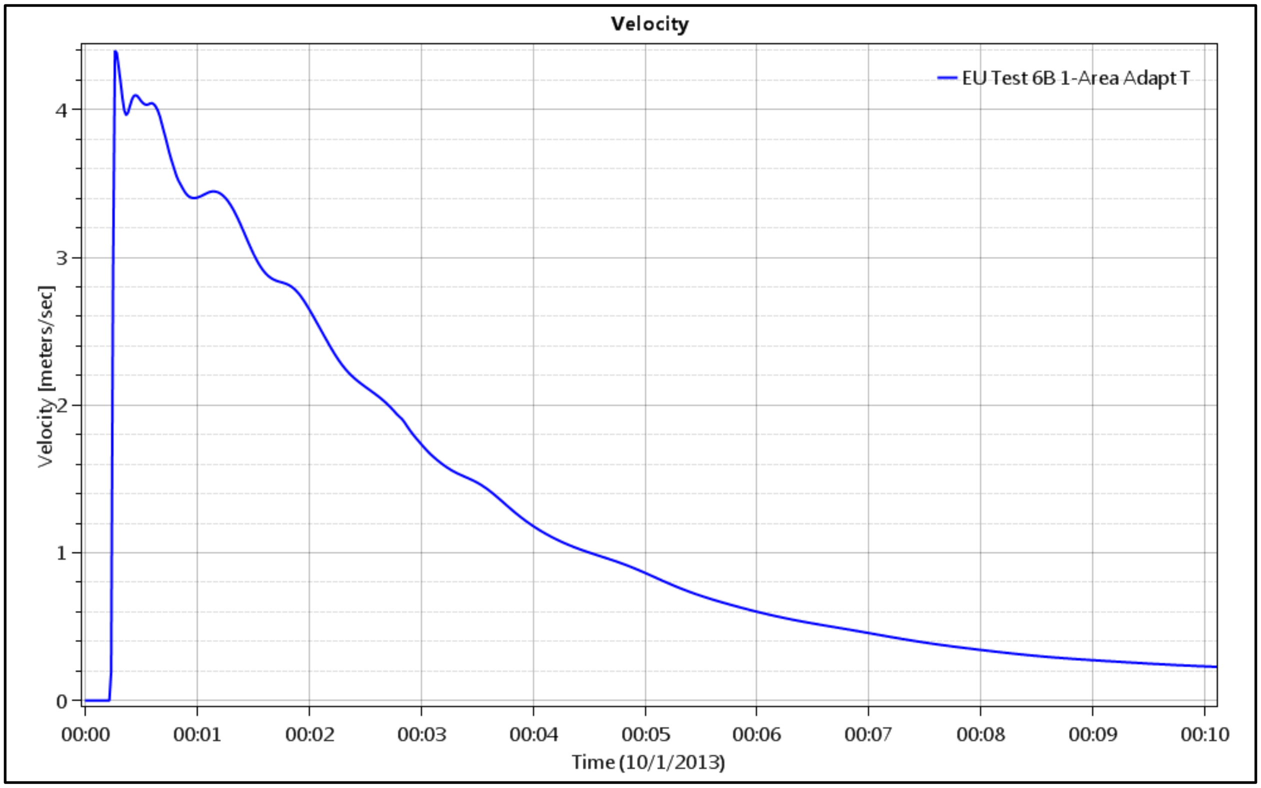


Figure 86. Test Point 3 - Velocity Time Series.

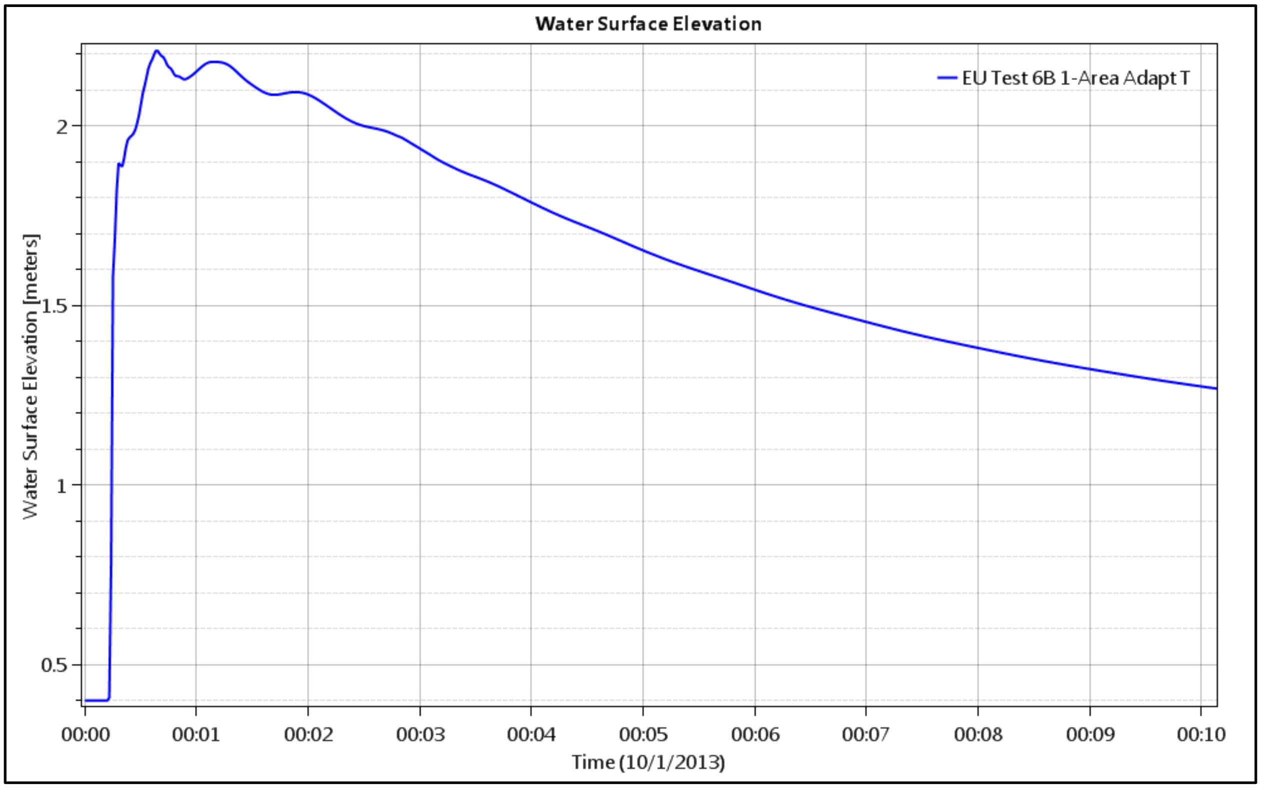


Figure 87. Test Point 4 - Water Level (Depth).

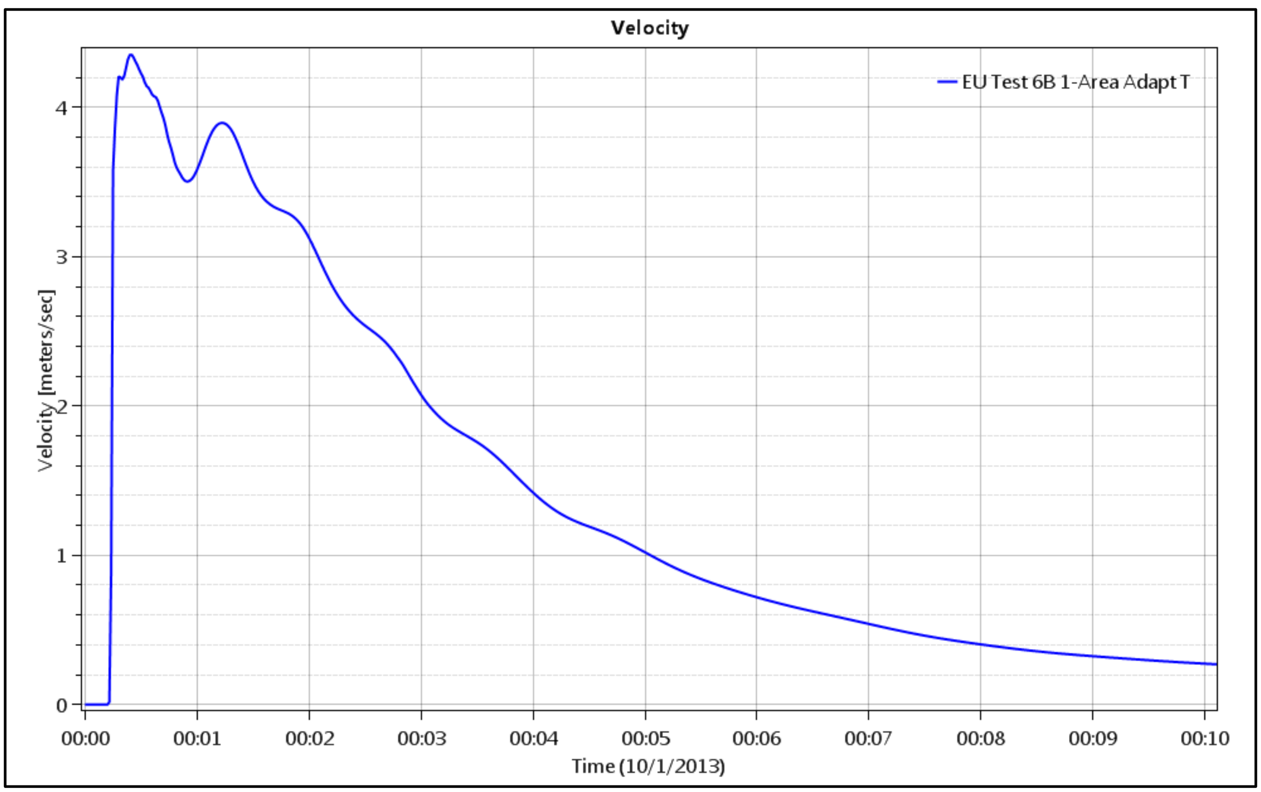


Figure 88. Test Point 4 - Velocity Time Series.

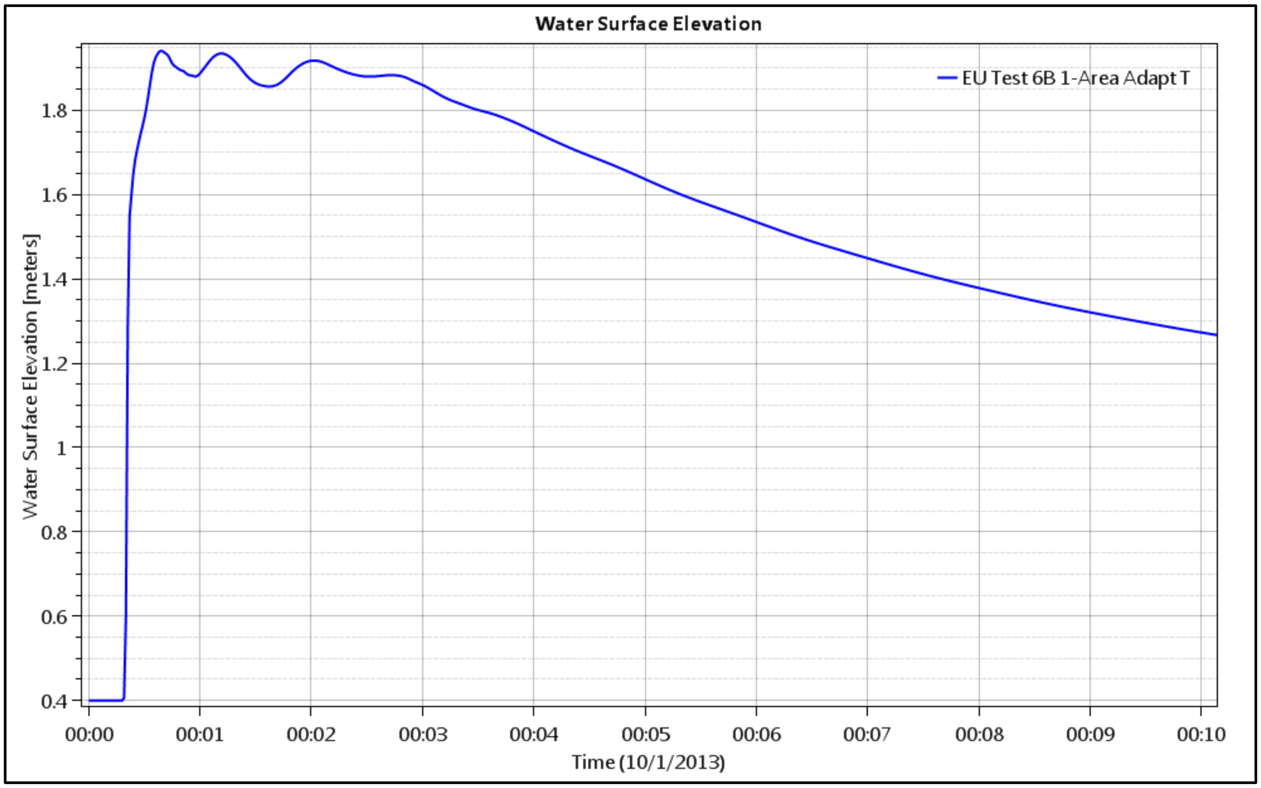


Figure 89. Test Point 5 - Water Level (depth).

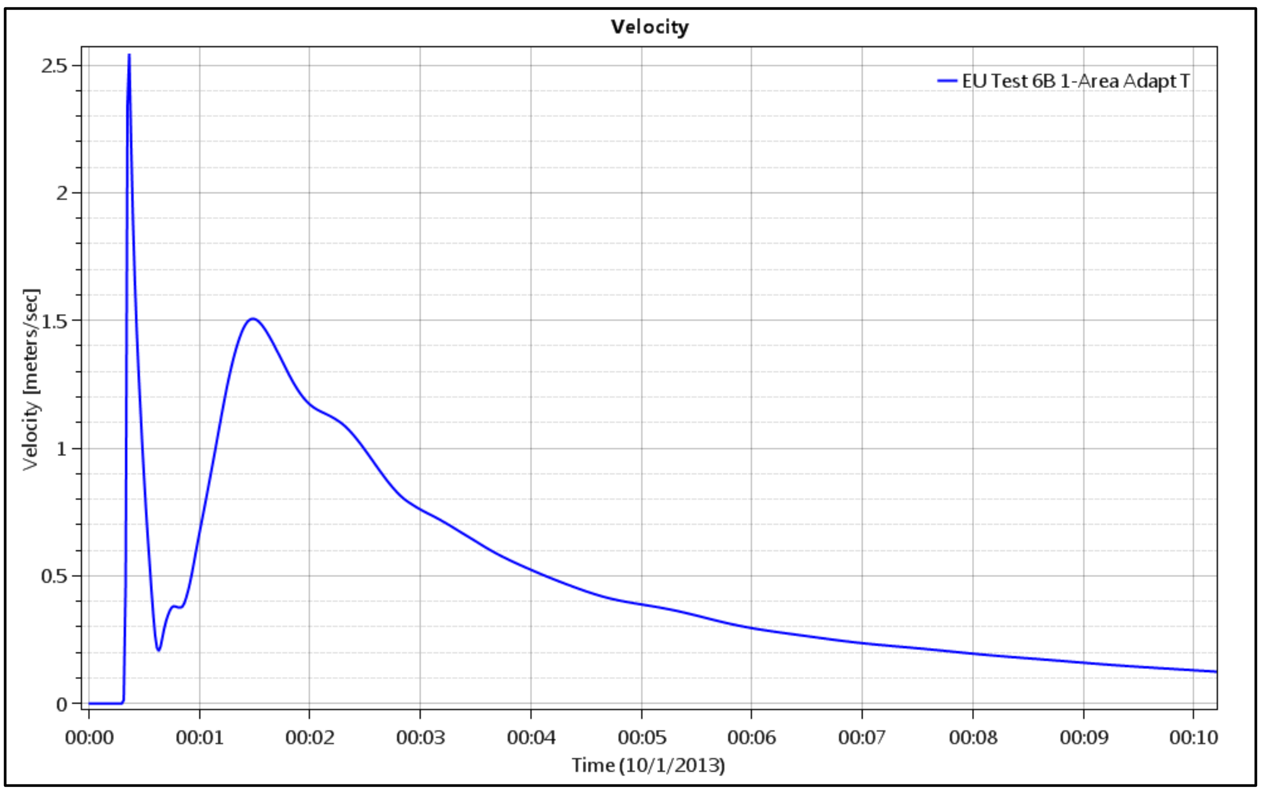


Figure 90. Test Point 5 - Velocity Time Series.

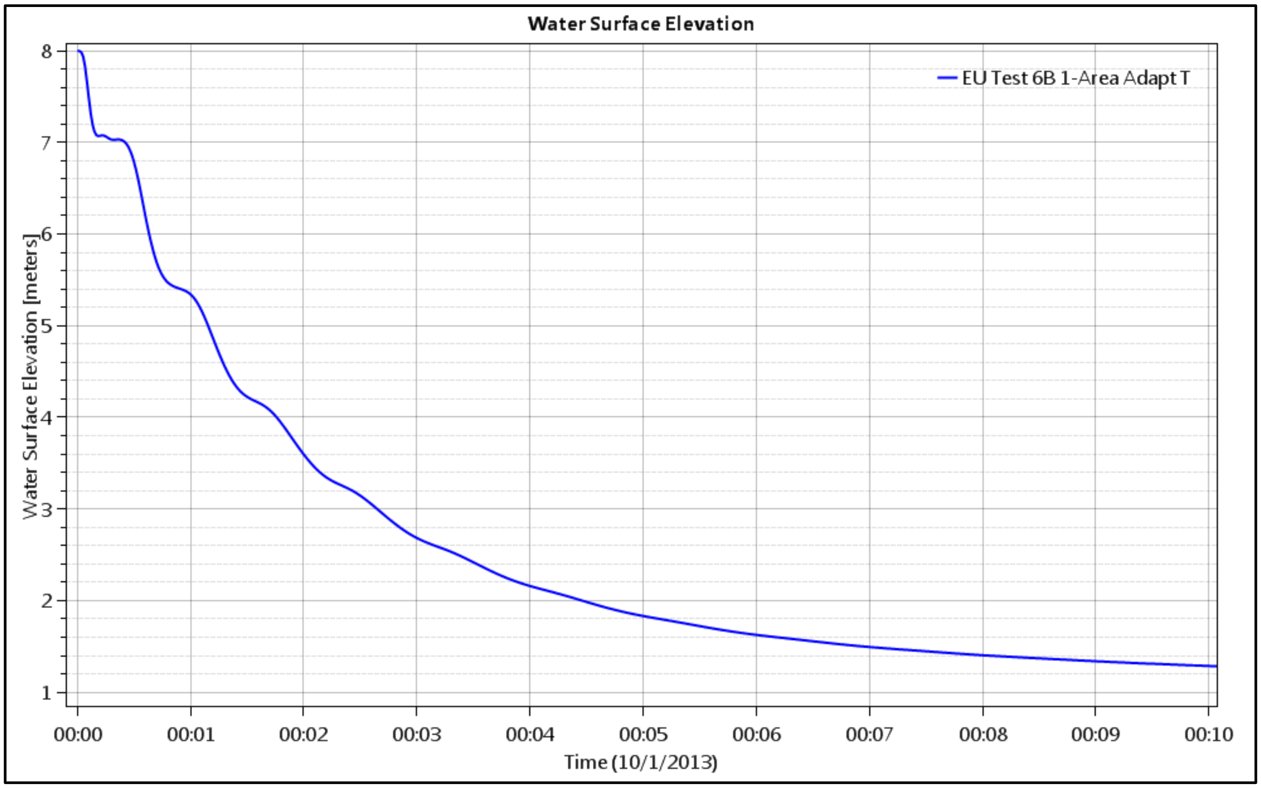


Figure 91. Test Point 6 - Water Level (depth).

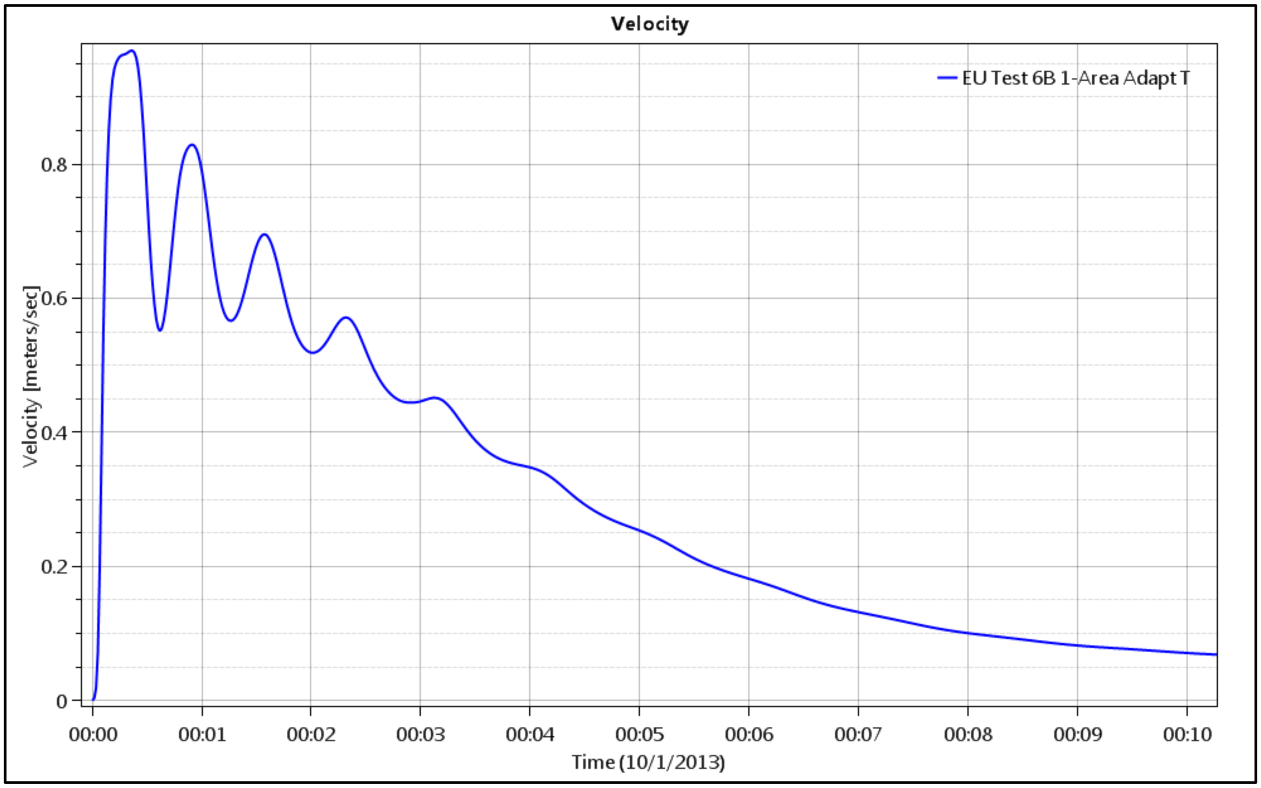


Figure 92. Test Point 6 - Velocity Time Series.

7.5.1 Spatial Plots of Maximum Water Surface and Max Velocity

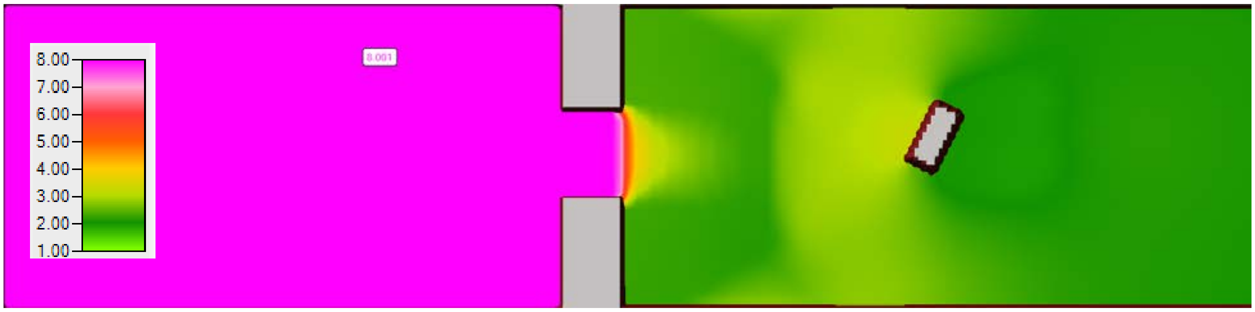


Figure 93. Maximum Water Surface Elevation (meters).

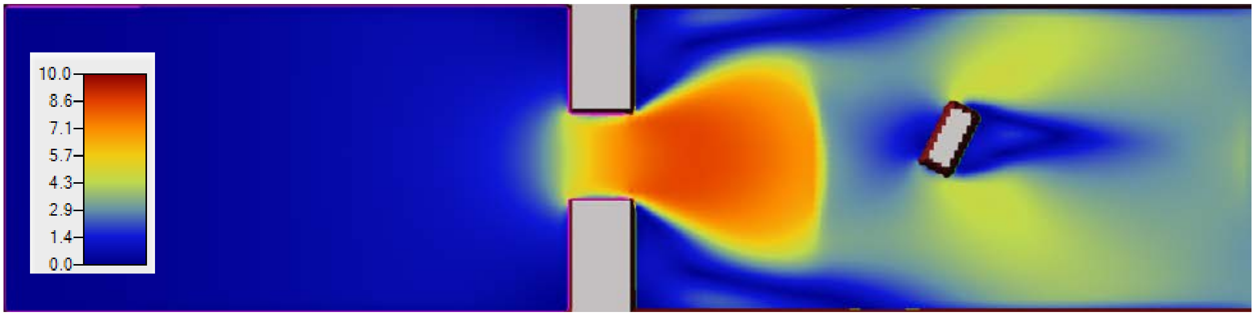


Figure 94. Velocity at time equal to 30 seconds (meter per second).

7.5.2 Maximum Water Surface and Velocity along Cross Section 1

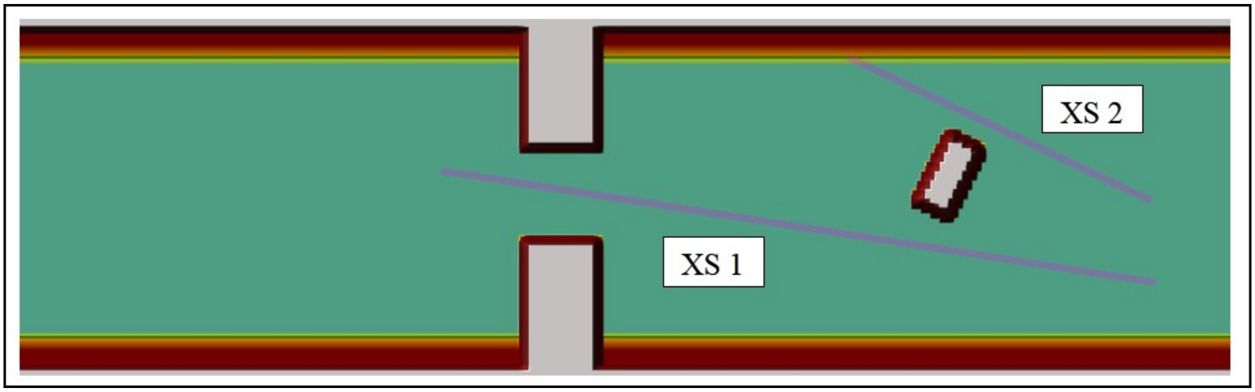


Figure 95. Maximum Water Surface and Velocity along Cross Sections 1 and 2.

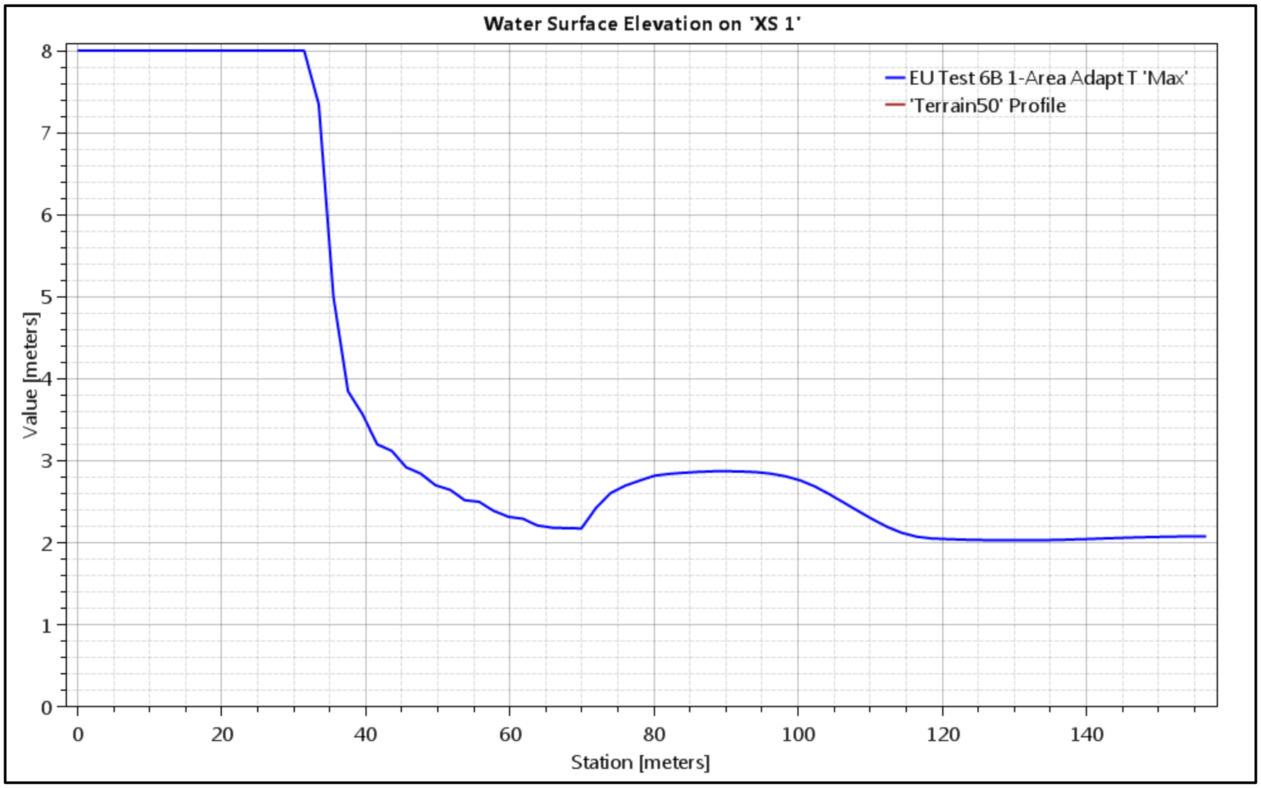


Figure 96. Maximum Water Surface Elevation along Cross Section 1.

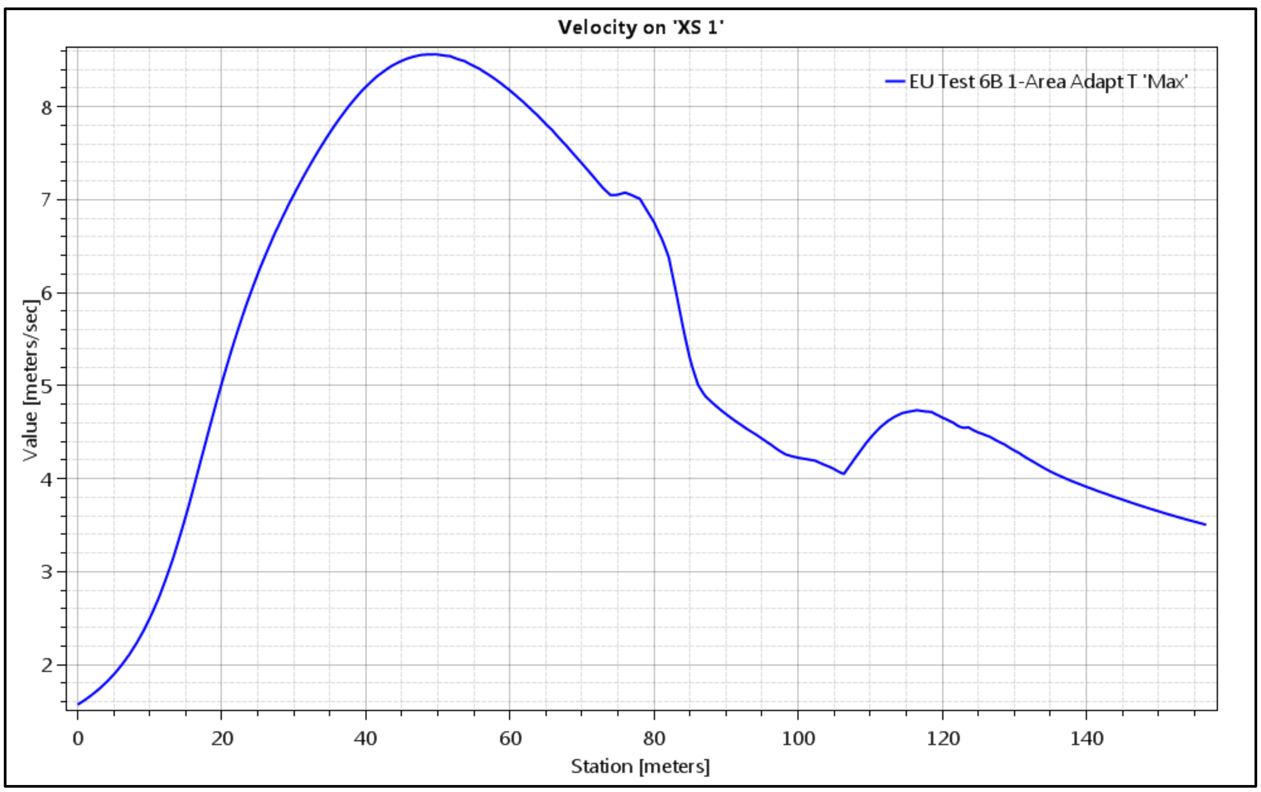


Figure 97. Maximum Velocity along Cross Section 1.

7.5.3 Maximum Water Surface and Velocity along Cross Section 2

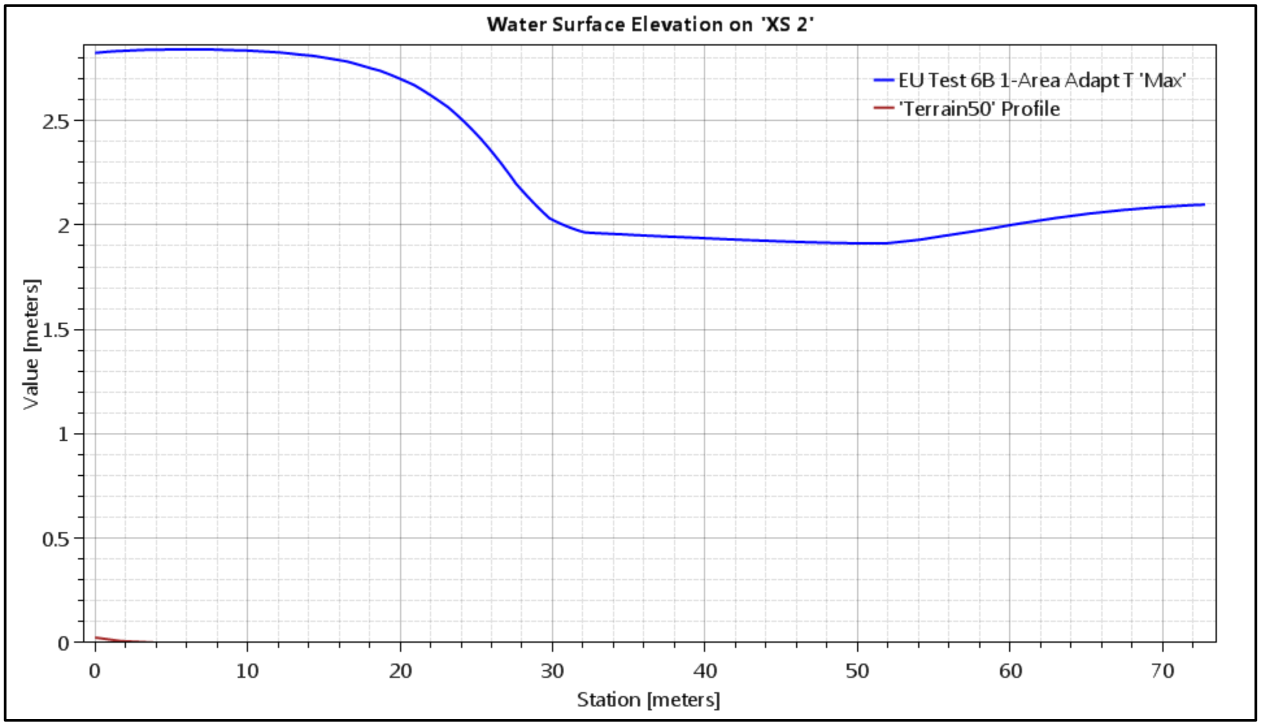


Figure 98. Maximum Water Surface Elevation along Cross Section 2.

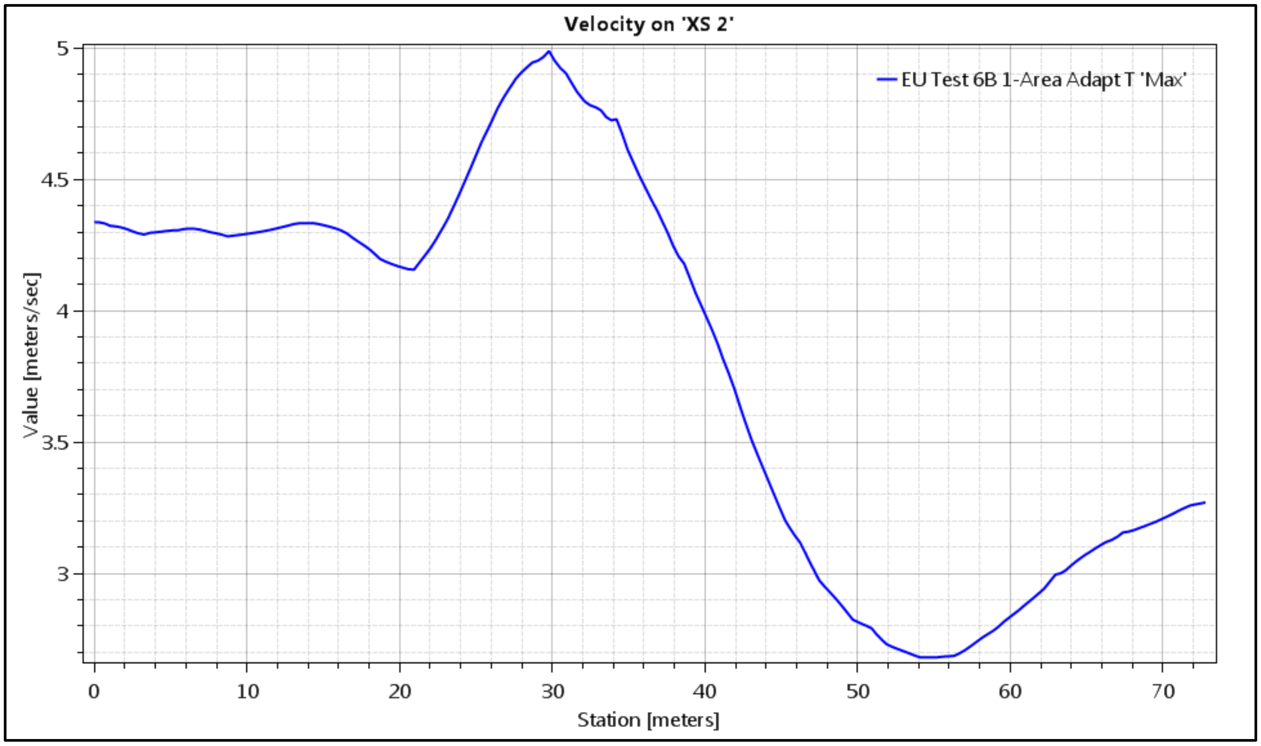


Figure 99. Maximum Velocity along Cross Section 2.

Chapter 8

Benchmark Test 7
River and Floodplain Linking

8.1 Objective

Benchmark Test 7 evaluates a two-dimensional model's capability to simulate fluvial flooding in a relatively large river, with floodplain flooding taking place as the result of river bank overtopping. The following capabilities are also tested: 1) the ability to link a one-dimensional river model component and a two-dimensional floodplain model component, with volume transfer occurring by embankment/bank overtopping and through culverts and other pathways; 2) the ability to build the one-dimensional river component using one-dimensional cross-sections; 3) the ability to process floodplain topography features supplied as three-dimensional breaklines to complement the DEM.

8.2 Description

The site to be modeled is approximately 7 km long by 0.75 to 1.75 km wide (Figure 99), and consists of a set of three distinct floodplains (Figures 100, 101, and 102) in the vicinity of the English village of Upton-upon-Severn, although the river Severn that flows through the site is modeled for a total distance of approximately 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 bankfull initial and final levels in the river, and a downstream rating curve. This combination poses a relatively challenging test through the need for the model to adequately identify and simulate flooding along separate floodplain flow paths, and predict correct bank/embankment overtopping volumes. The volume exchange takes place over natural river banks and/or embankments along which flood depths are expected to be small. The site has been subjected to flooding on a number of occasions but it is not the intention to replicate an observed flood for this exercise, hence the boundary conditions have been designed to provide a suitable benchmarking case.

8.3 River Channel Geometry

Cross section channel geometry was provided and 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. Three-dimensional "breaklines" are provided which define a) the boundary between the river channel and the area expected to be modeled in two dimensions, and b) elevations along these boundaries. These elevations are to be used in the prediction of bank/embankment overtopping. Wherever no floodplain is modeled along the river channel (more than fifty percent 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

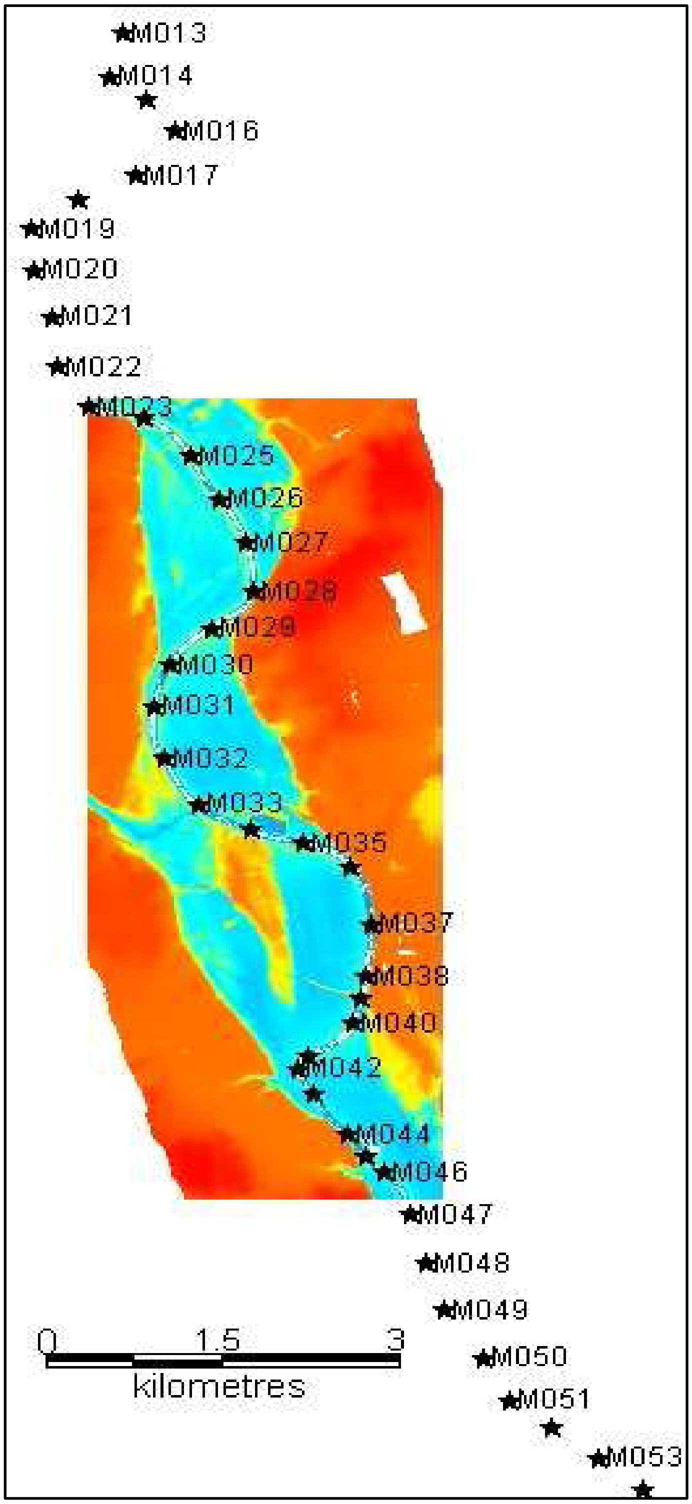


Figure 100. Map of the modeled reach of the River Severn and floodplain system around Upton-upon-Severn; river flows from North to South.

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

8.4 Floodplains

The extents of the three modeled floodplains are defined as follows (Figures 100, 101, 102):

> **Floodplain 1:** On the West bank of the river, from upstream from Cross Section M024, to upstream from Cross Section M030 (floodplain breakline Number 2).
>
> **Floodplain 2:** On the East bank of the river, from upstream from Cross Section M029, to upstream from Cross Section M036.
>
> **Floodplain 3:** On the West bank of the river, 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. Away from the river, for consistency in model extent, it is suggested to draw the boundaries of the two-dimensional models approximately along the 16 meter contour line. Floodplain 3 has a physical opening below the 16 meter altitude along the Pool Brook stream to the North-West of Upton. The model should extend to the edge of the DEM in this location. (However this boundary is to be treated as closed.)

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 two-dimensional modeling. Cross Sections M030 and M031 have been extended as far as the hillside to the West.

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

A number of features in the floodplains are expected to impact results significantly and will be modeled. These features include:

> - Embankments and elevated roads, for which three-dimensional breaklines are provided as part of the dataset. These can be used to adjust node elevations in the computational grid. They should be distinguished from the river/floodplain boundary breaklines mentioned in the previous section.
>
> - A set of low bridges of total width approximately 40 meters under the elevated causeway (A4104 road) immediately west of Upton. These bridges can be modeled as a single 40 meter opening through the A4104 causeway (elevations provided as floodplain breakline Number 7). A photograph and a datafile containing various parameters (including X/Y coordinates and dimensions) are provided as part of the dataset.

The modeled 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 is 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 modeled as ground, with elevations as given by the DEM.

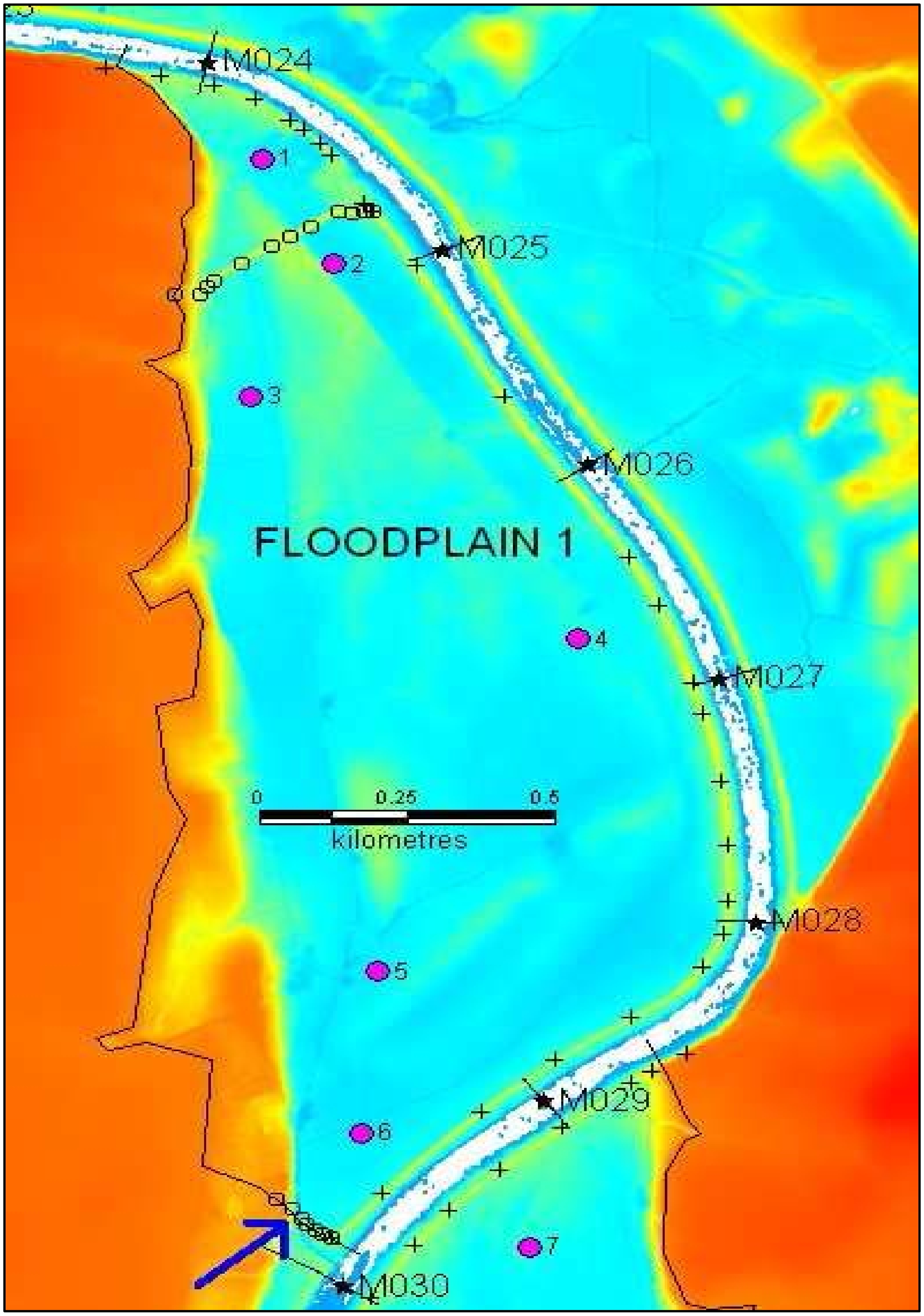


Figure 101. Map of Floodplain 1. Blue arrow - opening in embankment (sluice). Crosses - bank breakline vertices. Circles - floodplain breakline vertices. Purple dots - output points. Black line - outer extent of model.

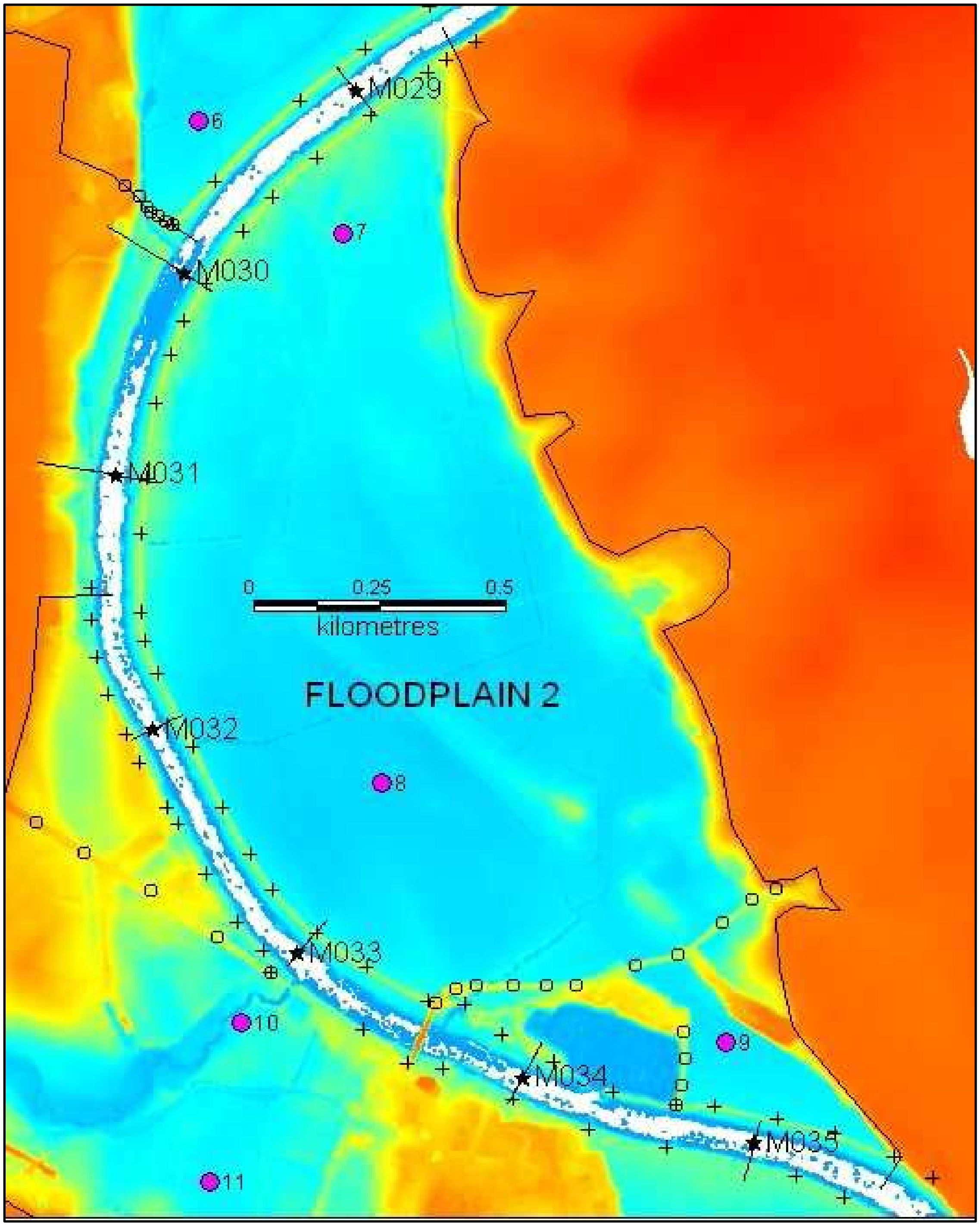


Figure 102. Map of Floodplain 2. Crosses - bank breakline vertices. Circles - floodplain breakline vertices. Purple dots - output points. Black line - outer extent of model.

8.5 One- and Two-Dimensional Volume Transfer

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

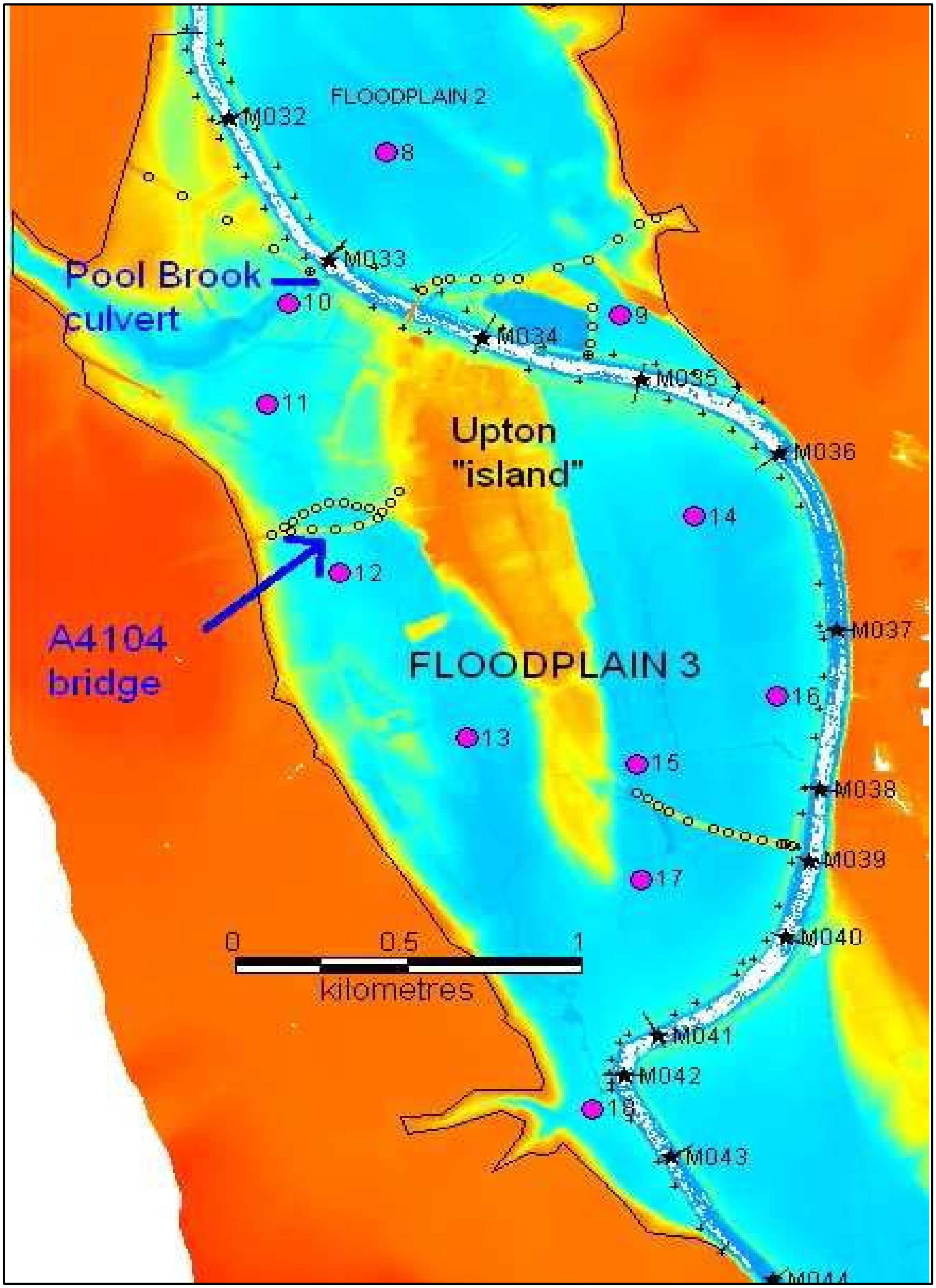


Figure 103. Map of Floodplain 3. Crosses: bank breakline vertices. Circles: floodplain breakline vertices. Purple dots: output points. Black line: outer extent of model.

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

A masonry culvert immediately upstream from the village of Upton ("Pool Brook") is however modeled (Figure 102). It is assumed circular in cross-section. A photograph and a spreadsheet containing various parameters (including X/Y 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 (Figure 100) 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 opening should be understood as a 10 meter wide opening (invert level 10 meter) is offering a pathway from Floodplain 1 to the river at Cross Section M030. The modeling of this feature is optional.

8.6 Miscellaneous

The DEM is a 1.0 meter resolution LiDAR Digital Terrain Model (no vegetation or buildings) provided by the Environment Agency (http://www.geomatics-group.co.uk). (Minor processing has been done, consisting in merging tiles and filling small areas of missing data in the modeled floodplains.) It should be noted that any areas of missing data (-9999) in the DEM are not expected to be part of the modeled two-dimensional domain.

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

8.7 Boundary and Initial Conditions

- River Channel:
  - Upstream: inflow versus time applied at the northernmost cross section, Cross Section M013
  - Downstream: rating curve (flow versus head), applied at the southernmost cross section, Cross Section M054

- Initial condition: a uniform water level of 9.8 meters

- Floodplains: Linked to the river channel along the river bank breaklines provided, and through the Pool Brook culvert (Floodplain 3) and the opening (sluice) at the South end of Floodplain 1.

- All other boundaries are closed (no flow)

8.8 Miscellaneous Parameter Values

- Manning's n: 0.028 uniformly in river, 0.04 uniformly in floodplains
- Model grid resolution: 20 meter (or an equivalent node density in the model extent defined in Section 8.4)

- Time of end: the model is to be run until time t equals 72 hours (if an alternative end time is used run times must be reported for t equals 72 hours)

8.9 Results

Note: The Benchmark Test 7 data set was run with both the Full Saint Venant equations (Full EQ) and the Diffusion Wave equations (Diff Wave). Results for both equation sets are shown Figures 103 - 157. The Test results show that the Diffusion wave equations produce similar results for water surface elevations and timing as the Full Saint Venant equations, but the velocities difference somewhat at some of the locations. Velocity differences are due to the fact that the Diffusion wave equations do not include the acceleration terms in the momentum equations. Therefore the Full equation velocities are most likely more accurate.

Note: The Benchmark Test 7 data set was also used to demonstration sensitivity to the computational grid resolution. Results are shown for multiple points in each floodplain to demonstrate the HEC-RAS ability to use larger grid cells and get similar results.

The grid resolution tests show that, because HEC-RAS uses the subgrid bathymetry to develop detailed property tables for the cells and the cell faces, it can get similar results as the originally stated problem (20 meter grid), with a grid resolution twice as large (40 meter grid). Run times with the larger grid cell size are dramatically lower than with the smaller grid cell size. This capability provides a major advantage of the HEC-RAS two-dimensional capability over other software that does not support detailed cell and face property tables, and partial cell wetting.

Table 9. Benchmark Test 7 Specific Summary Information

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	Variable (5s start) Full Saint Venant, (10s start) Diff Wav
Grid resolution (or number of cells)	20 meter x 20 meters 40 meters x 40 meters
Total computational time	20 meter Grid Full EQ: 12 minutes 25 seconds Diff Wav: 6 minutes 5 seconds 40 meter Grid Full EQ: 2 minutes 8 seconds Diff Wav: 1 minutes 51 seconds

8.9.1 Test 7 – One-Dimensional Cross Section Locations

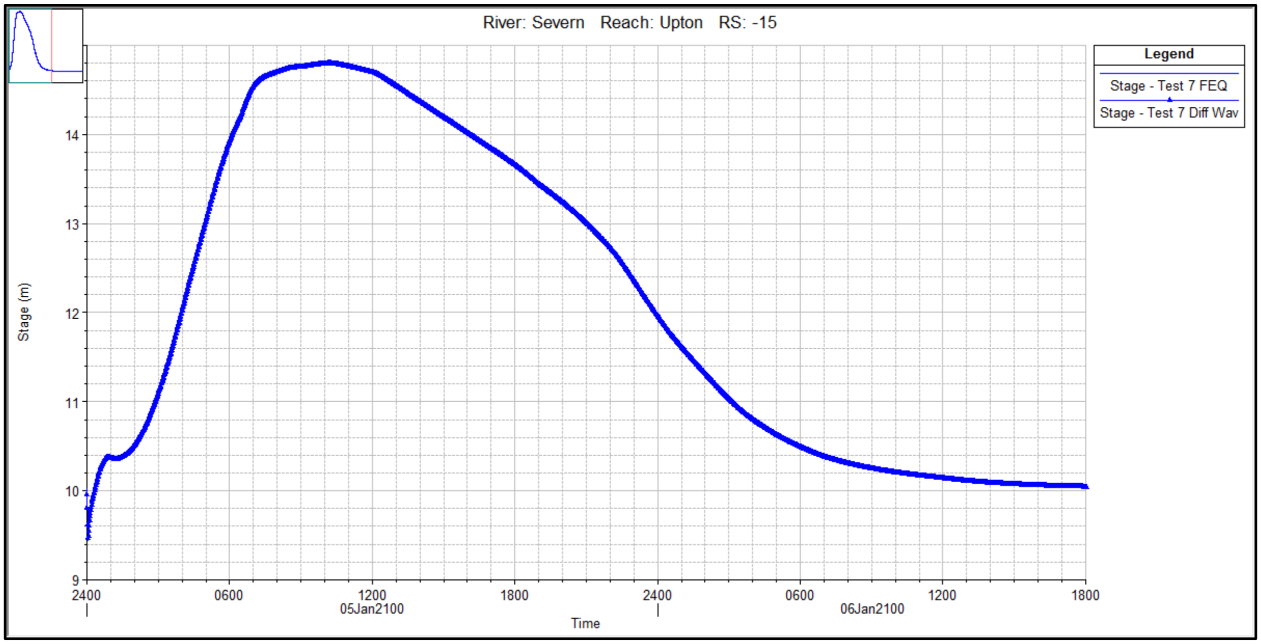


Figure 104. Test Point M015 - Water Level (depth).

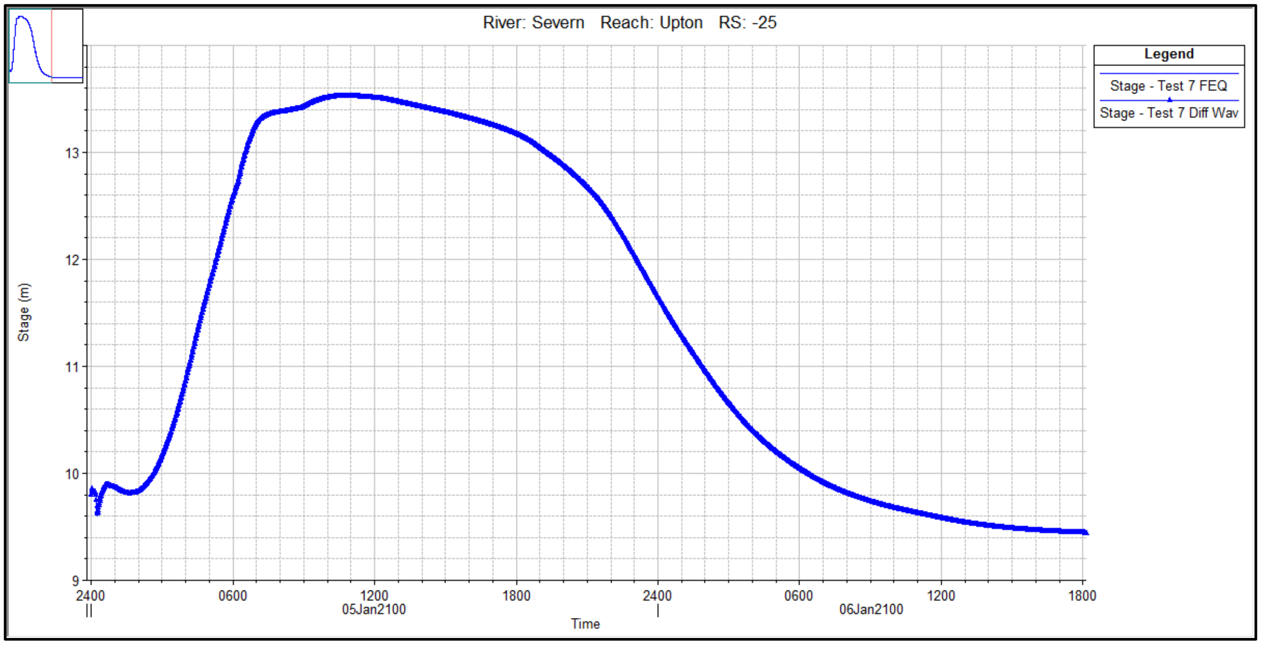


Figure 105. Test Point M025 - Water Level (depth).

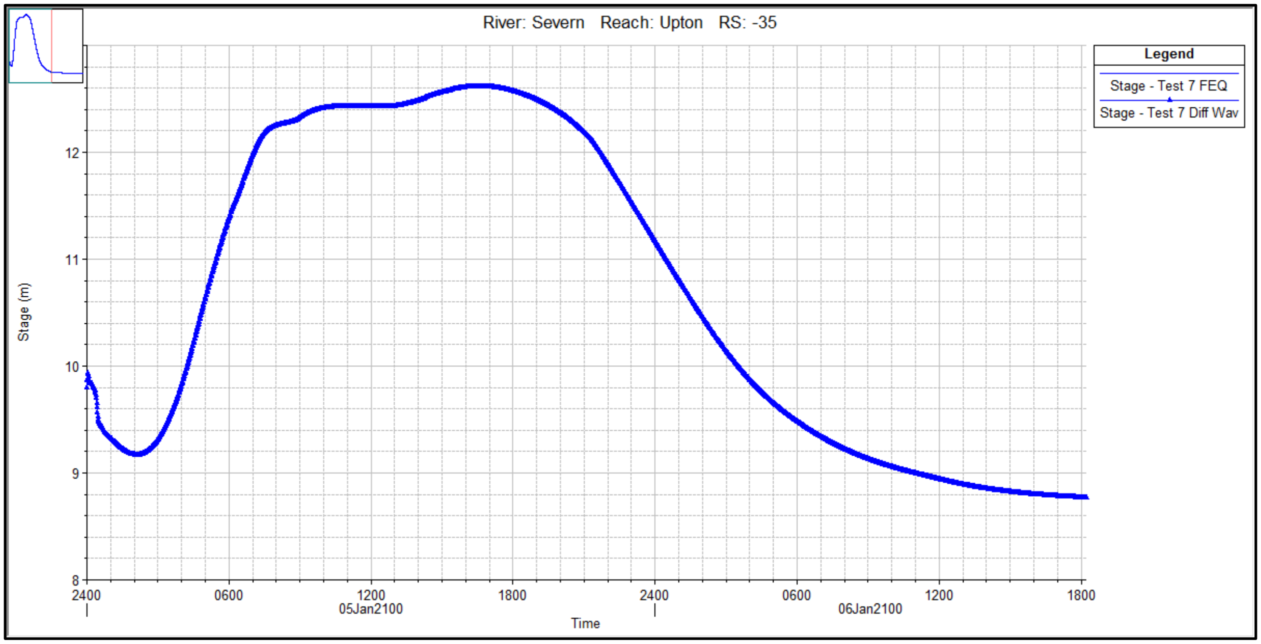


Figure 106. Test Point M035 - Water Level (depth).

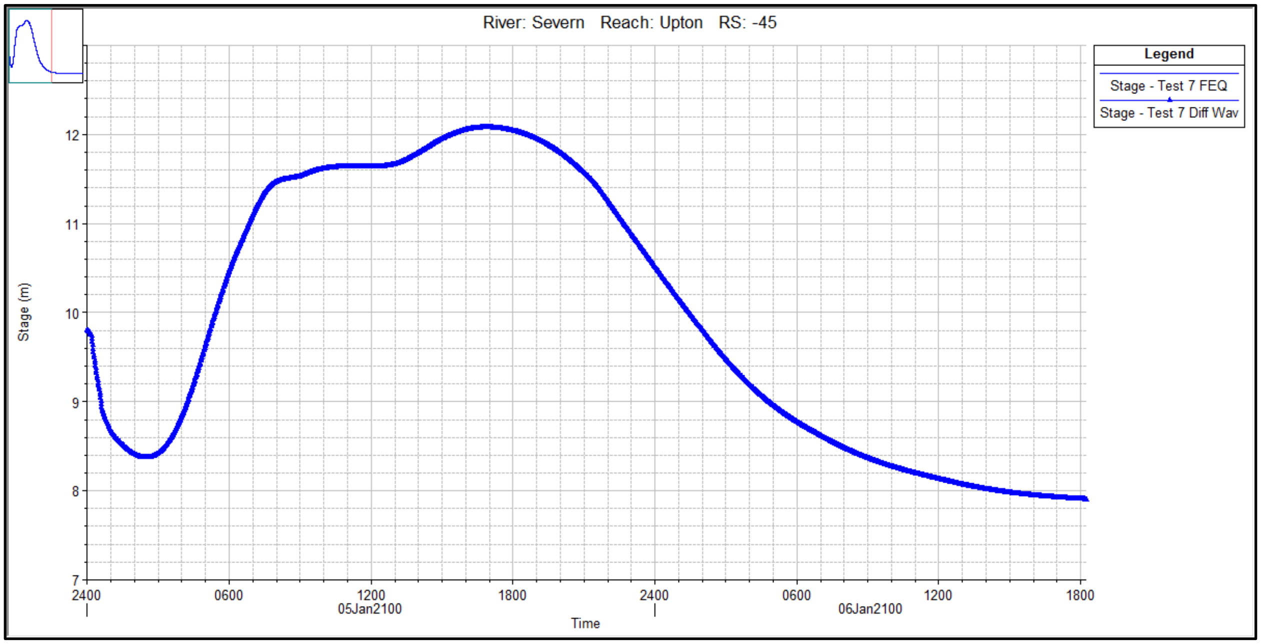


Figure 107. Test Point M045 - Water Level (depth).

8.9.2 Test 7 – Two-Dimensional Floodplain Locations

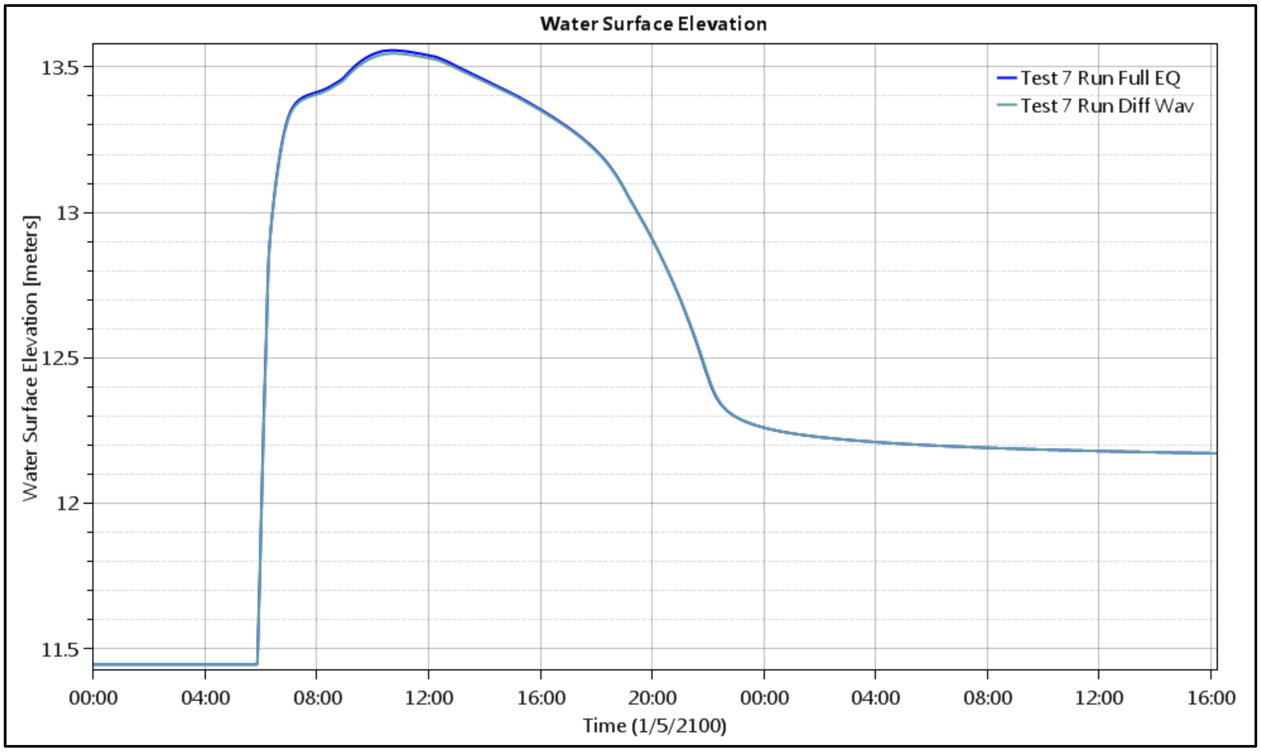


Figure 108. Floodplain 1 - Test Point 1 - Water Level.

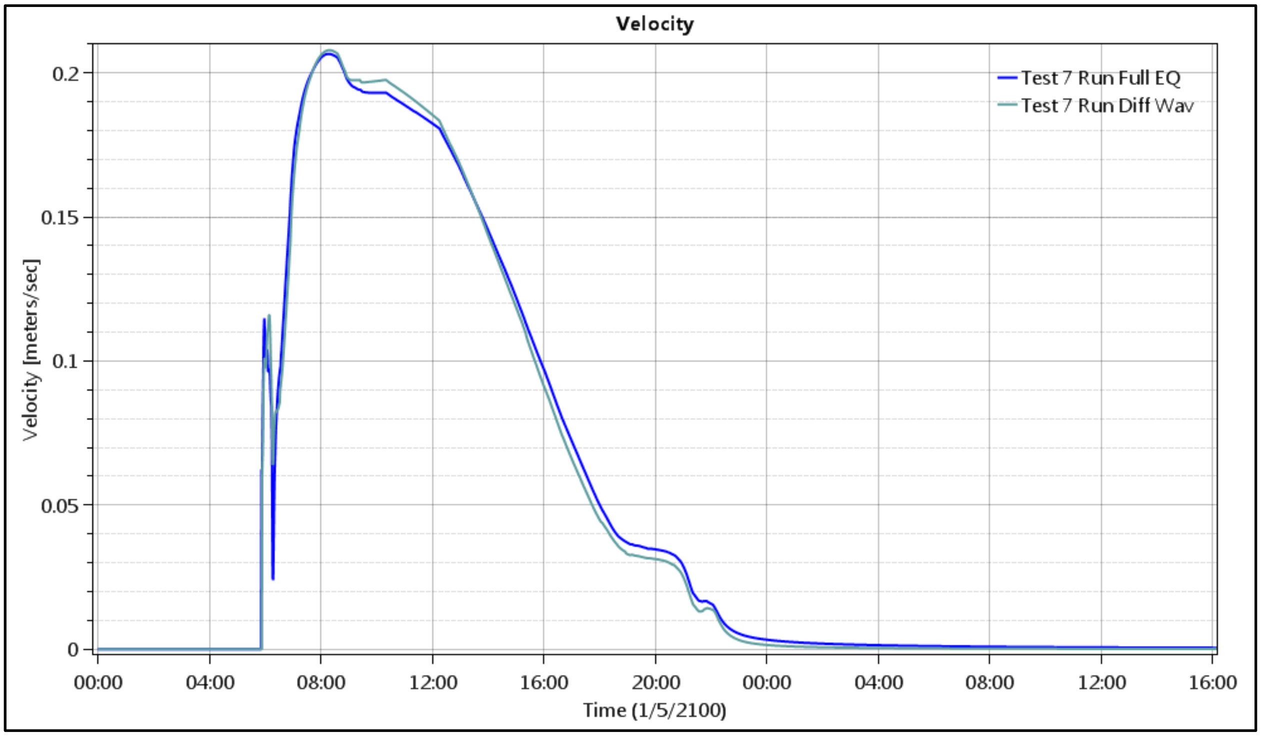


Figure 109. Floodplain 1 - Test Point 1 - Velocity.

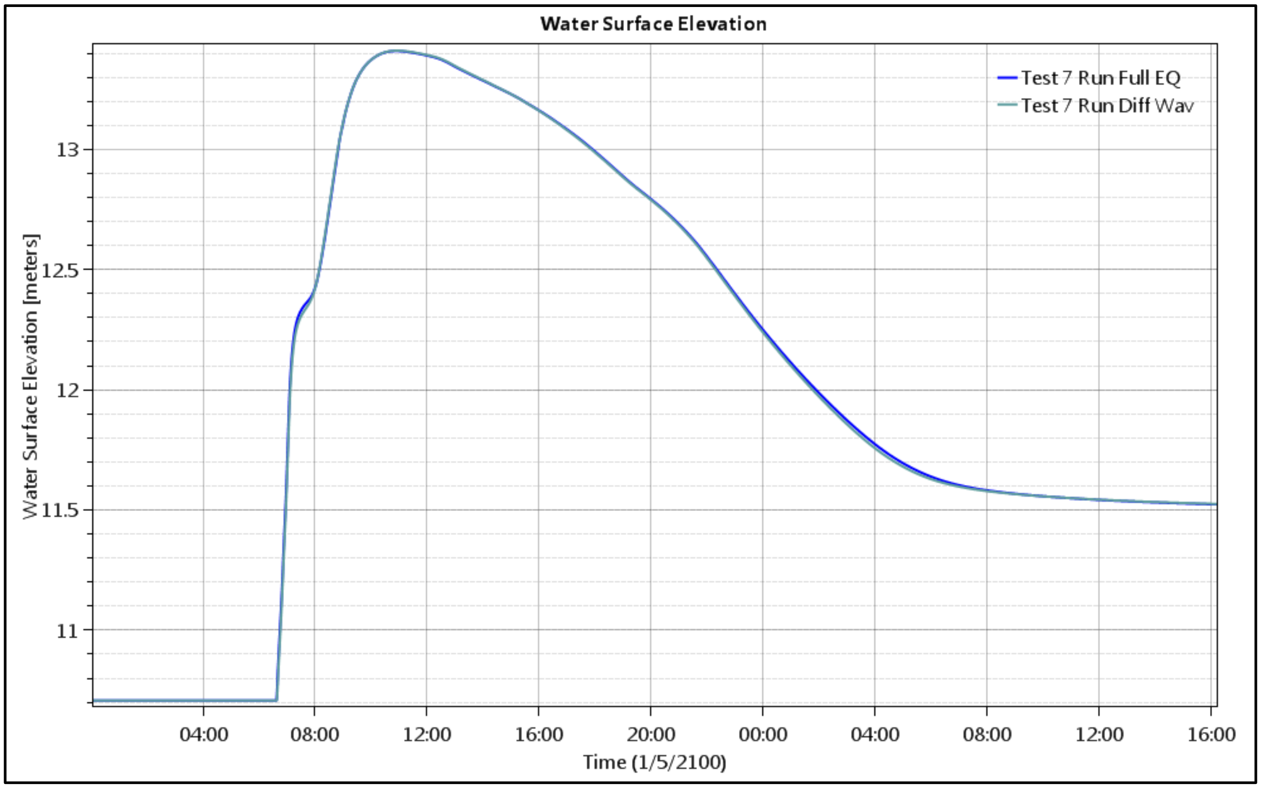


Figure 110. Floodplain 1 - Test Point 2 - Water Level.

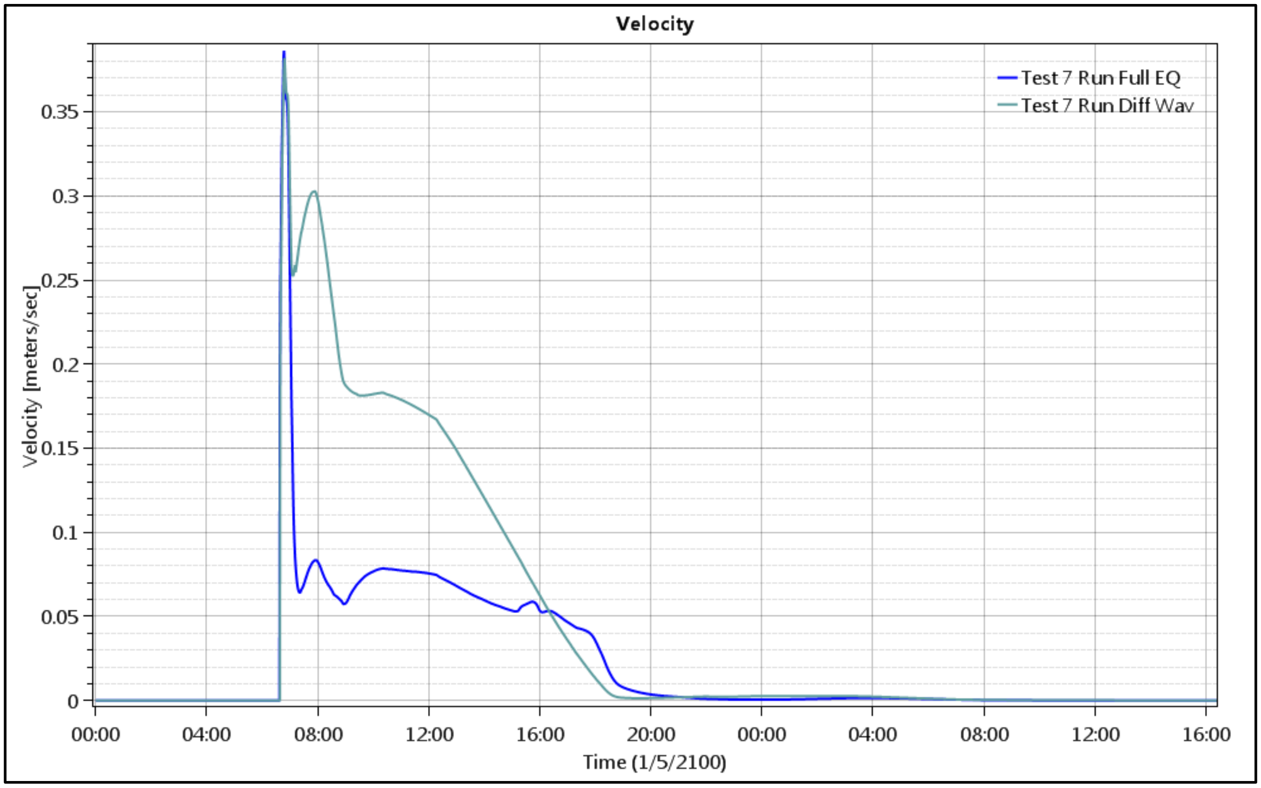


Figure 111. Floodplain 1 - Test Point 2 – Velocity.

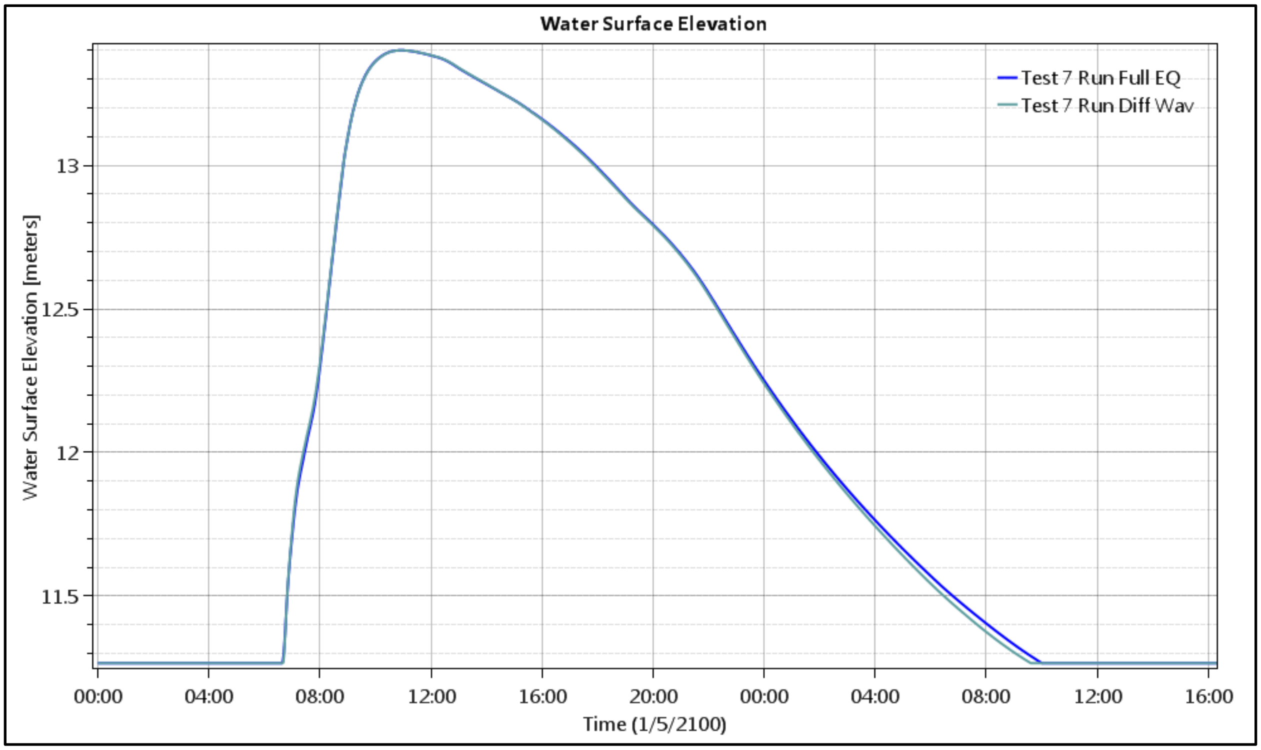


Figure 112. Floodplain 1 - Test Point 3 - Water Level.

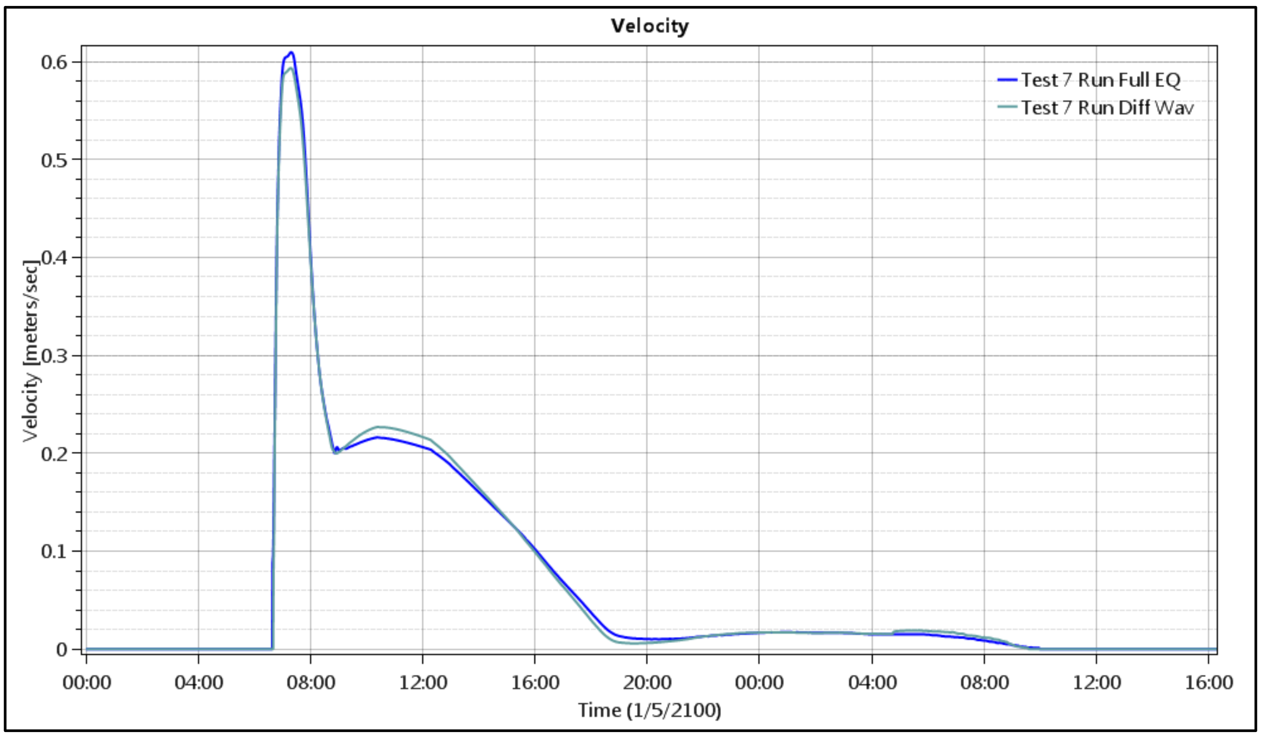


Figure 113. Floodplain 1 - Test Point 3 – Velocity.

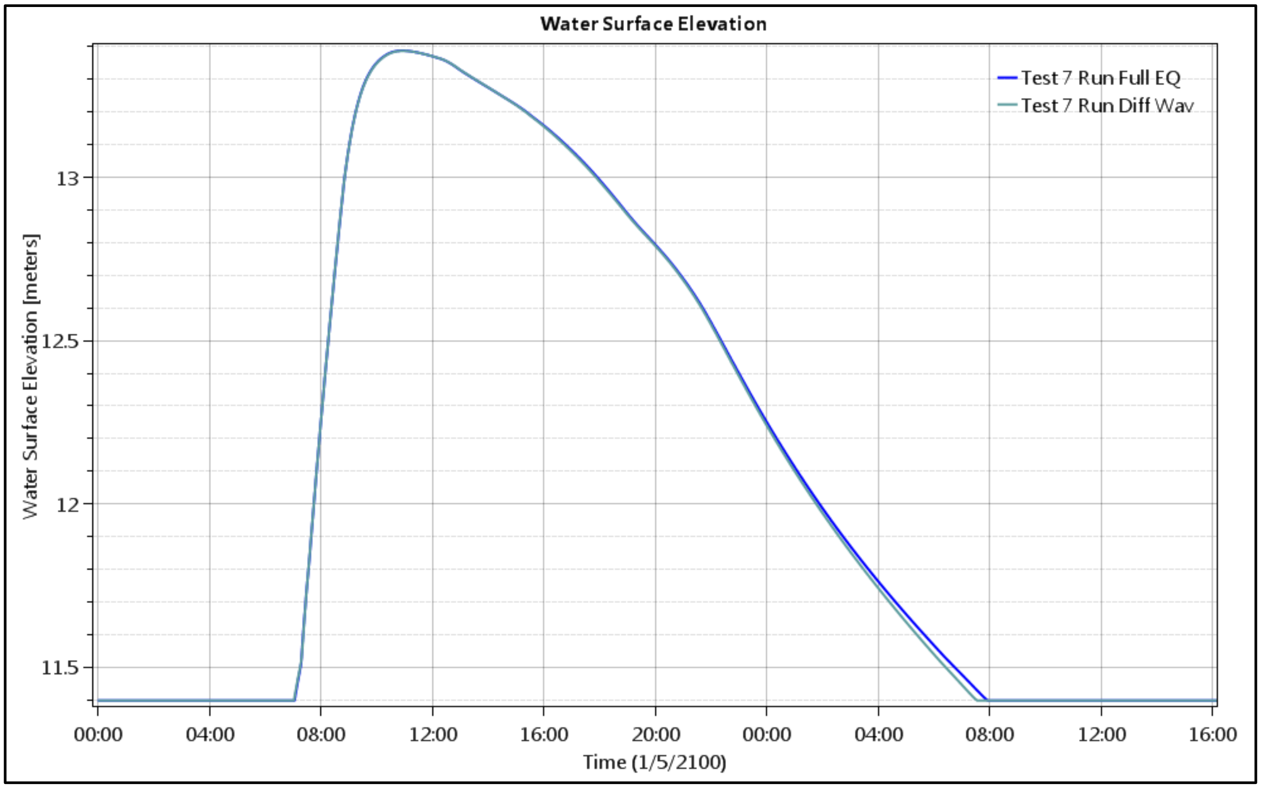


Figure 114. Floodplain 1 - Test Point 4 - Water Level.

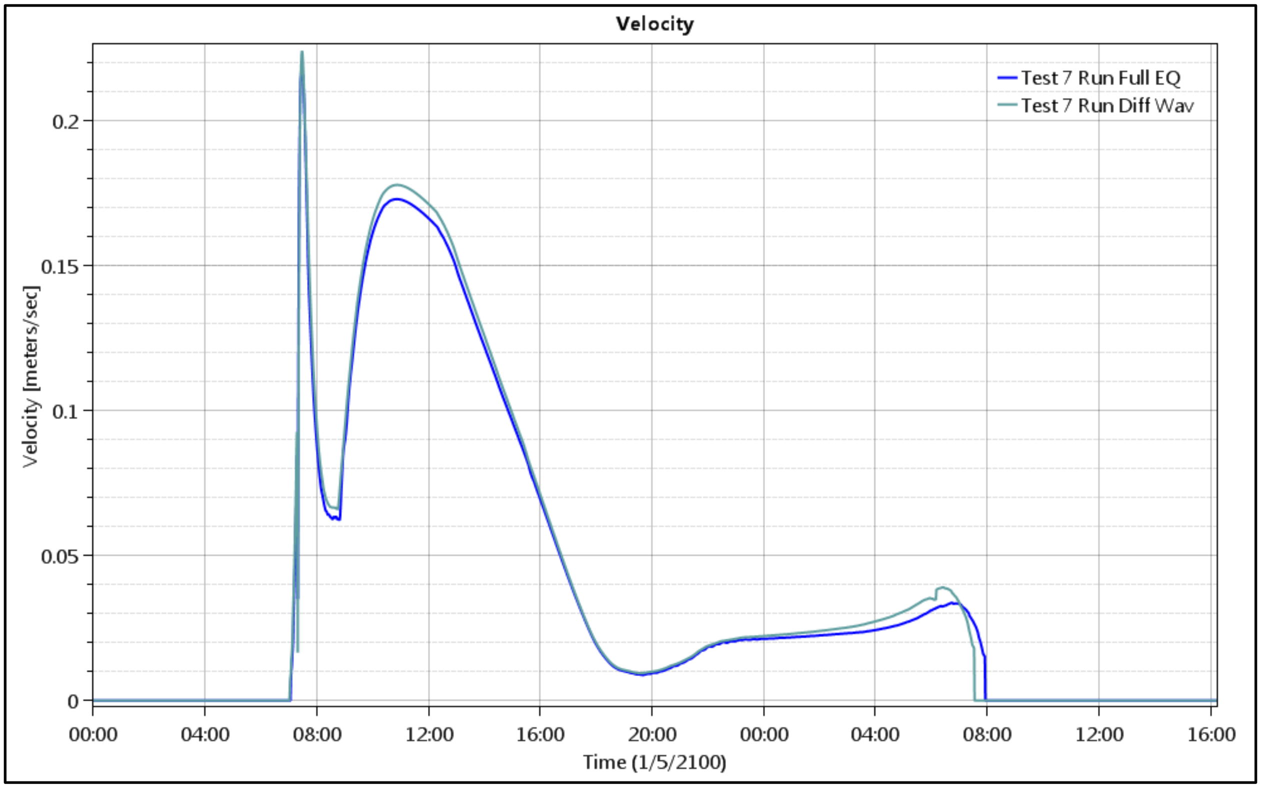


Figure 115. Floodplain 1 - Test Point 4 - Velocity.

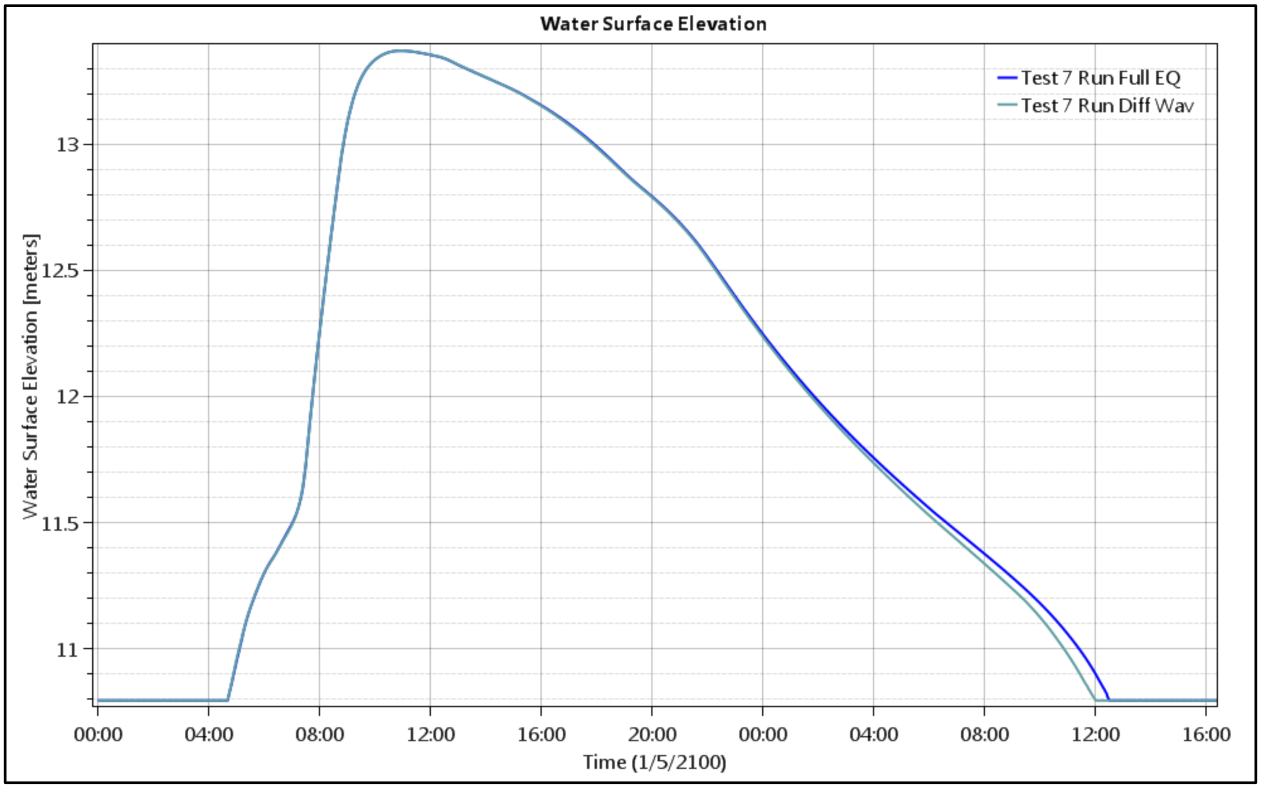


Figure 116. Floodplain 1 - Test Point 5 - Water Level.

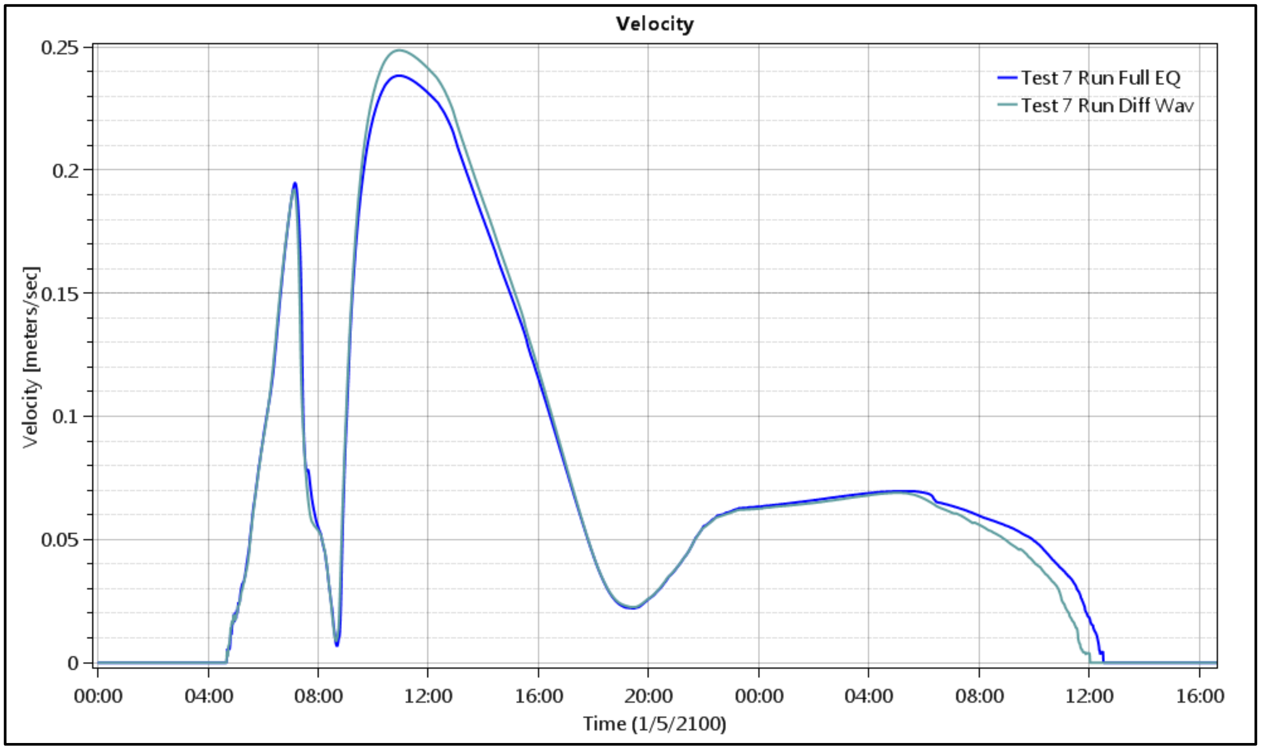


Figure 117. Floodplain 1 - Test Point 5 - Velocity.

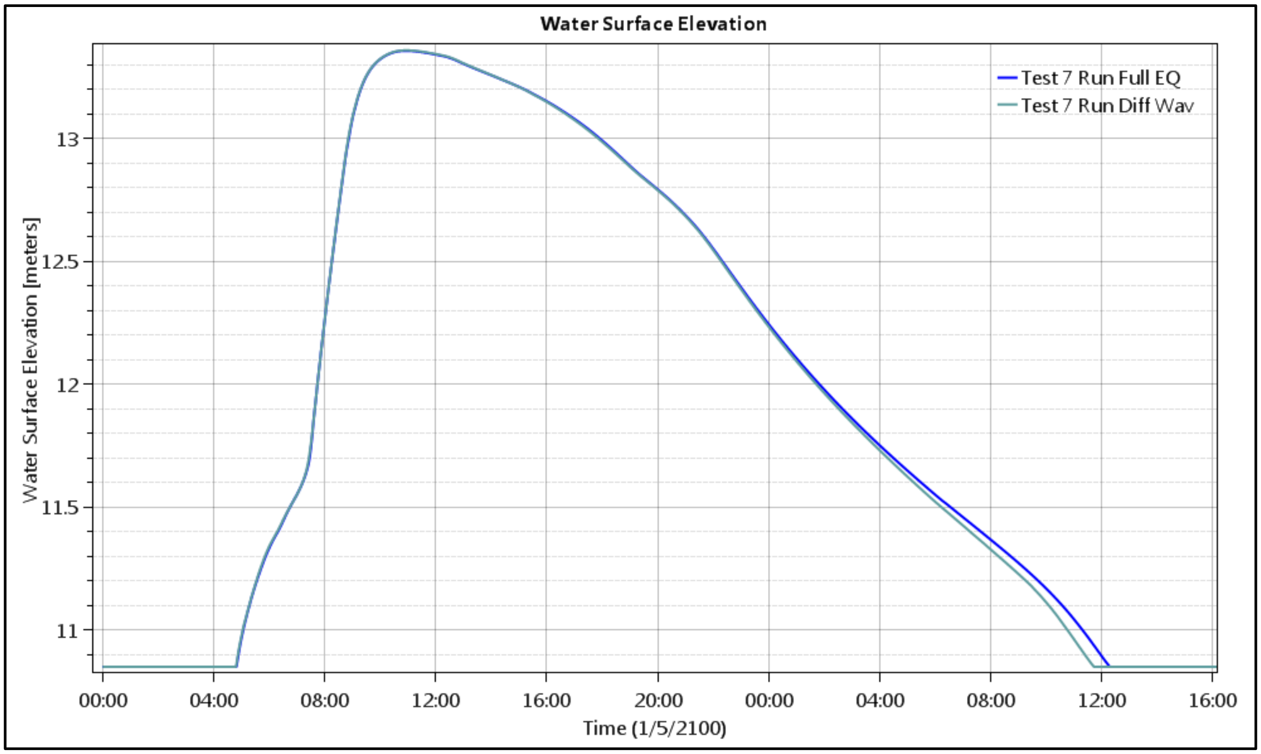


Figure 118. Floodplain 1 - Test Point 6 - Water Level.

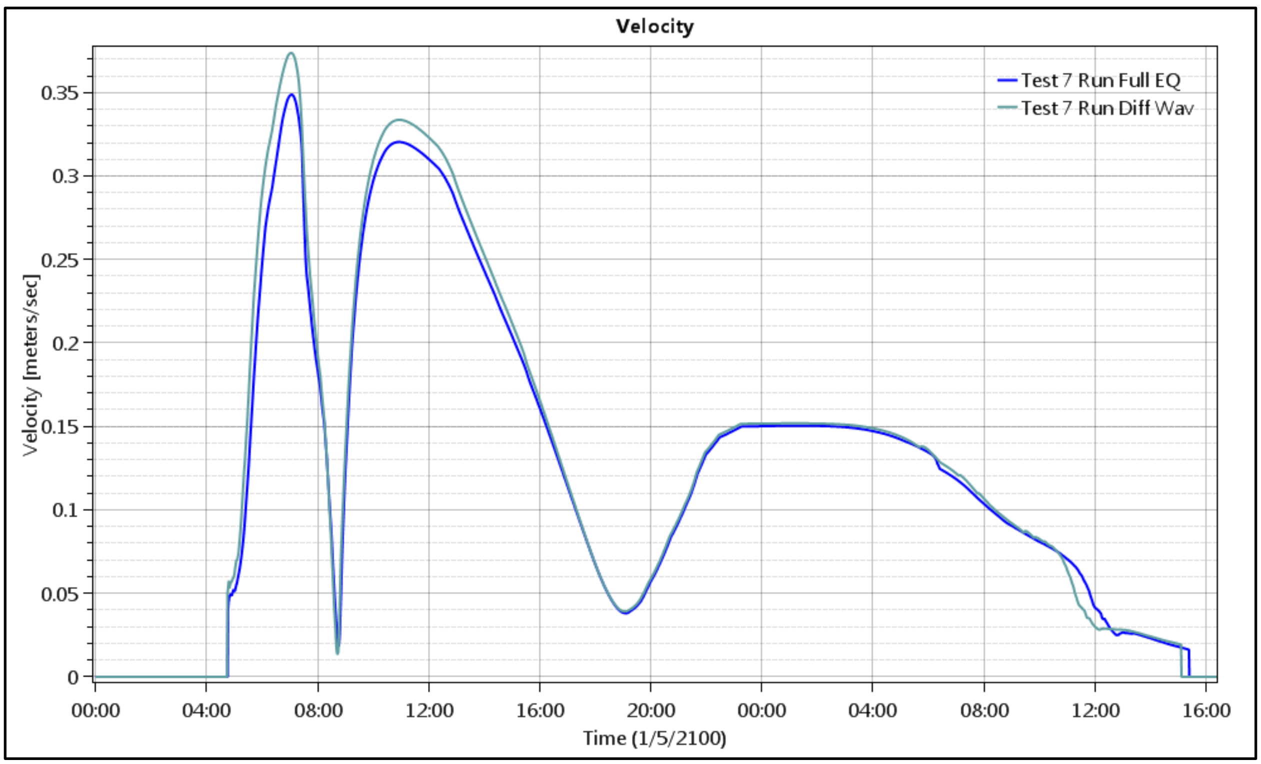


Figure 119. Floodplain 1 - Test Point 6 - Velocity.

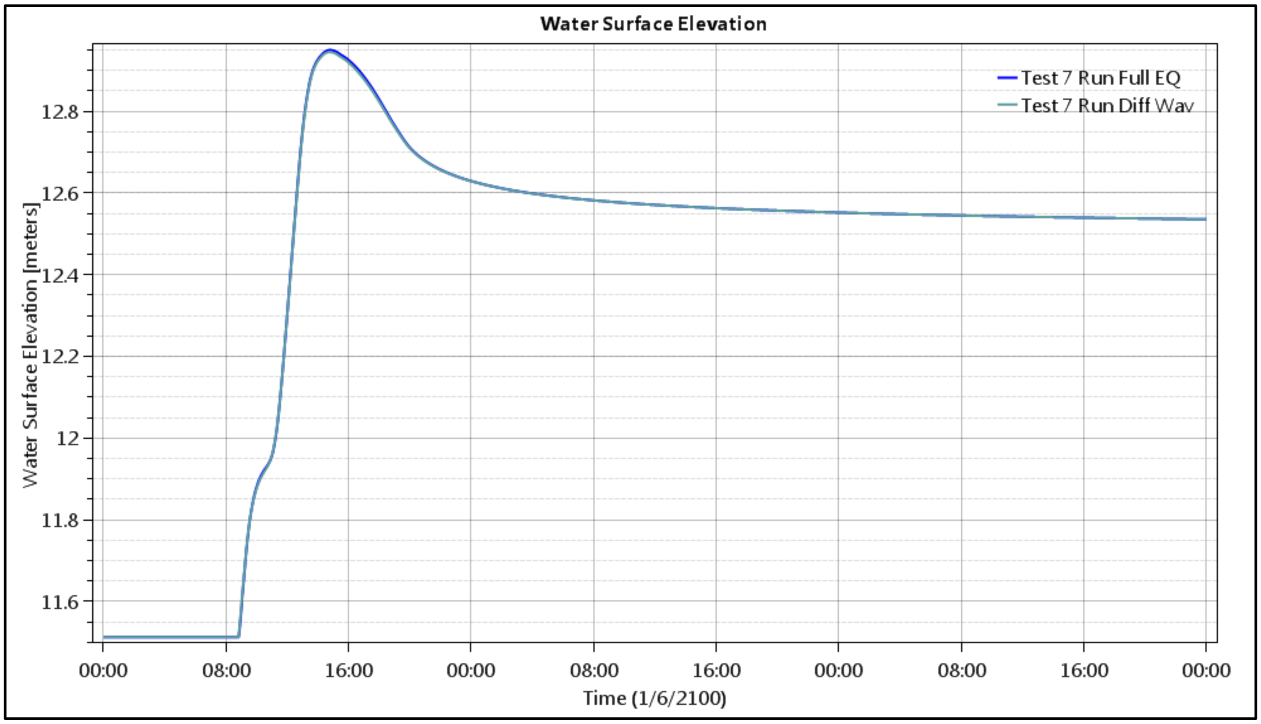


Figure 120. Floodplain 2 - Test Point 7 - Water Level.

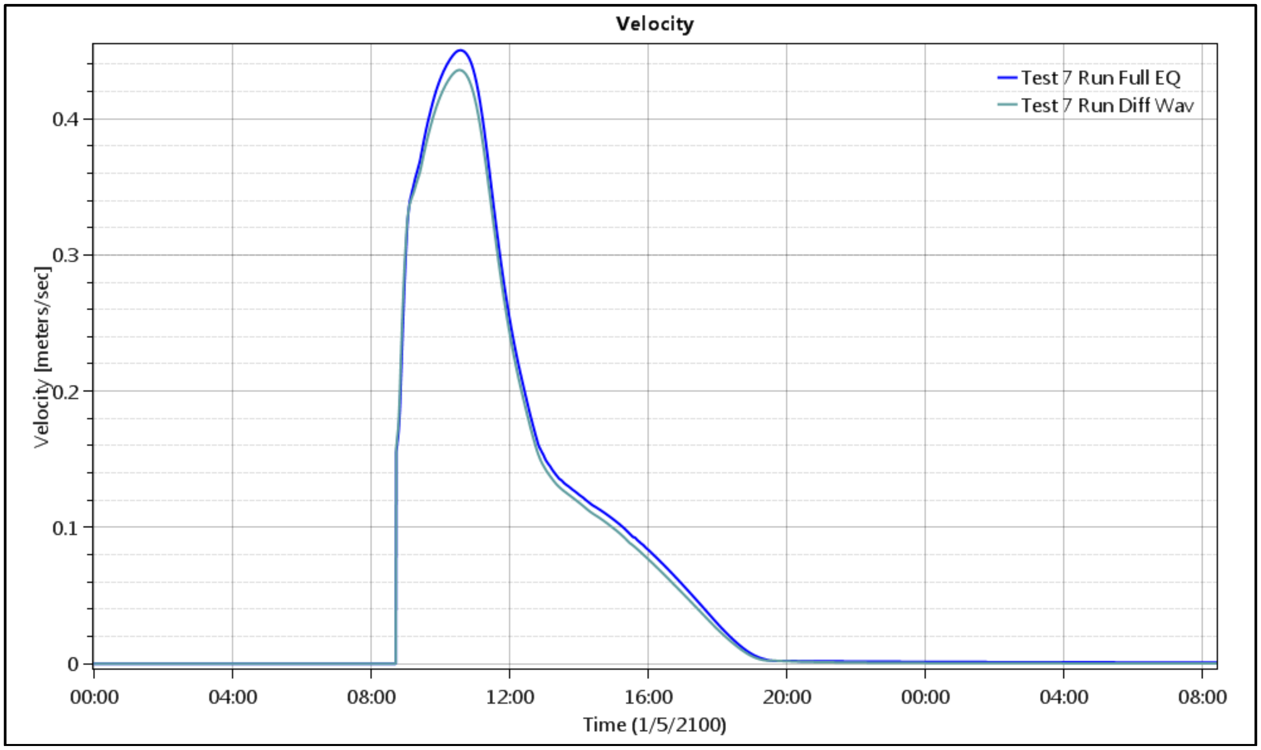


Figure 121. Floodplain 2 - Test Point 7 - Velocity.

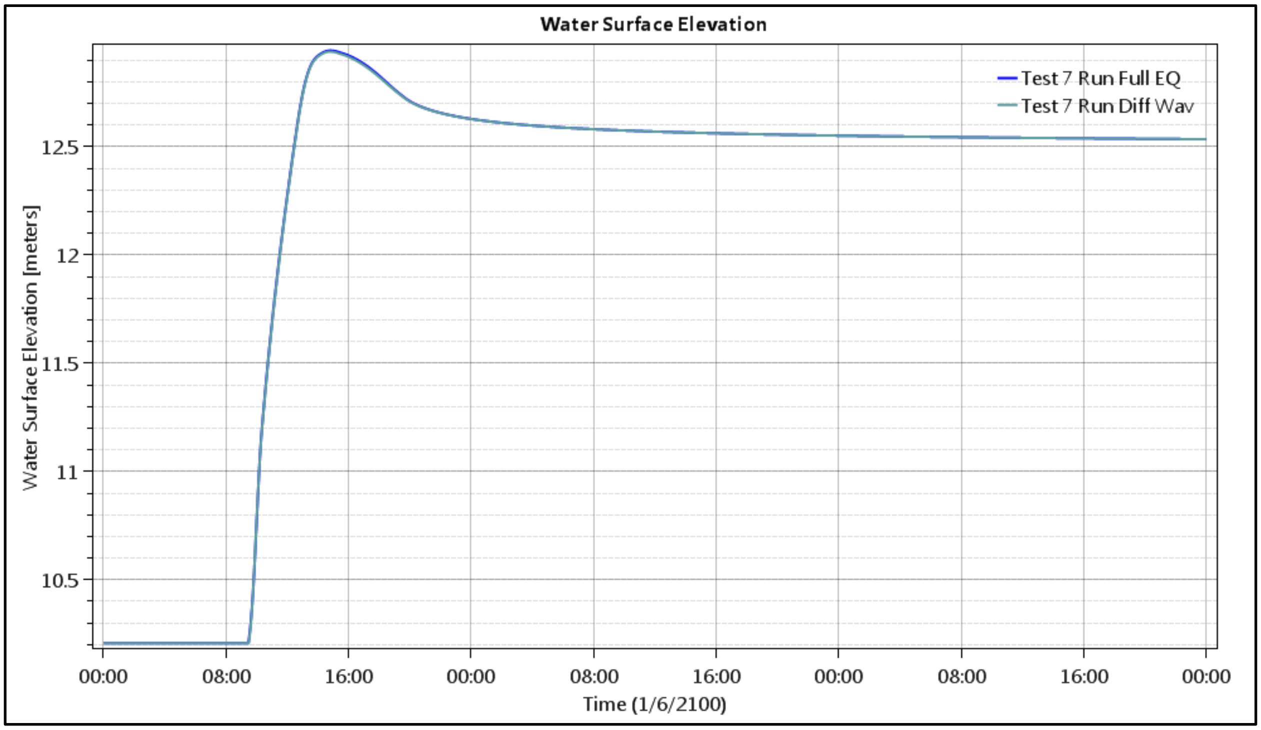


Figure 122. Floodplain 2 - Test Point 8 - Water Level.

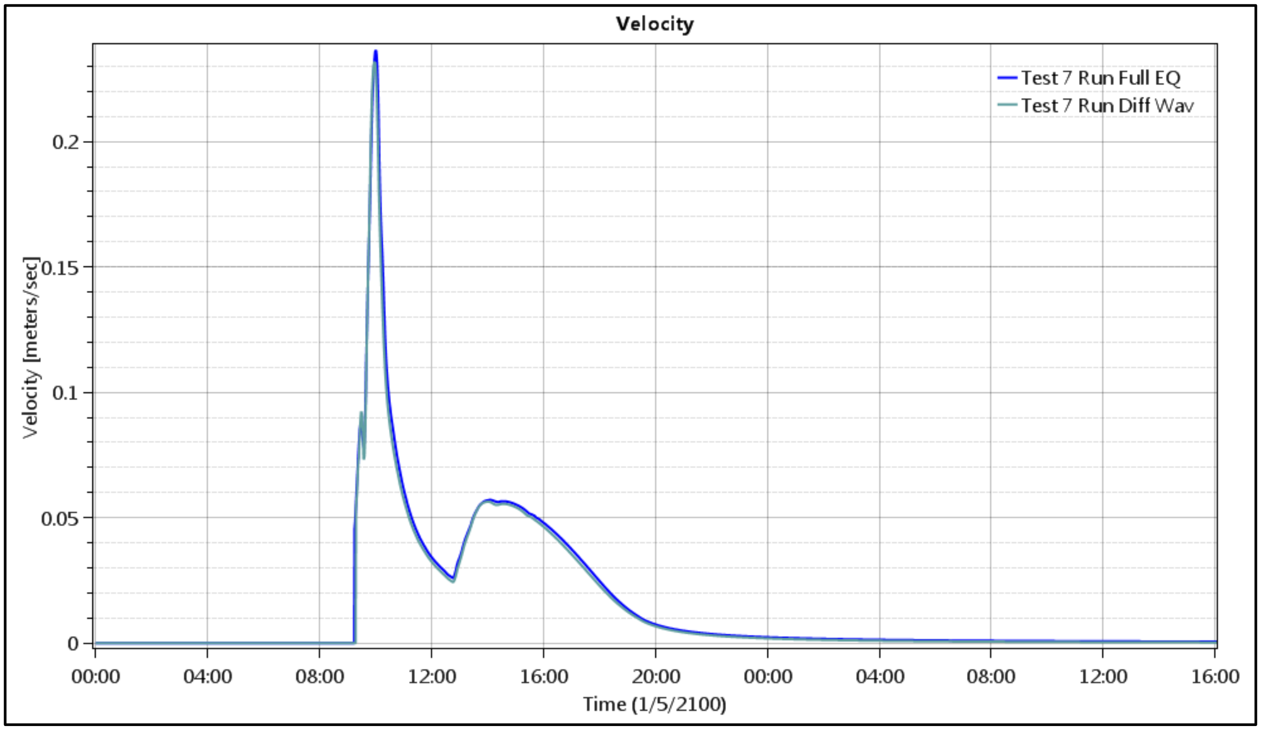


Figure 123. Floodplain 2 - Test Point 8 - Velocity.

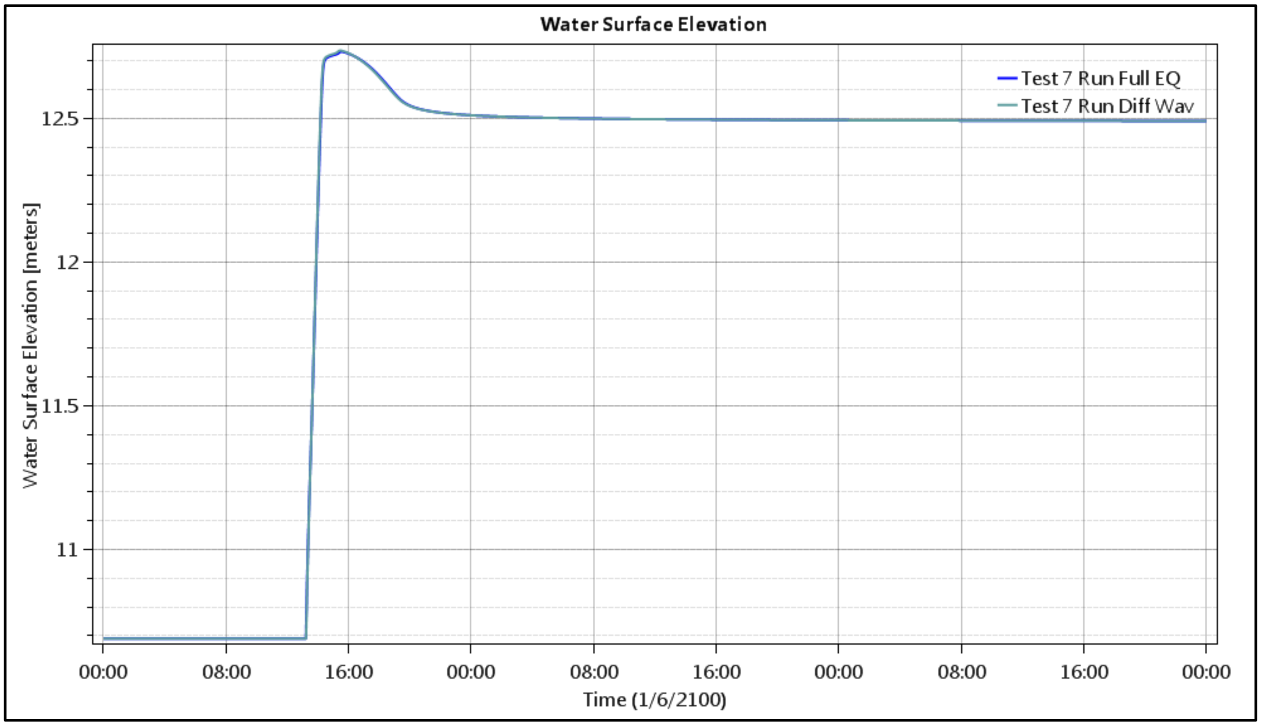


Figure 124. Floodplain 2 - Test Point 9 - Water Level.

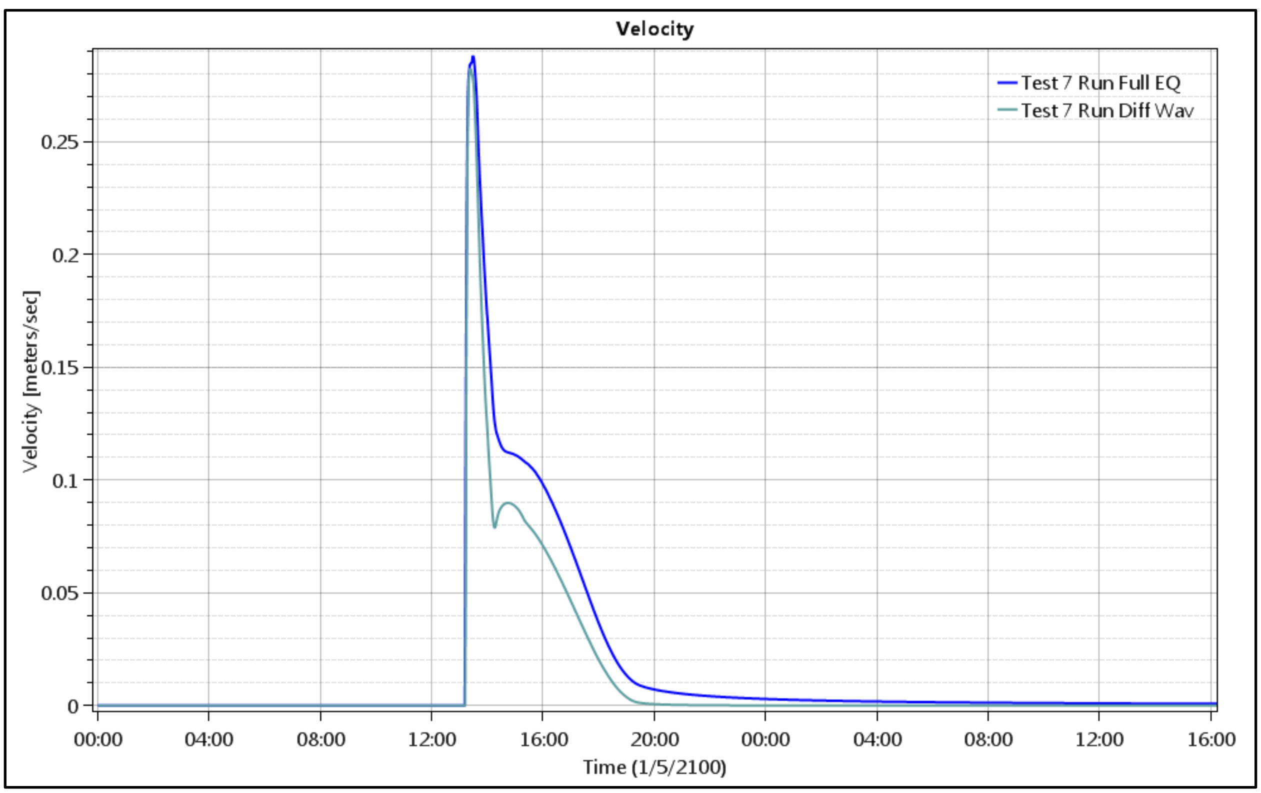


Figure 125. Floodplain 2 - Test Point 9 - Velocity.

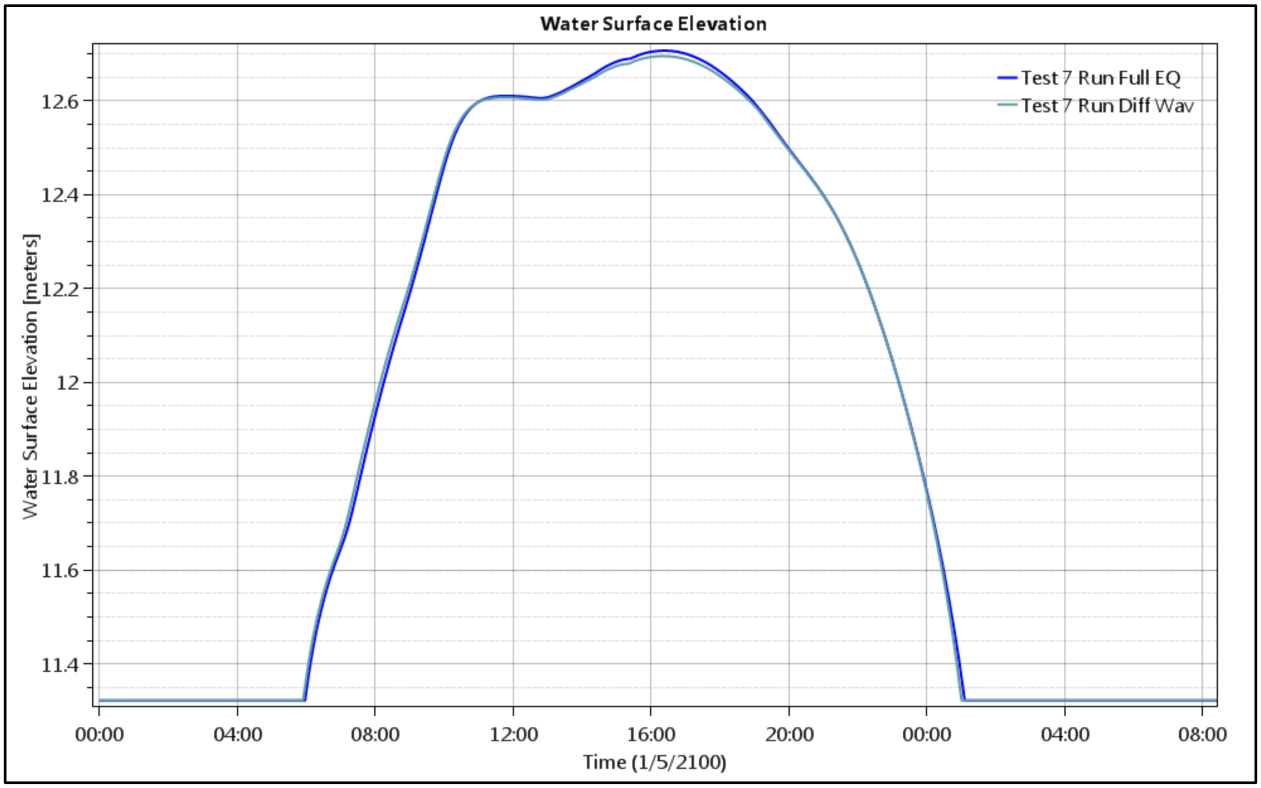


Figure 126. Floodplain 3 - Test Point 10 - Water Level.

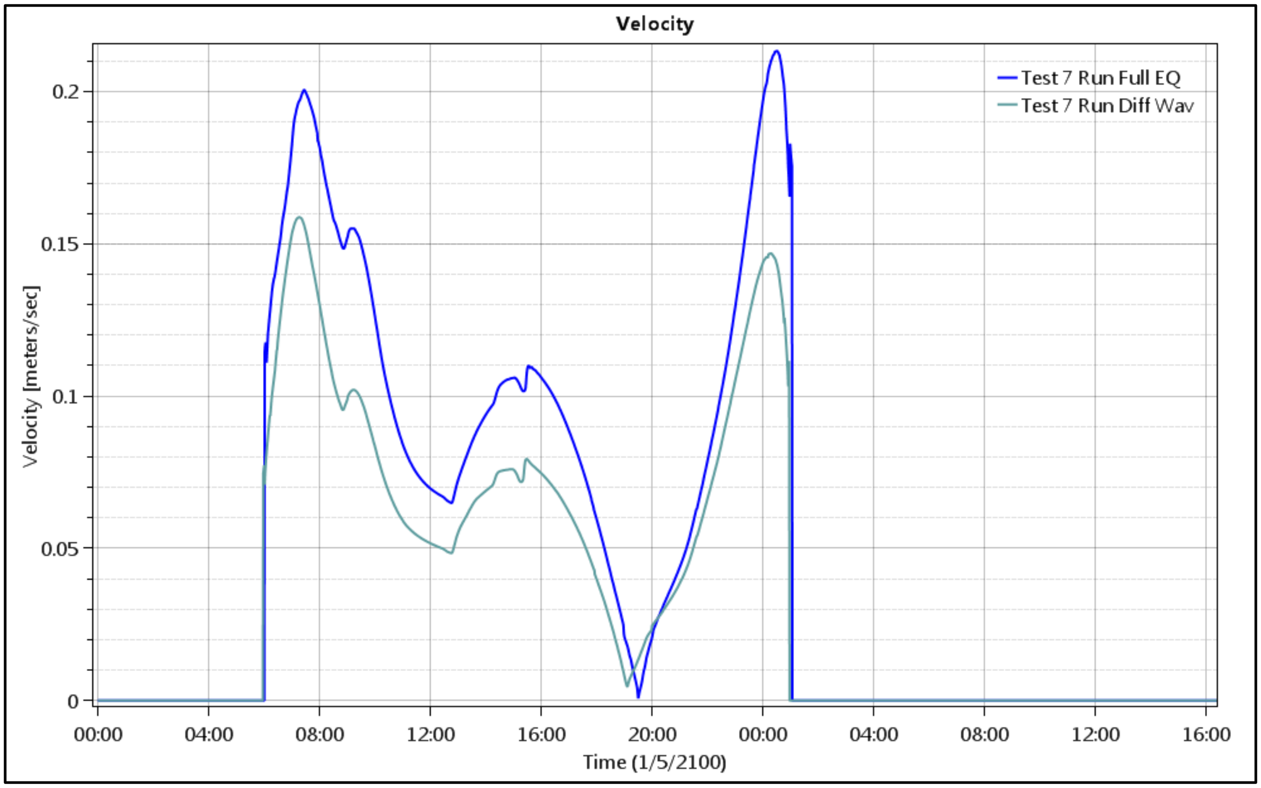


Figure 127. Floodplain 3 - Test Point 10 - Velocity.

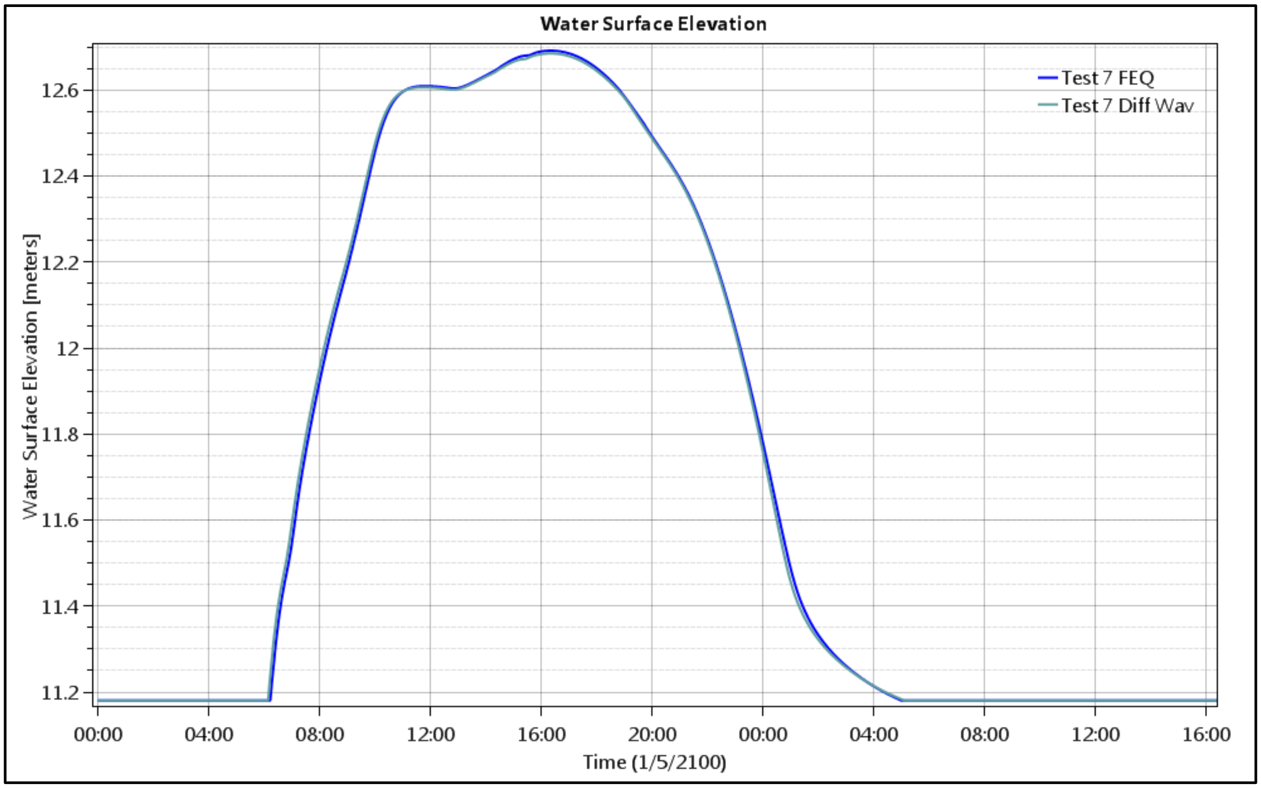


Figure 128. Floodplain 3 - Test Point 11 - Water Level.

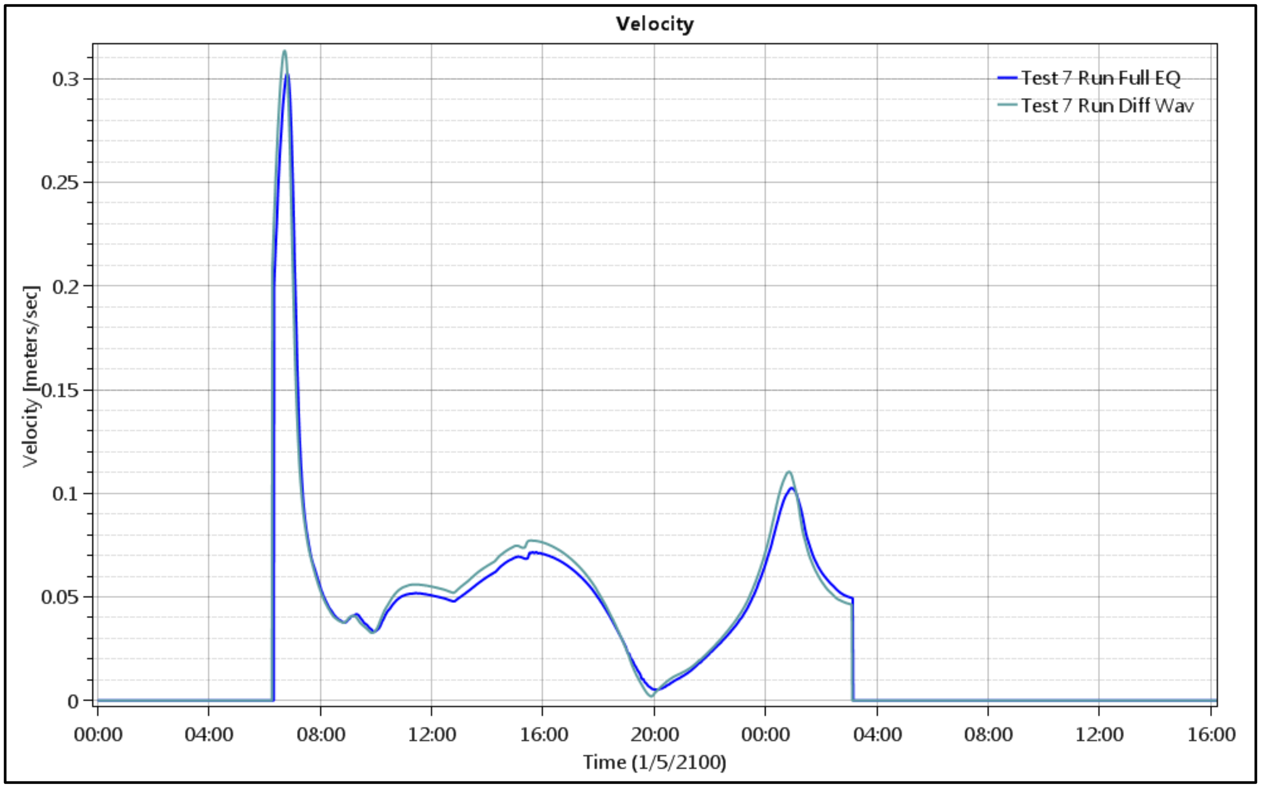


Figure 129. Floodplain 3 - Test Point 11 - Velocity.

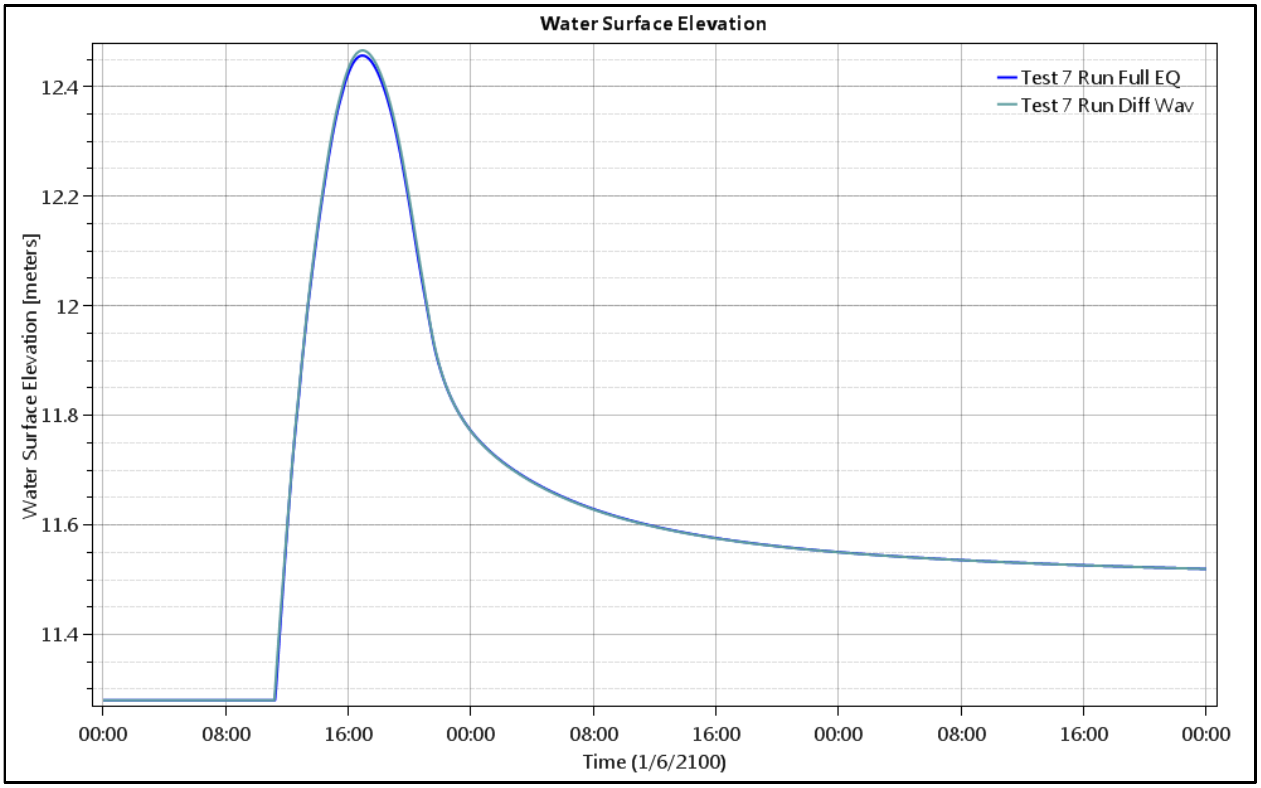


Figure 130. Floodplain 3 - Test Point 12 - Water Level.

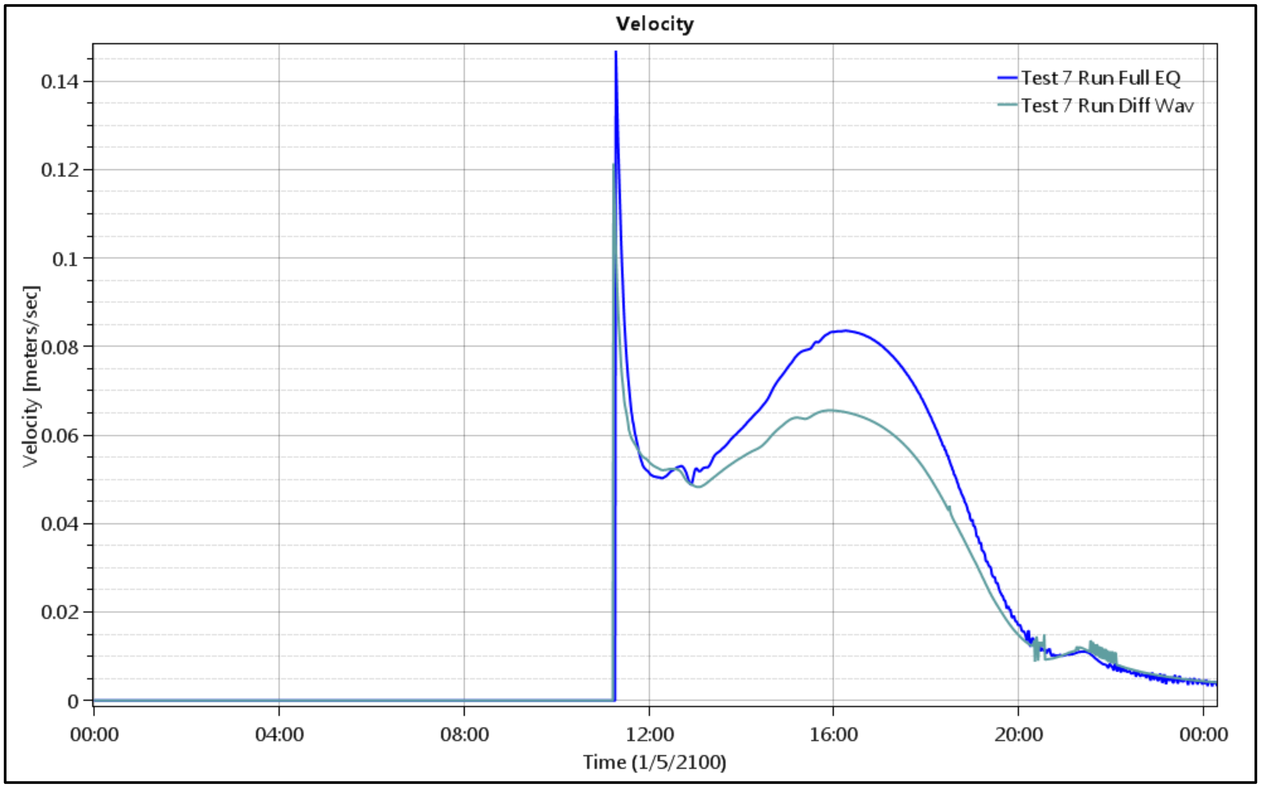


Figure 131. Floodplain 3 - Test Point 12 - Velocity.

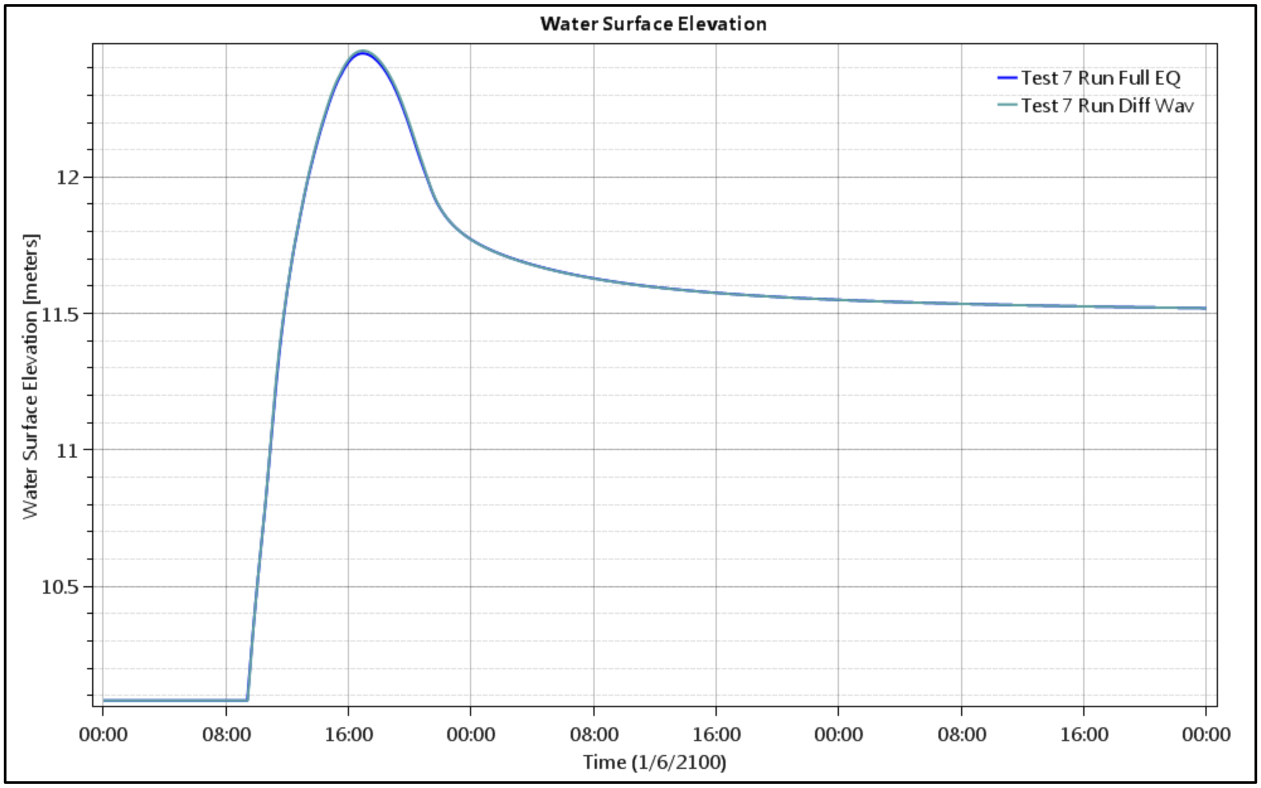


Figure 132. Floodplain 3 - Test Point 13 - Water Level.

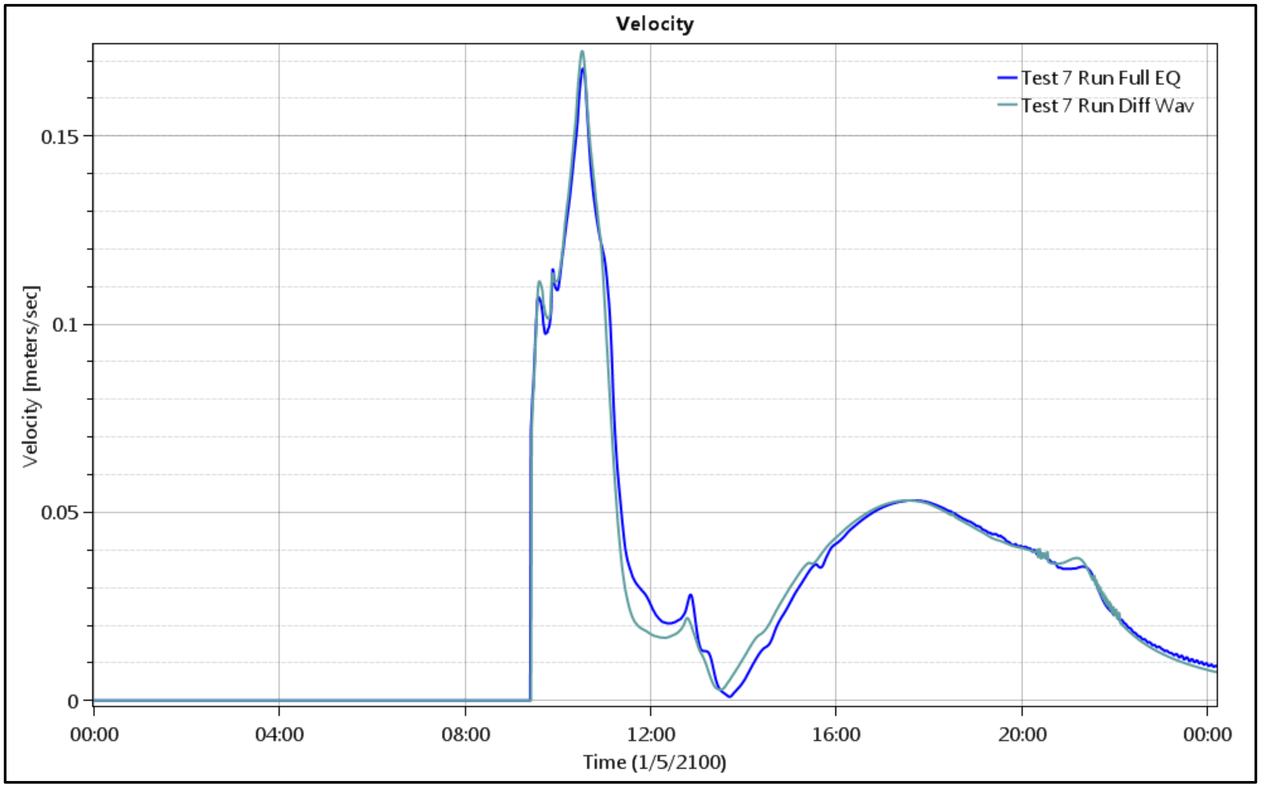


Figure 133. Floodplain 3 - Test Point 13 - Velocity.

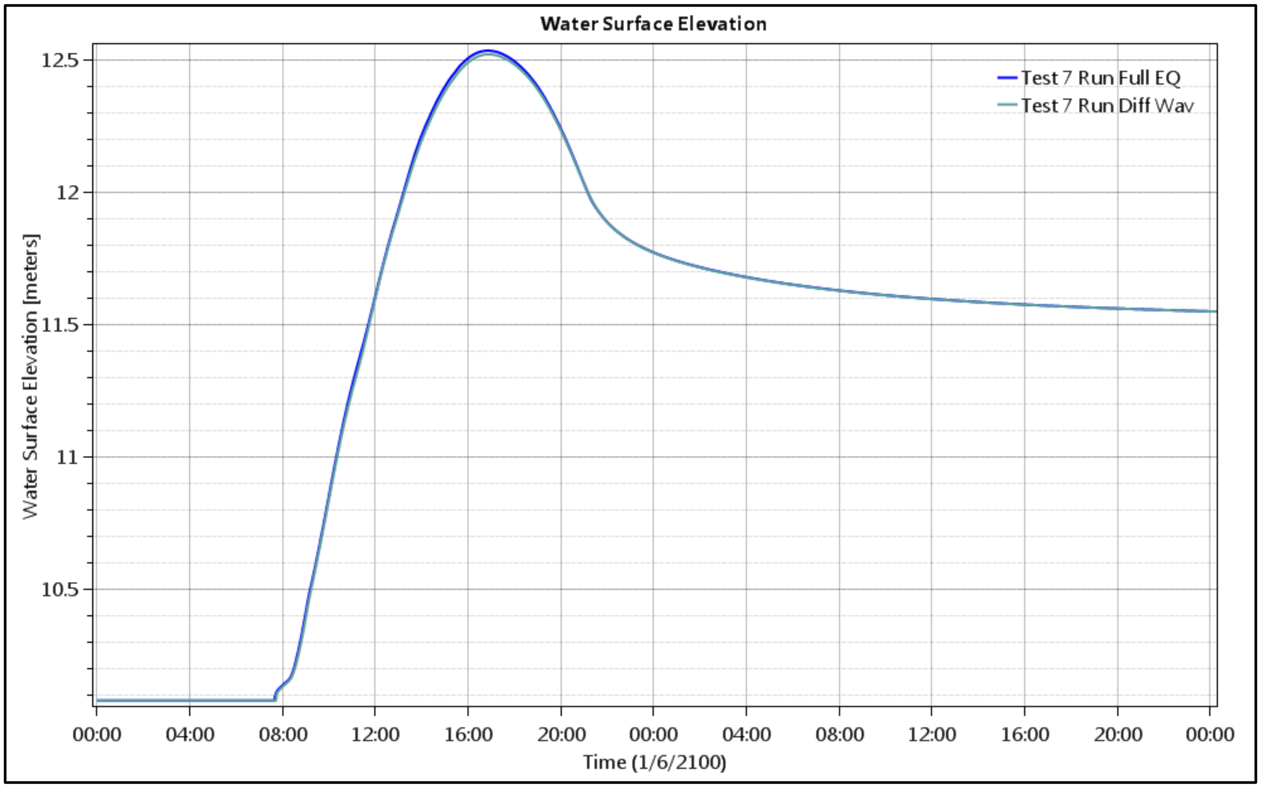


Figure 134. Floodplain 3 - Test Point 14 - Water Level.

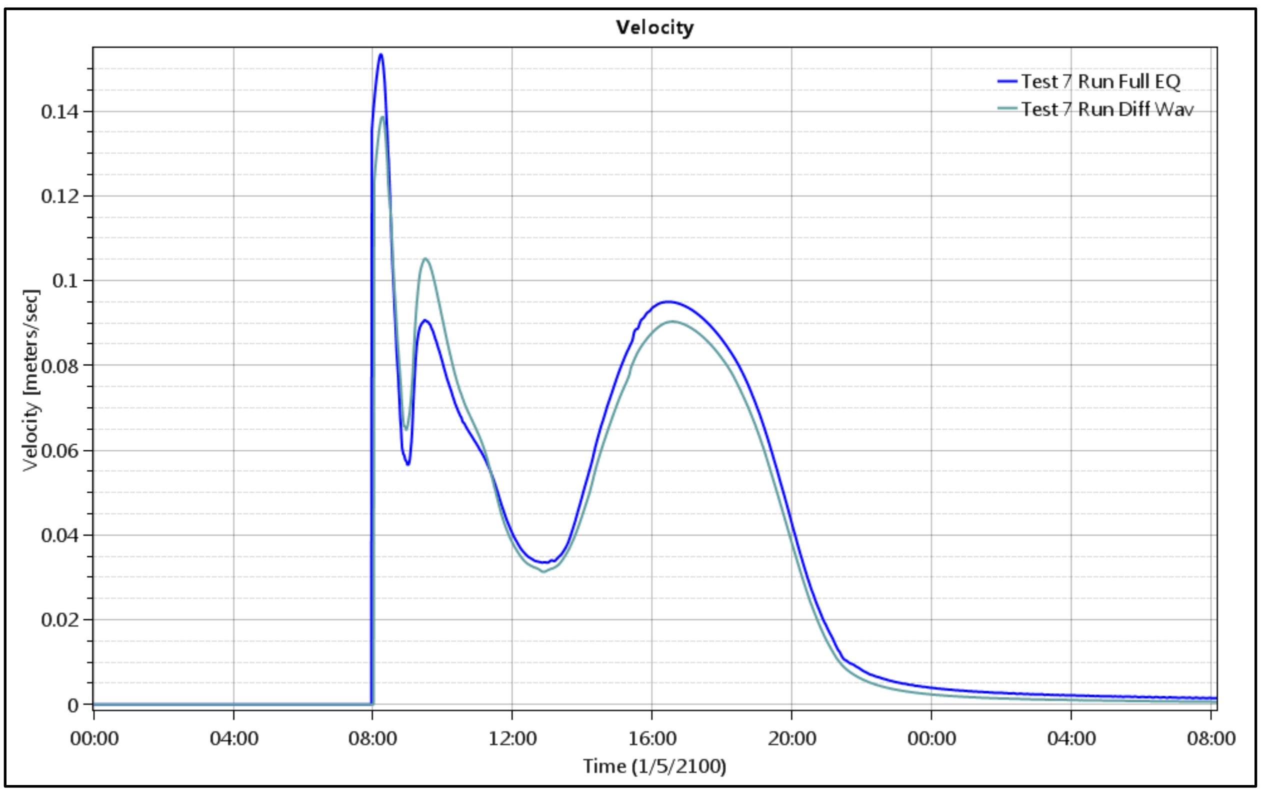


Figure 135. Floodplain 3 - Test Point 14 - Velocity.

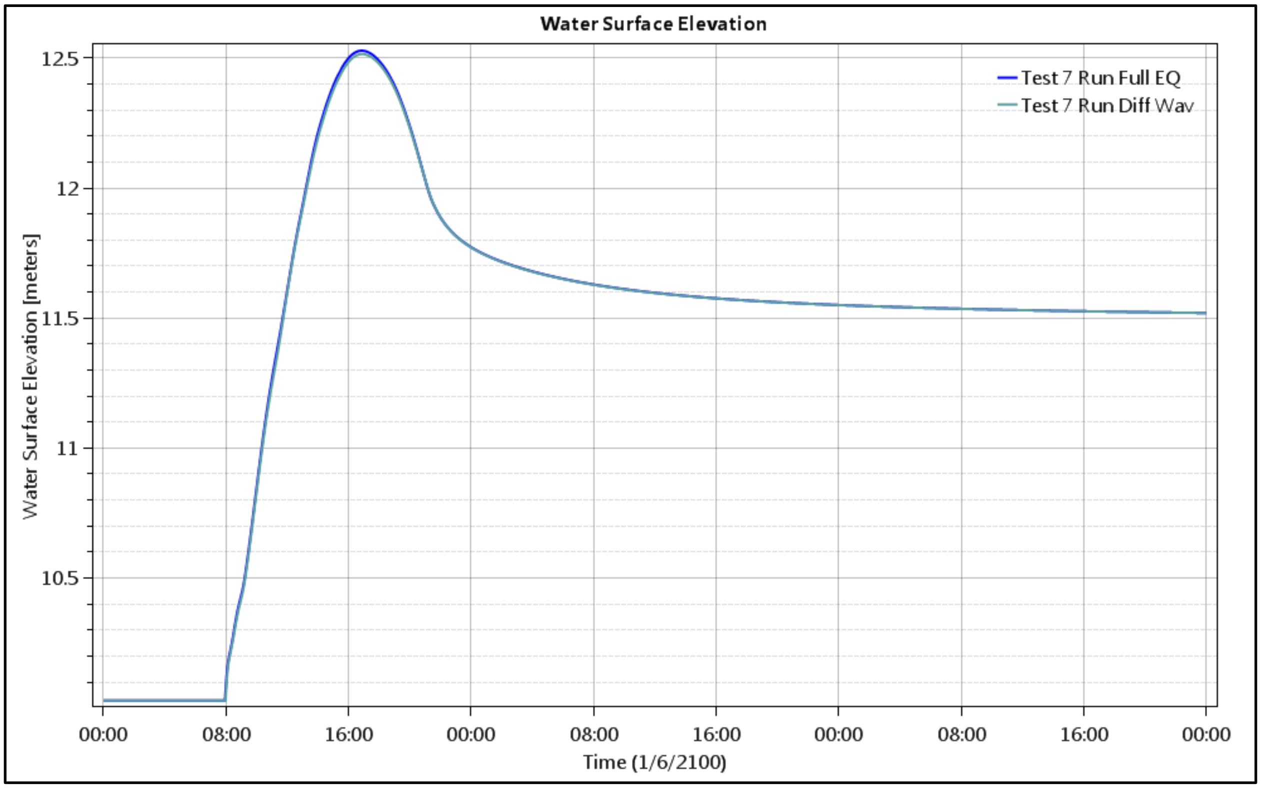


Figure 136. Floodplain 3 - Test Point 15 - Water Level.

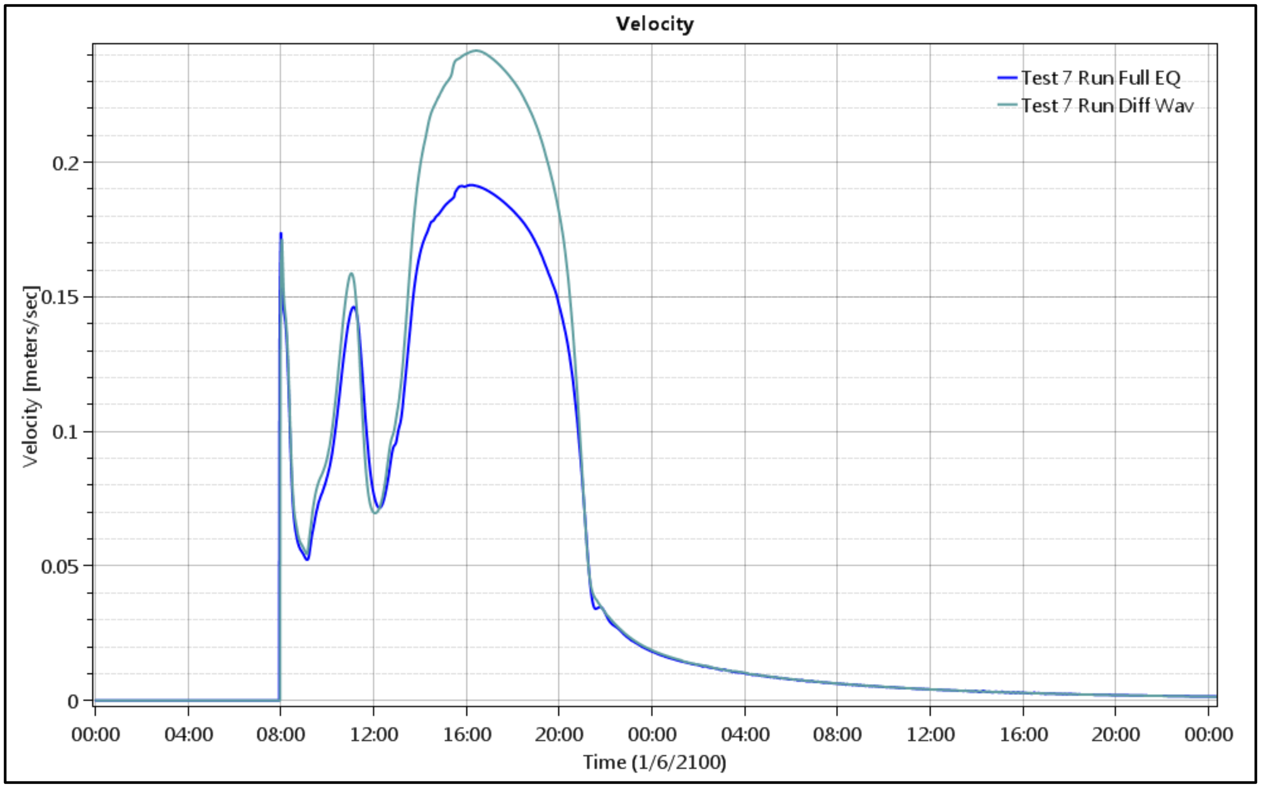


Figure 137. Floodplain 3 - Test Point 15 - Velocity

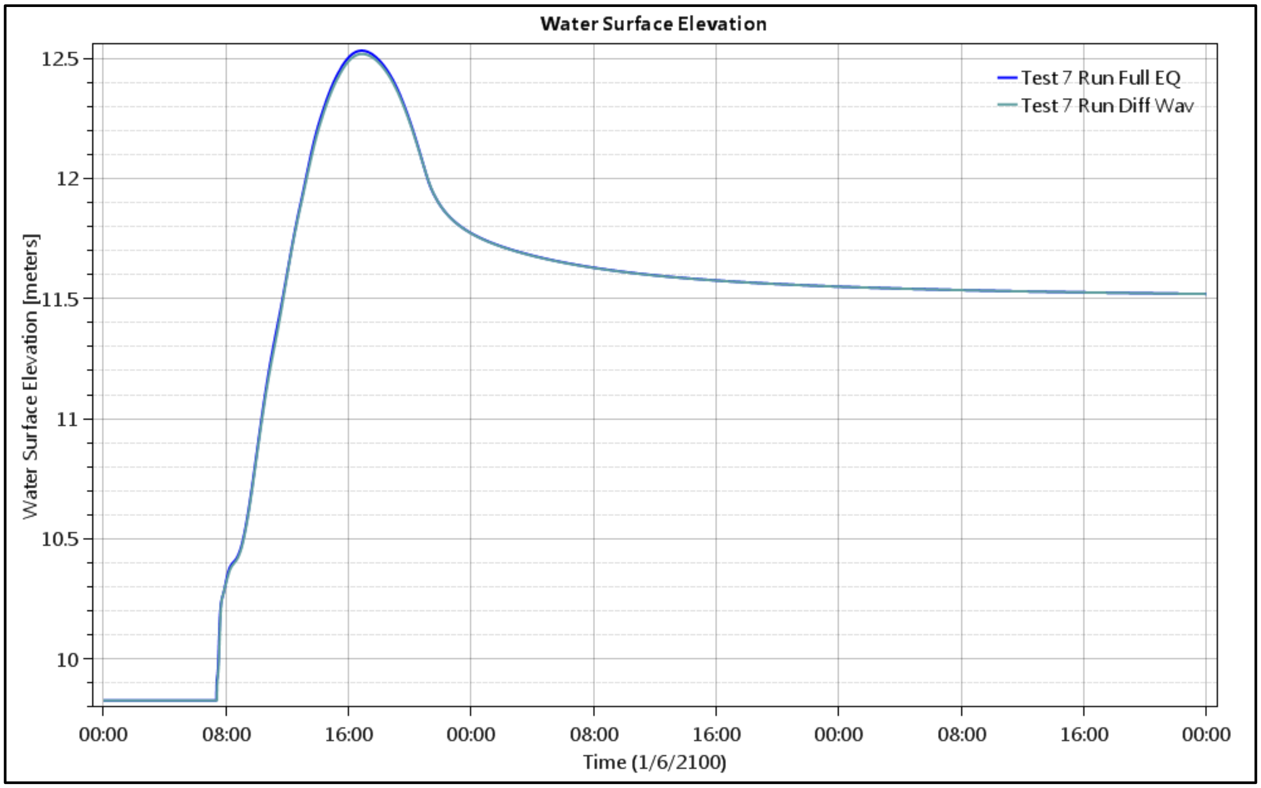


Figure 138. Floodplain 3 - Test Point 16 - Water Level.

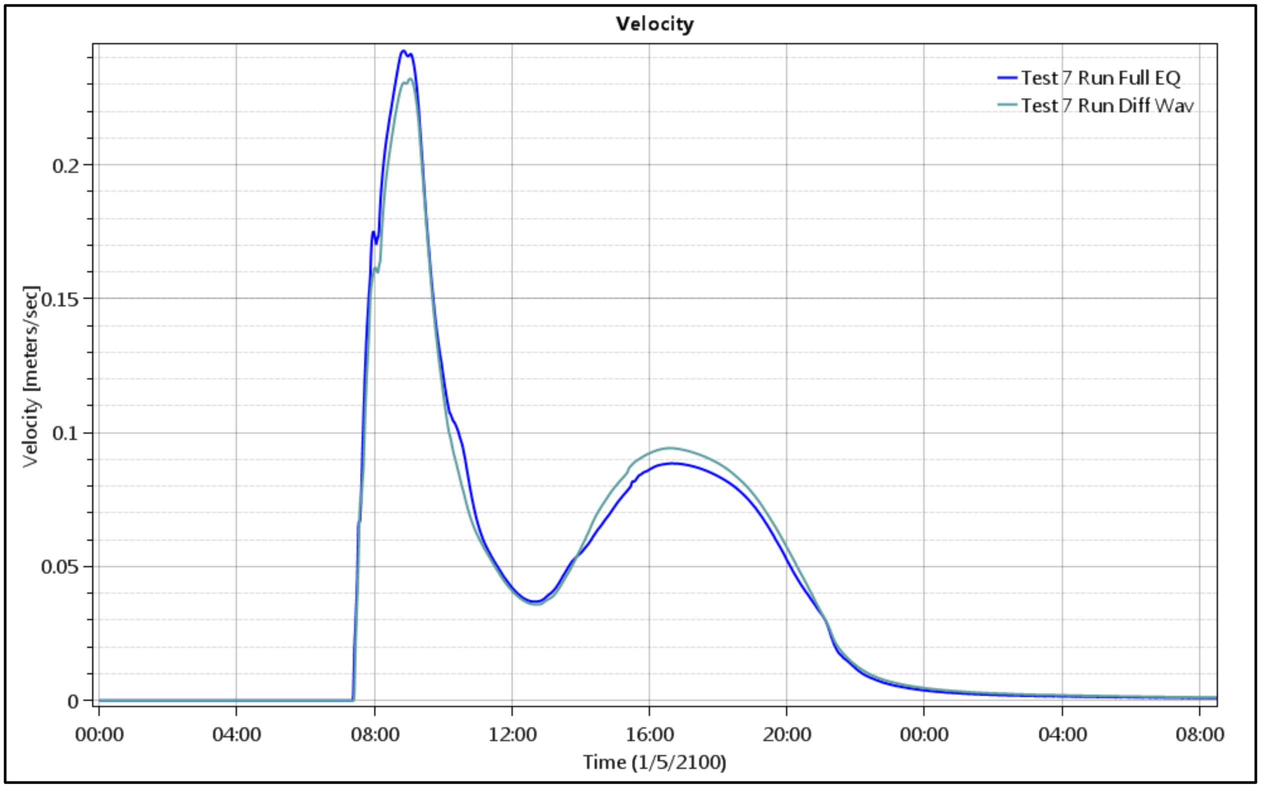


Figure 139. Floodplain 3 - Test Point 16 - Velocity.

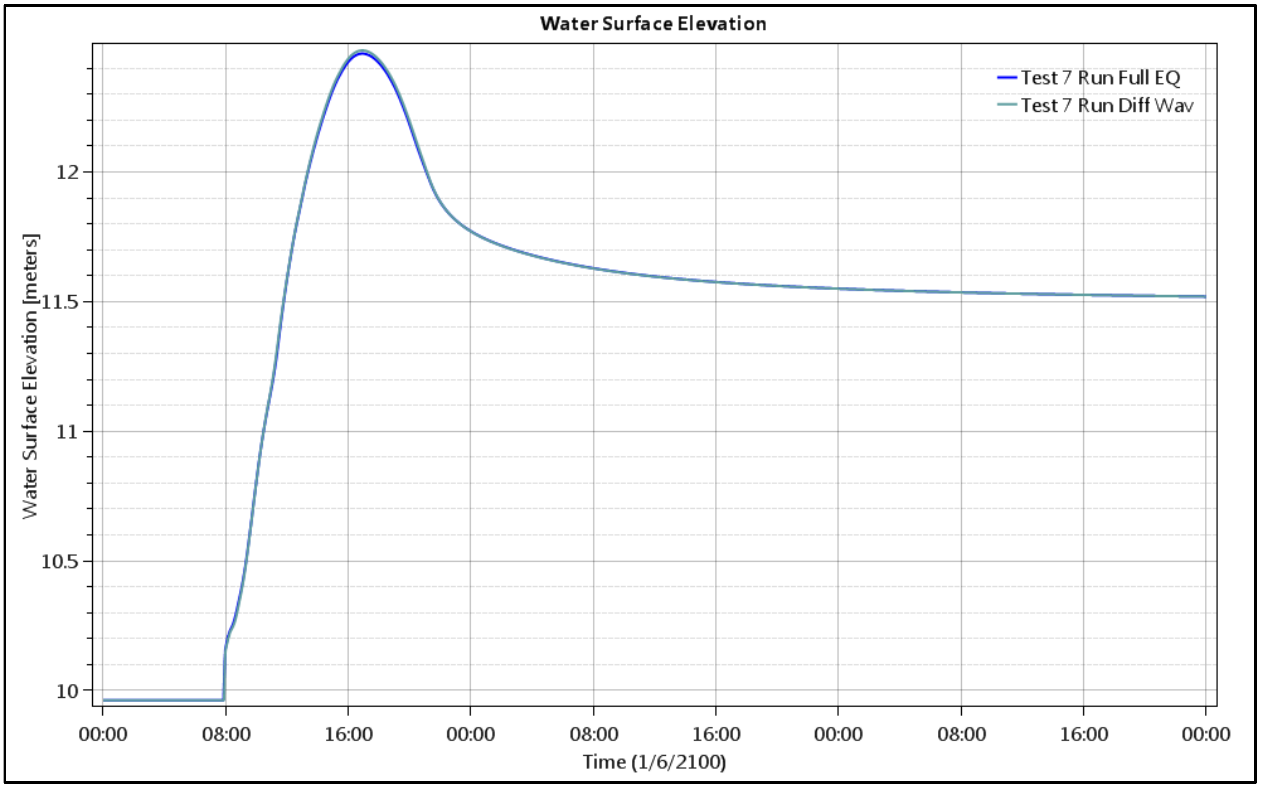


Figure 140. Floodplain 3 - Test Point 17 - Water Level.

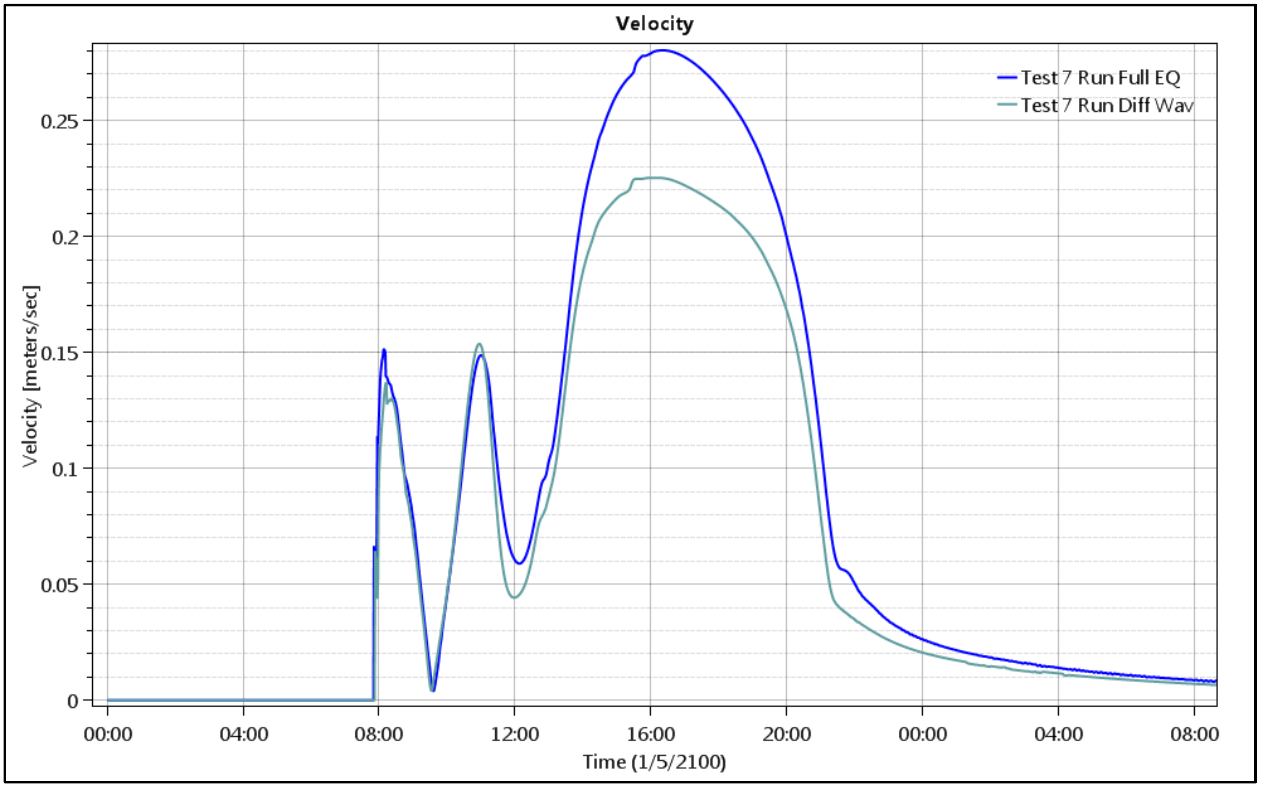


Figure 141. Floodplain 3 - Test Point 17 - Velocity.

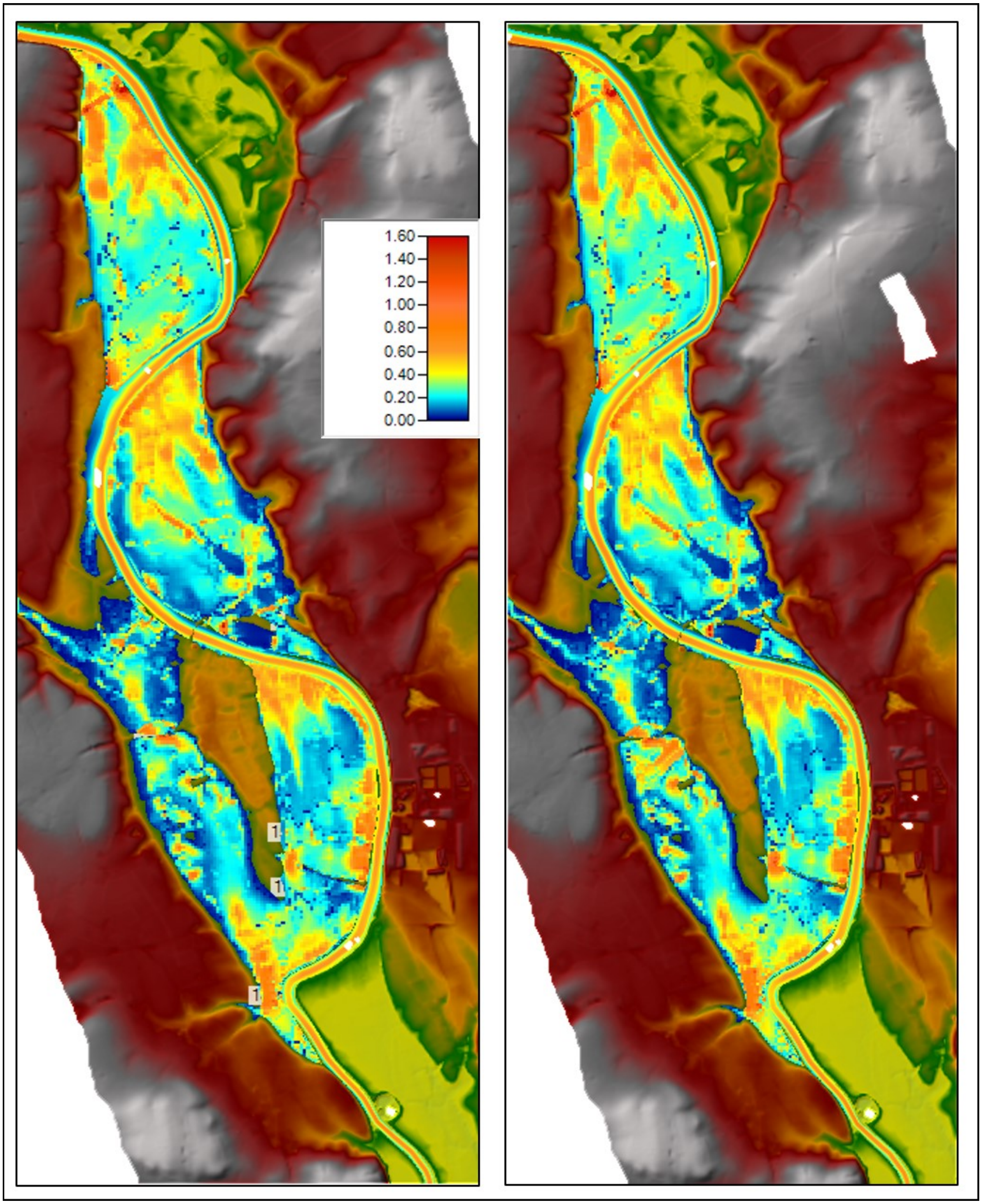


Figure 142. Spatial Plots of Maximum Velocity (meter/second), Full Equations (left) and Diffusion Wave (right).

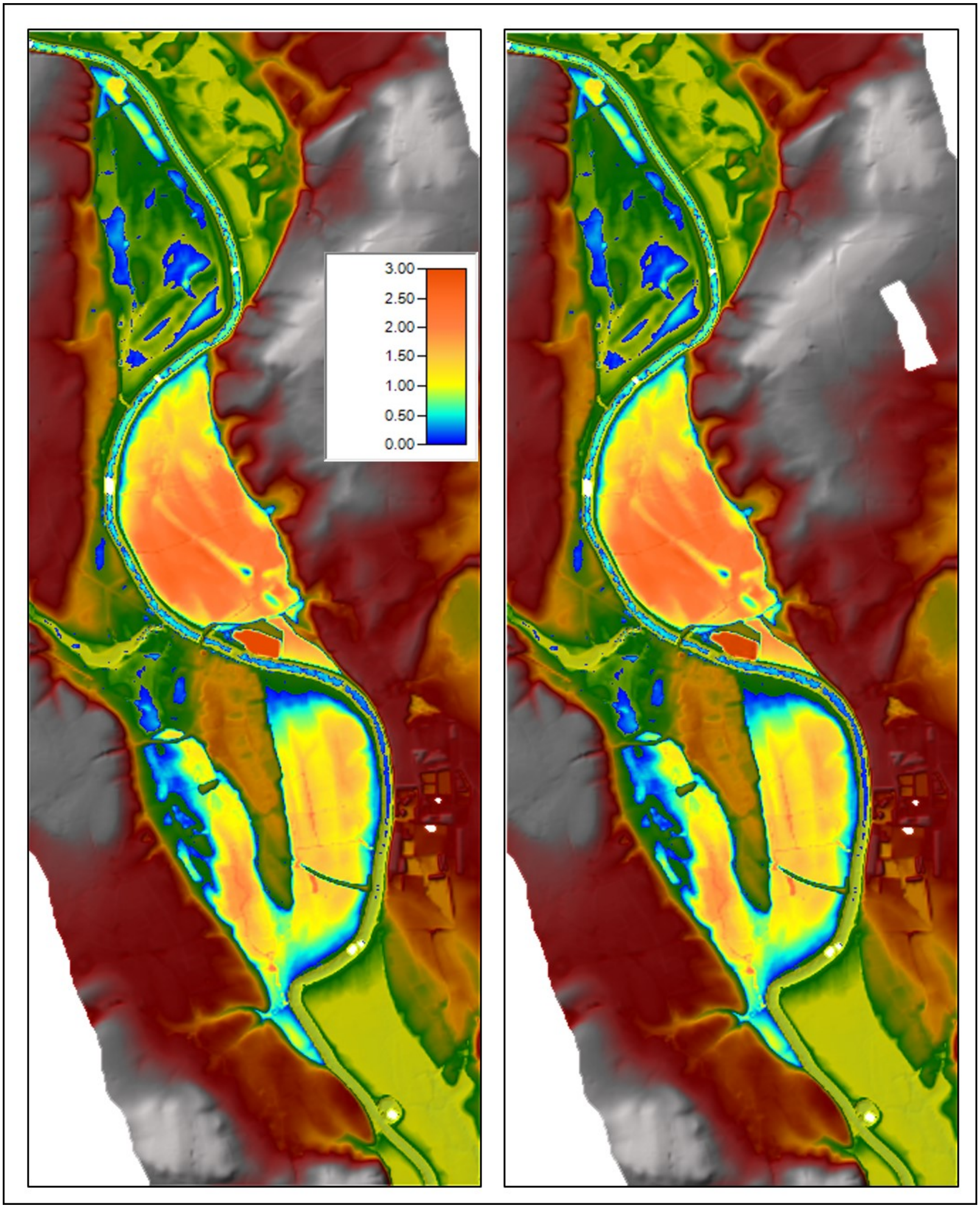


Figure 143. Spatial Plots of Final Depth (meter), Full Equations (left) and Diffusion Wave (right).

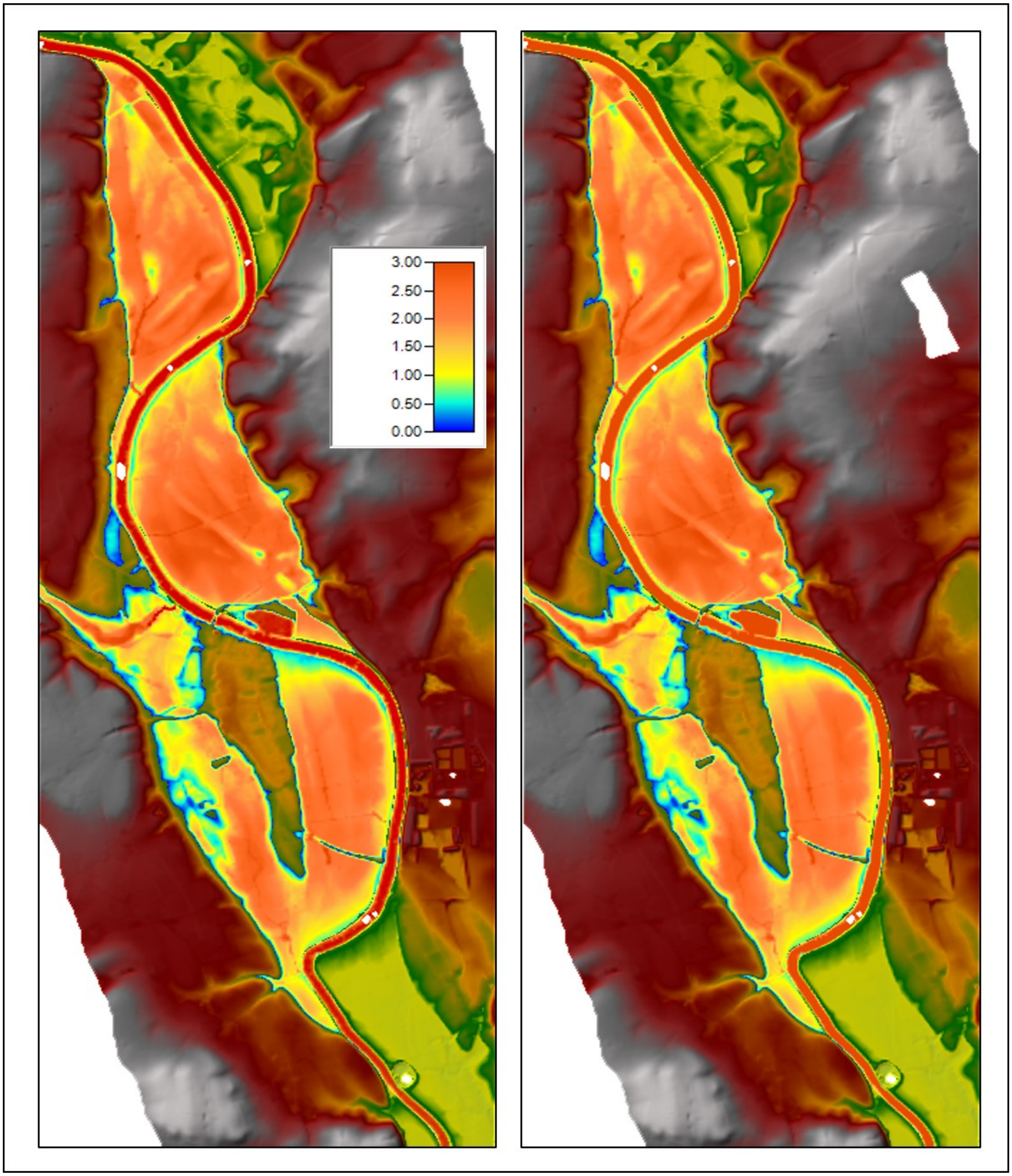


Figure 144. Spatial Plots of Maximum Depth (meter), Full Equations (left) and Diffusion Wave (right).

8.9.3 Sensitivity to Grid Resolution – Full Saint Venant Equations (20 meter and 40 meter grids)

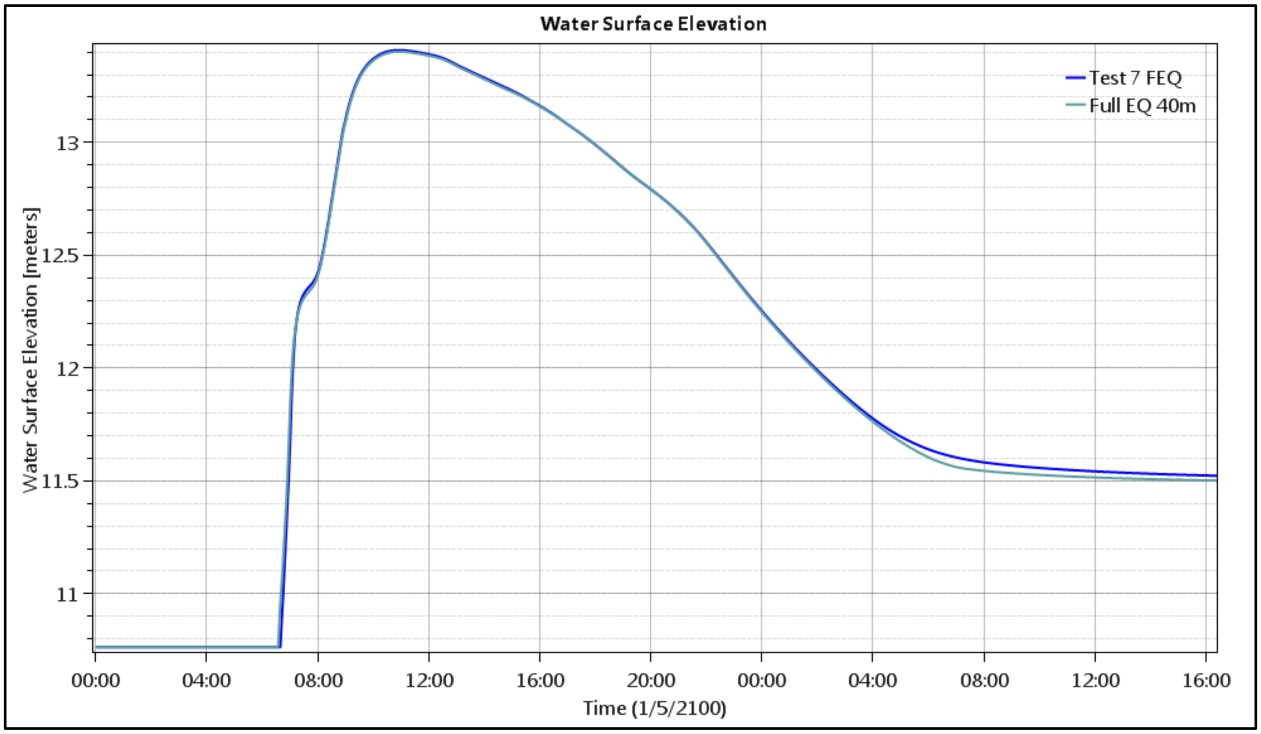


Figure 145. Floodplain 1 - Test Point 2 - Water Level.

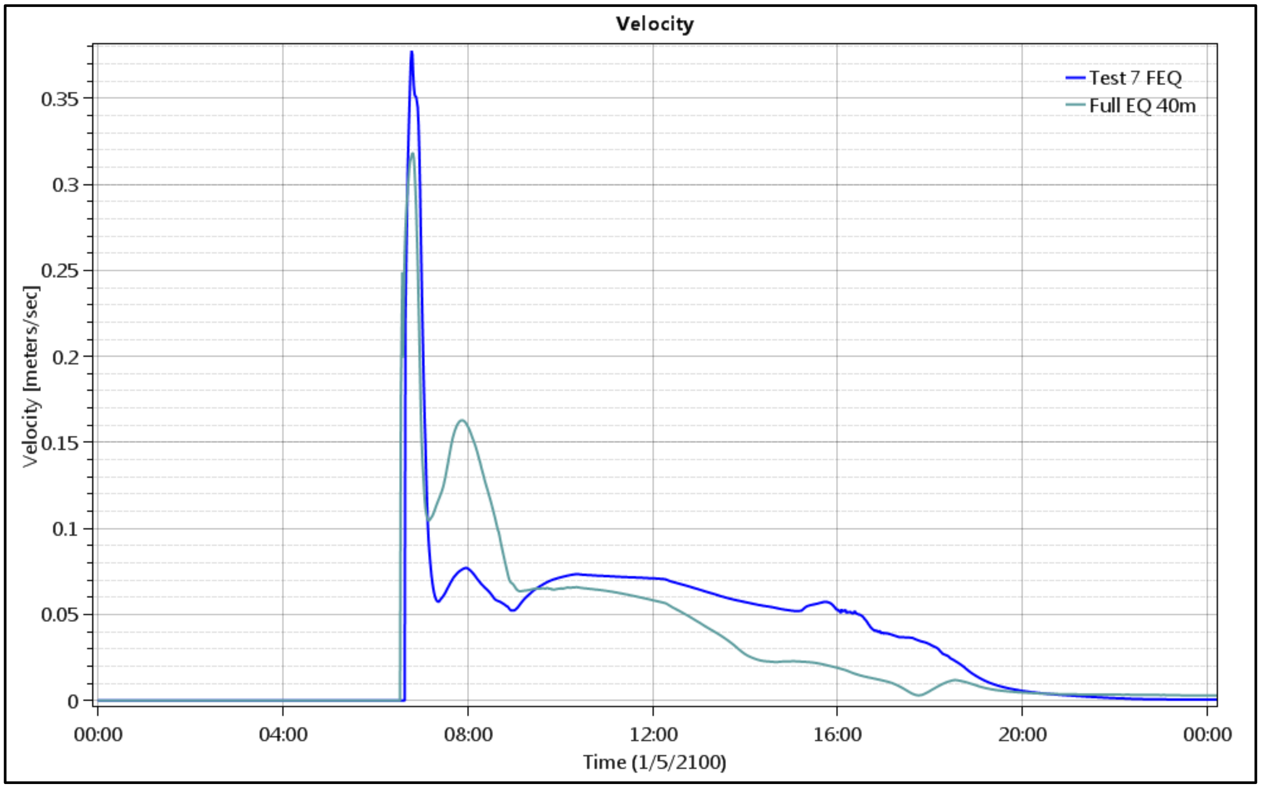


Figure 146. Floodplain 1 - Test Point 2 - Velocity.

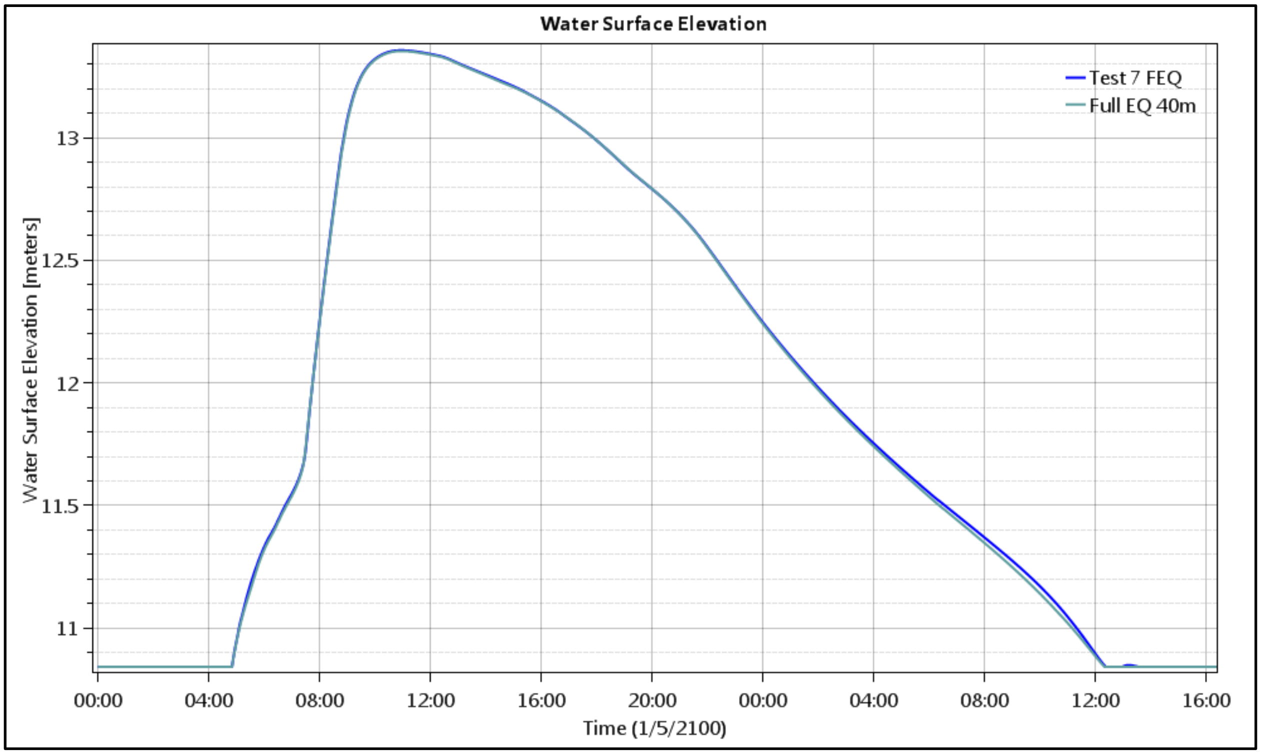


Figure 147. Floodplain 1 - Test Point 6 - Water Level.

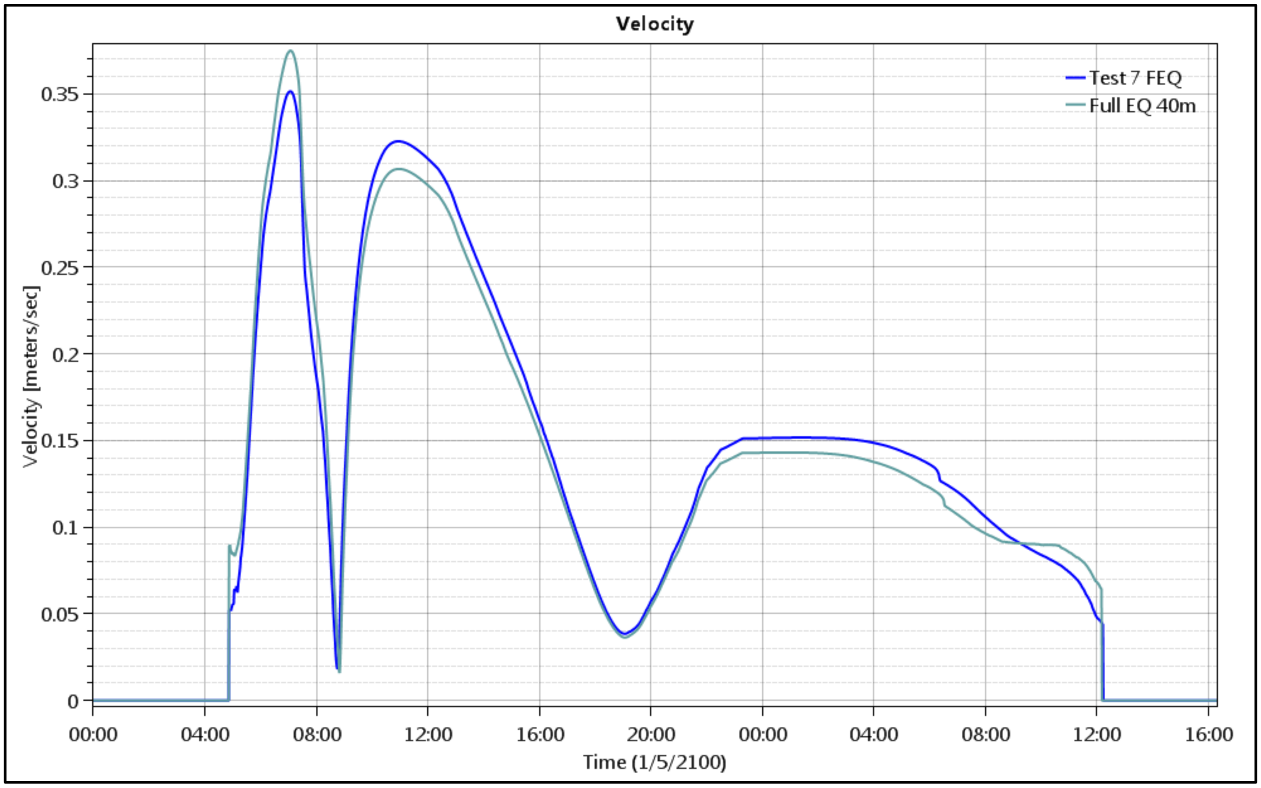


Figure 148. Floodplain 1 - Test Point 6 - Velocity.

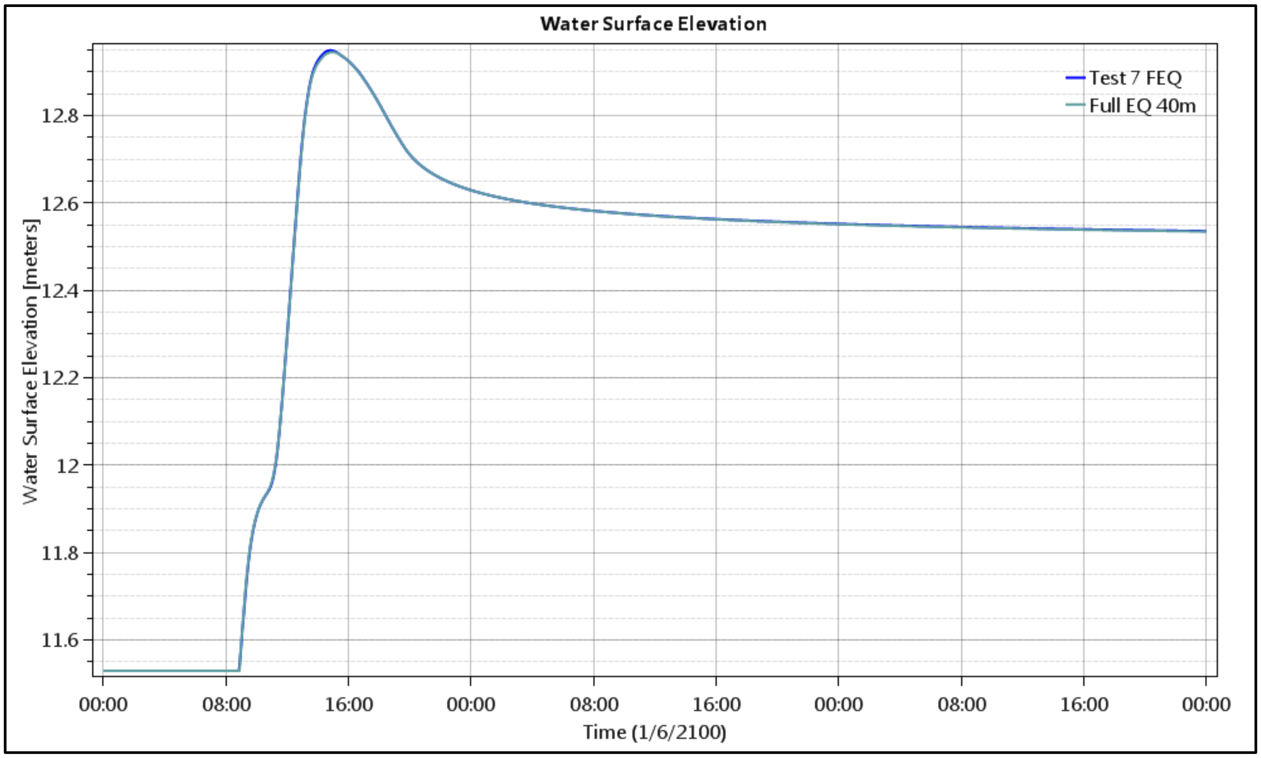


Figure 149. Floodplain 2 - Test Point 7 - Water Level.

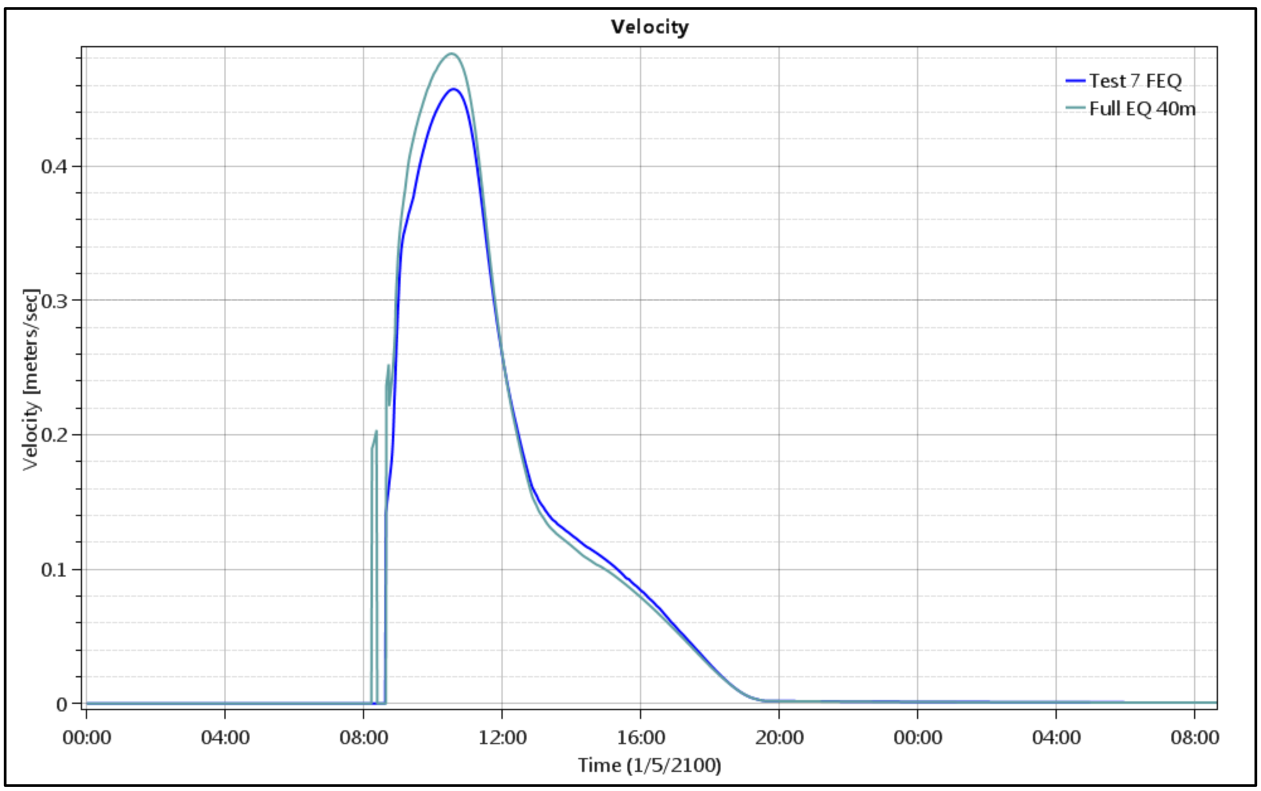


Figure 150. Floodplain 2 - Test Point 7 - Velocity.

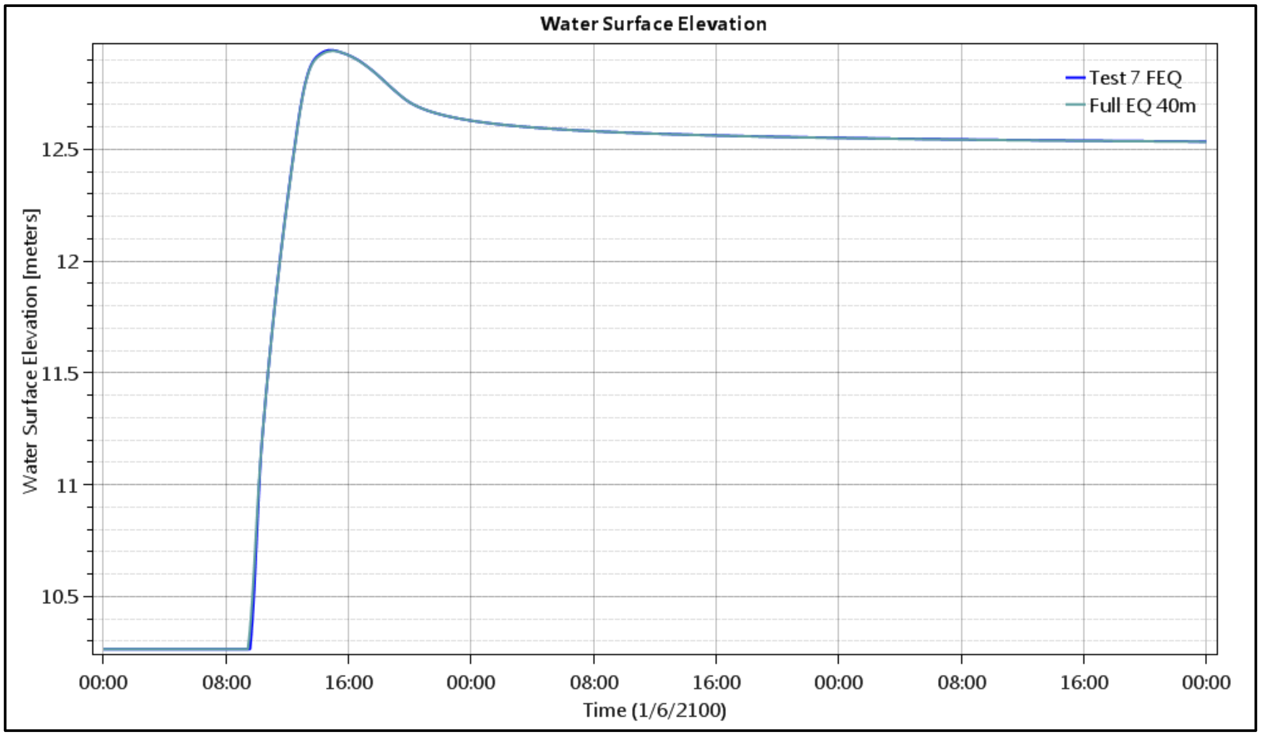


Figure 151. Floodplain 2 - Test Point 8 - Water Level.

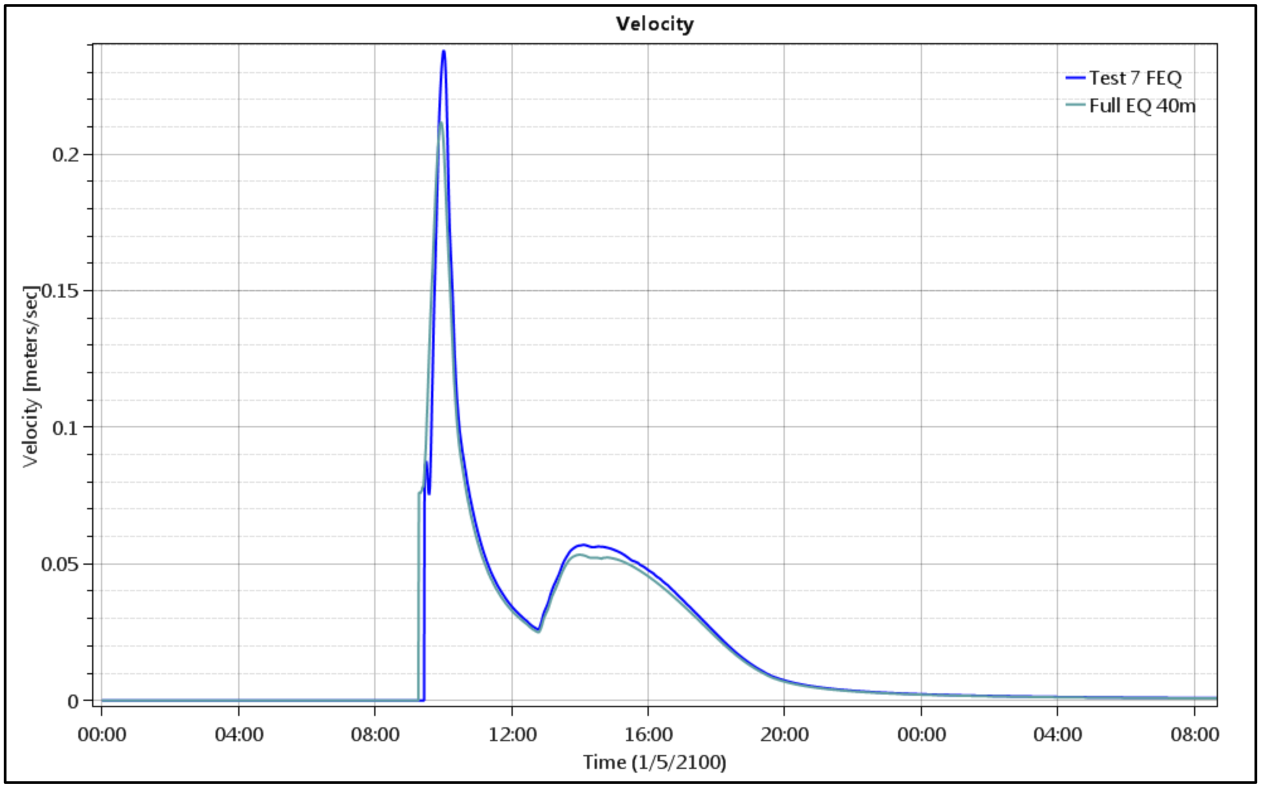


Figure 152. Floodplain 2 - Test Point 8 - Velocity.

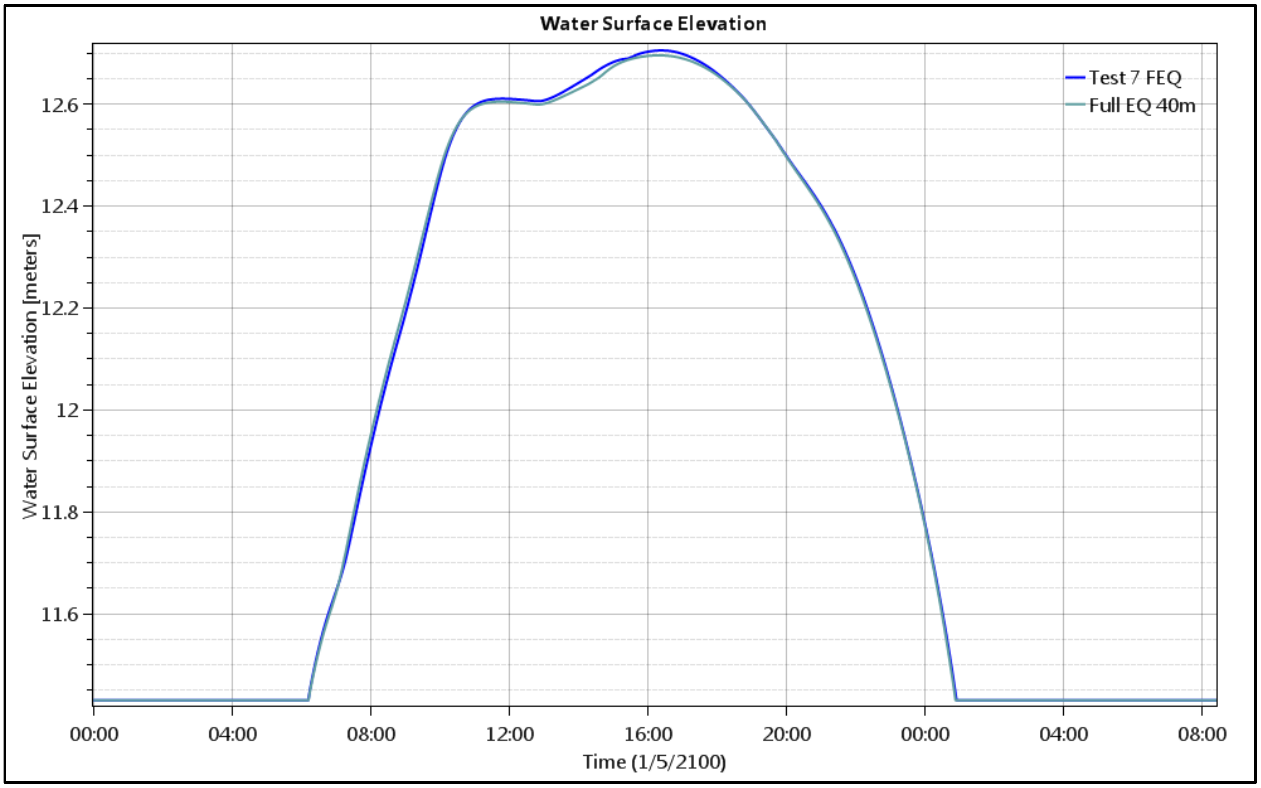


Figure 153. Floodplain 3 - Test Point 10 - Water Level.

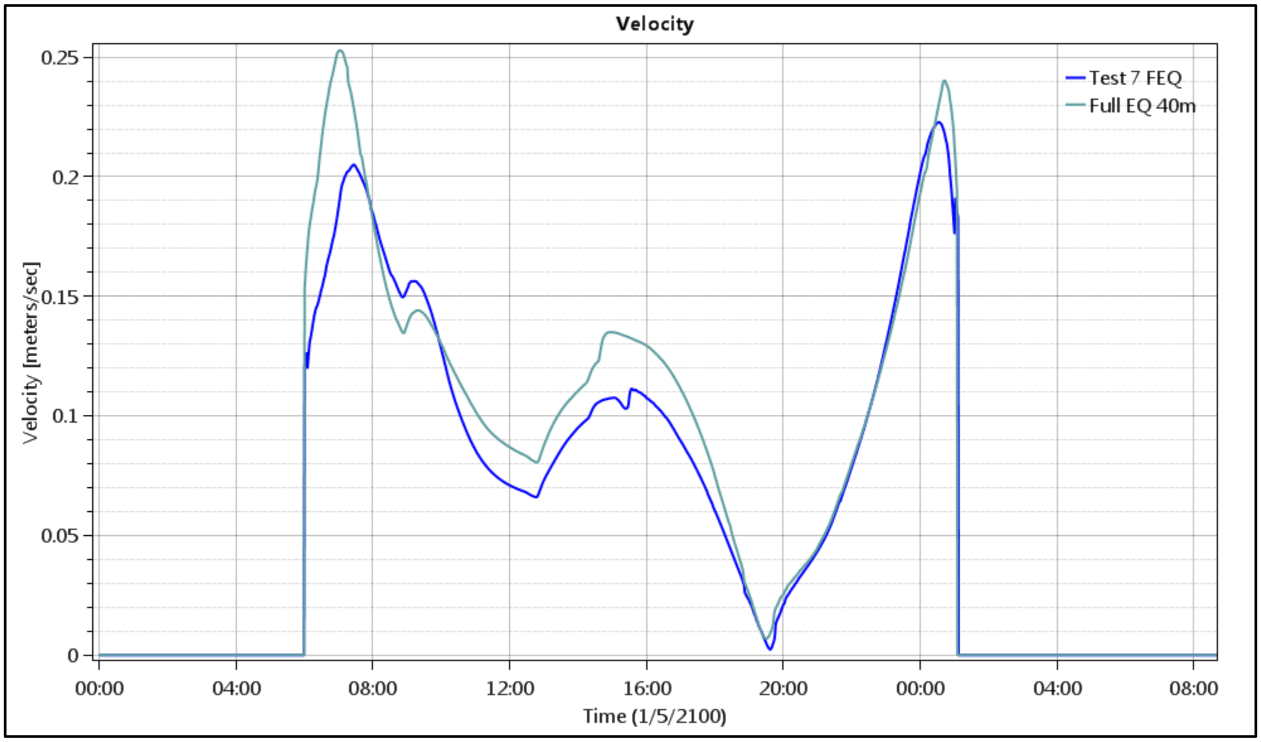


Figure 154. Floodplain 3 - Test Point 10 - Velocity.

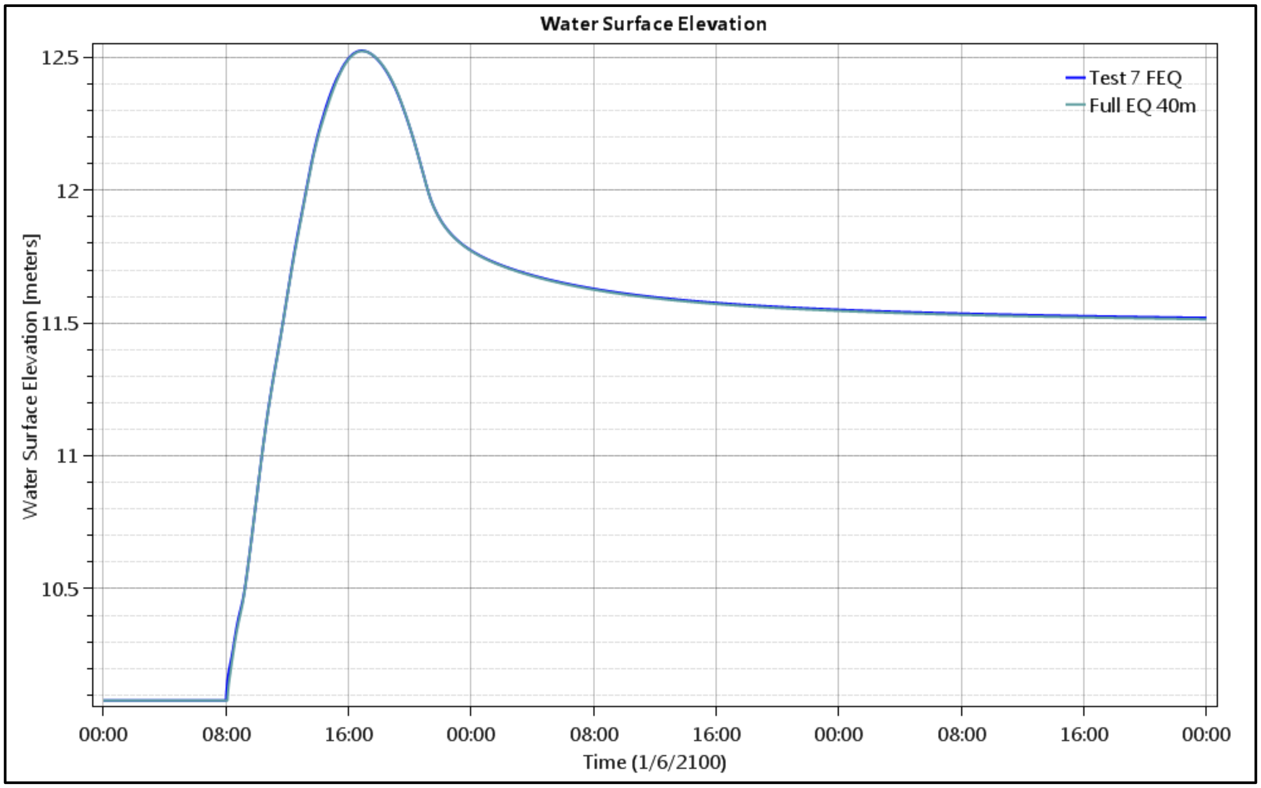


Figure 155. Floodplain 3 - Test Point 15 - Water Level.

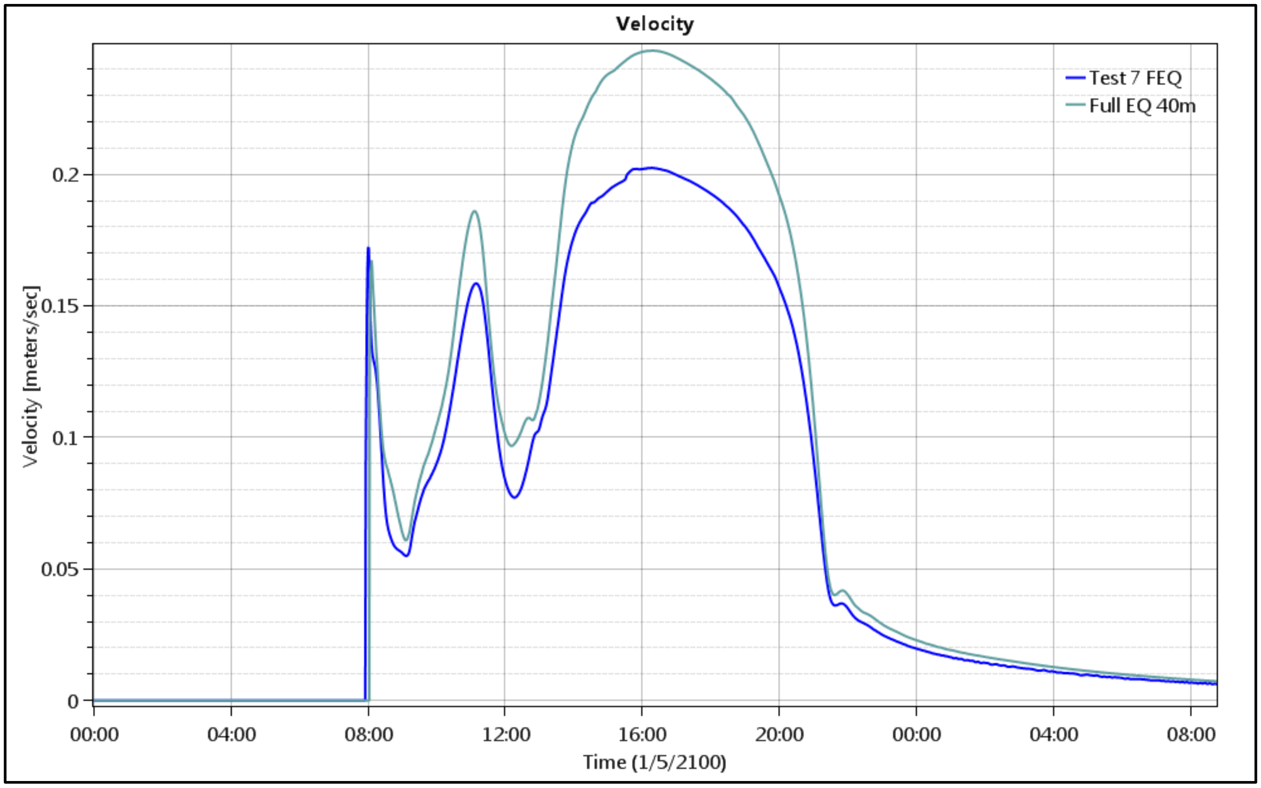


Figure 156. Floodplain 3 - Test Point 15 - Velocity.

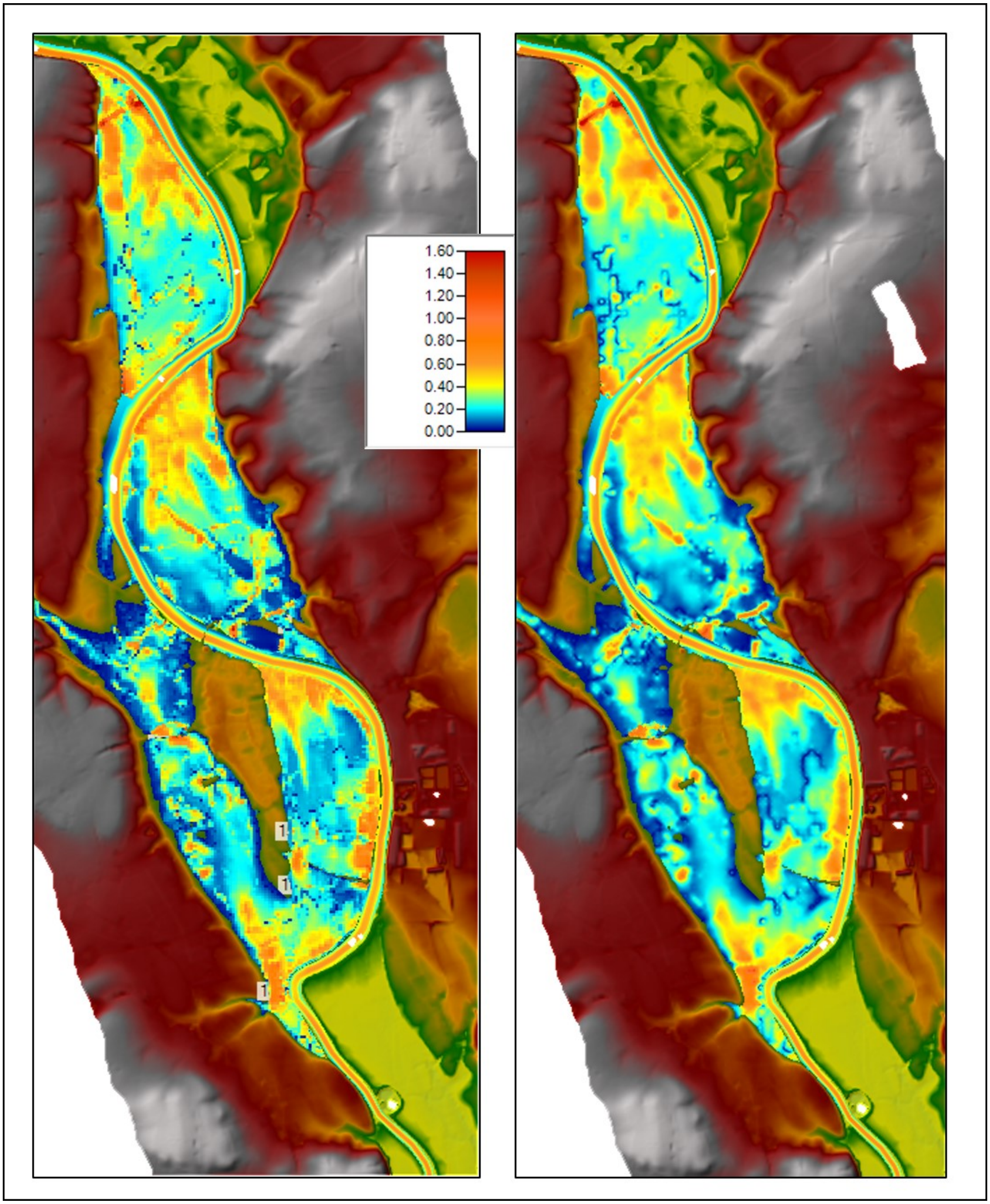


Figure 157. Spatial Plots of Maximum Velocity (meter/second), Full Equations 20 meters (left) and 40 meters (right).

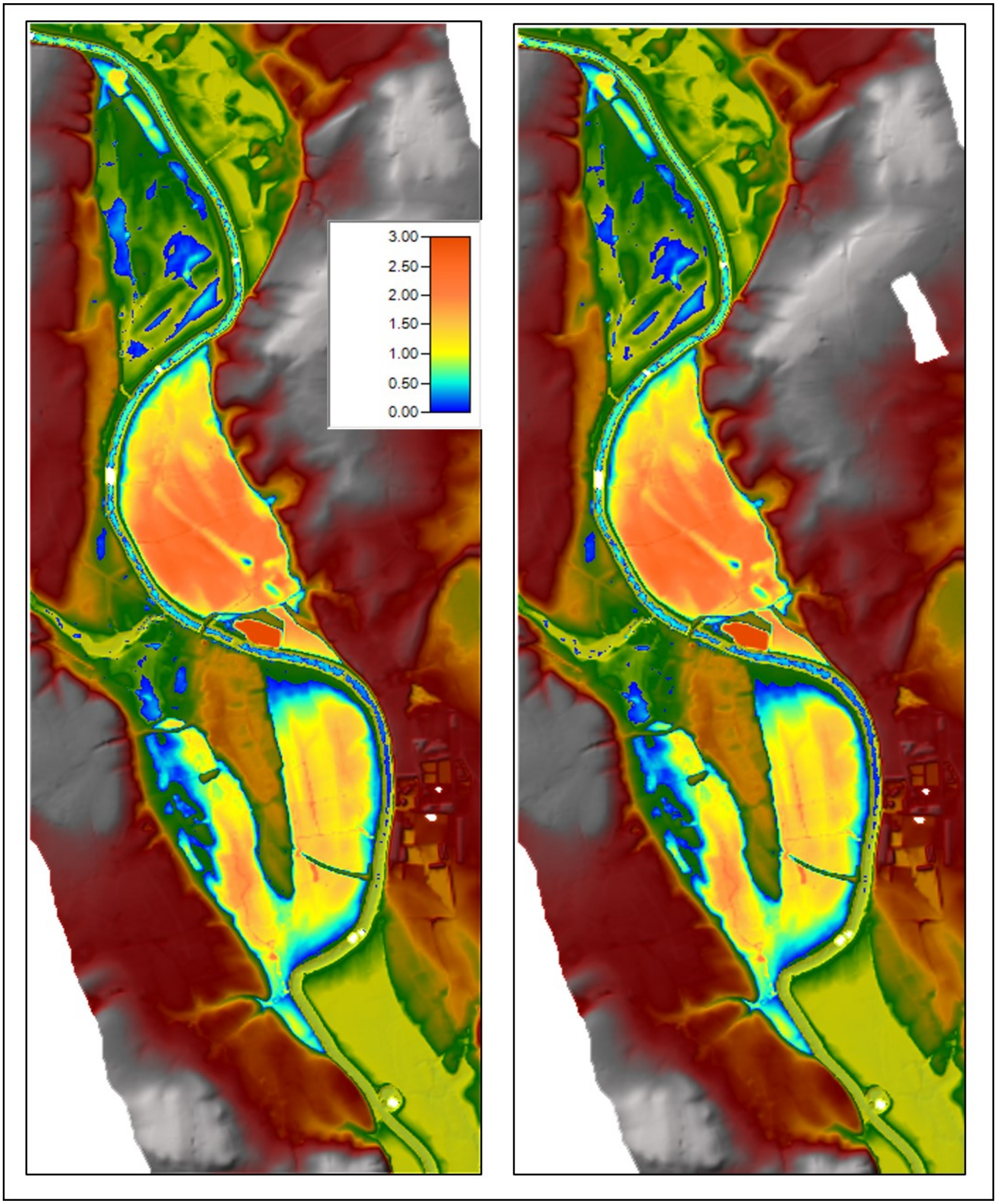


Figure 158. Spatial Plots of Final Depth (meter), Full Equations 20 meters (left) and 40 meters (right).

Chapter 9
Benchmark Test 8A
Rainfall and Point Source Surface Flow

9.1 Objective

Benchmark Test 8A tests a two-dimensional model's capability to simulate shallow flow over an urban area from rainfall and a point source inflow.

9.2 Description

Benchmark Test 8A is designed to test 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. The modelled area is approximately 0.4 km by 0.96 km and covers entirely the DEM provided and is shown in Figure 159. Ground elevations span a range of ~21m to ~37m. The flood is assumed to arise from two sources:

- a uniformly distributed rainfall event illustrated by the hyetograph in Figure 160. This is applied to the modelled area only (the rest of the catchment is ignored).

- a point source at the location represented in Figure 159, and illustrated by the inflow time series in Figure 161.

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

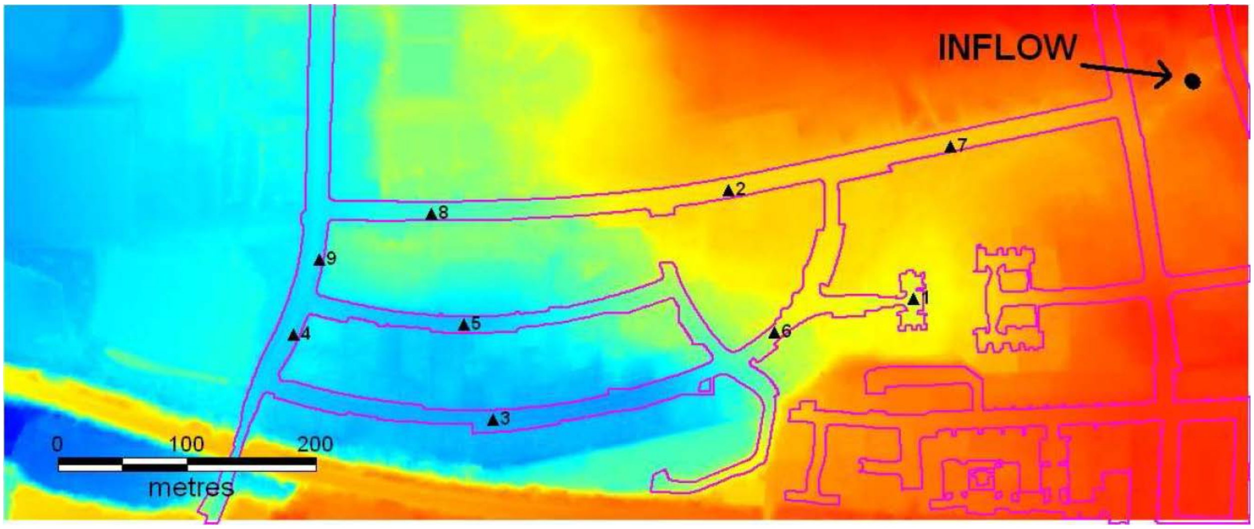


Figure 159. DEM for Test 8A.

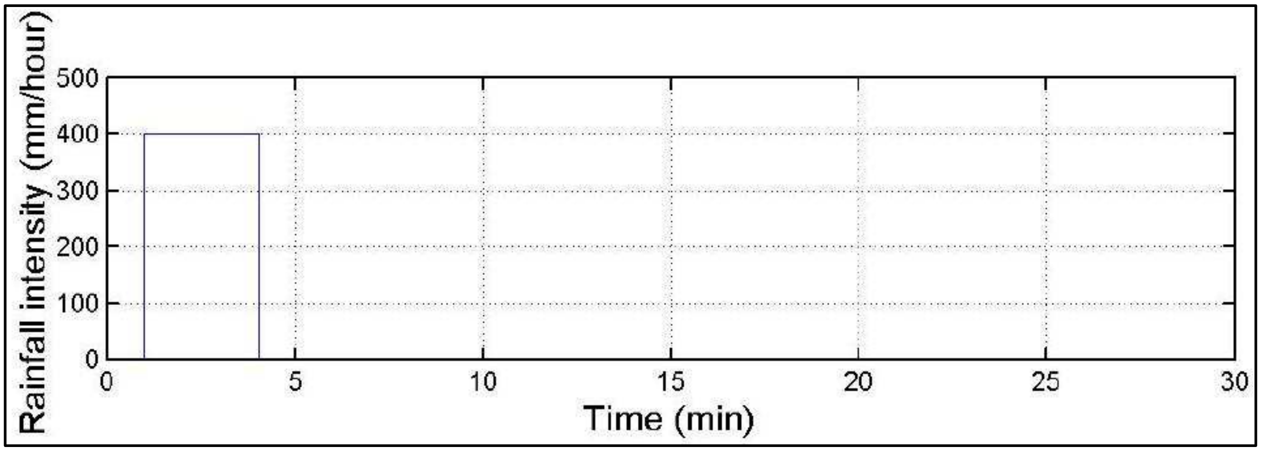


Figure 160. Rainfall Hyetograph Applied to Test 8A Area.

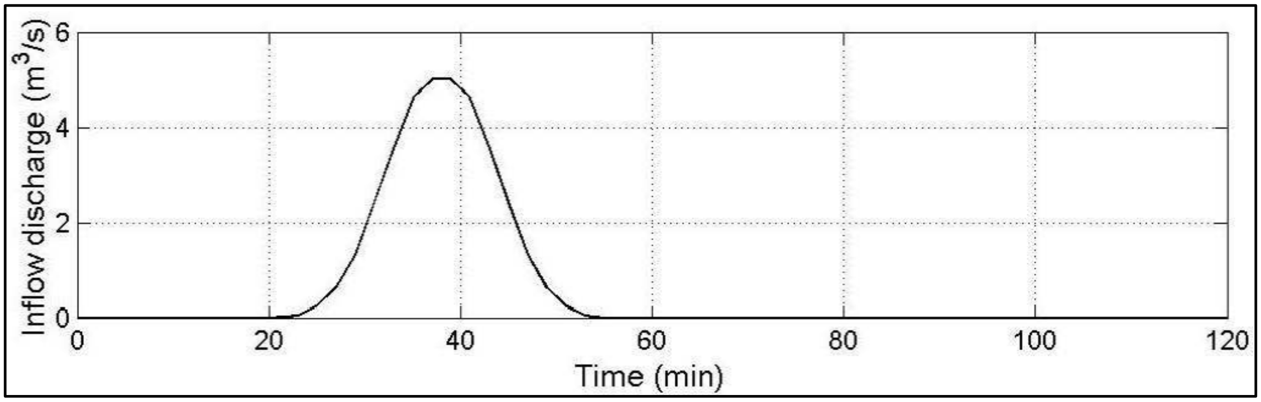


Figure 161. Inflow Hydrograph Applied in Test 8A at Point Location.

9.3 Boundary and Initial Conditions

- Rainfall as described above in Figure 160.
- Point source inflow hydrograph as shown Figure 161. Location is shown in Figure 159.
- All boundaries of the modeled area are closed.
- Initial condition: Dry bed.

9.4 Parameter Values

- Manning's n: 0.02 for roads and pavement, 0.05 everywhere else.
- Model grid resolution: 2 meters (or approximately 97,000 nodes)
- Time of end: the model is to be run until time t = 5 hours (if an alternative end time is used run times must be reported for t=5 hours)

9.5 Results

Results for water surface elevations and velocities are shown for evaluation points 1-6 in Figure 159. HEC-RAS performed extremely well compared to the leading 2D models that were used in the original Benchmarking Study, such as TUFLOW, MIKE FLOOD, ISIS 2D, and SOBEK. Results for both the full equations runs and the diffusion wave runs were very good compared to the other leading models used in this study.

Note: Benchmark Test 8A was run with both the Full Saint Venant equations (Full EQ) and the Diffusion Wave equations (Diff Wave). Results for both equation sets are shown in Figures 162 - 167.

Note: Benchmark Test 8A was also used to demonstration sensitivity to the grid resolution. Results are shown for Test Points 1-6, for two different grid resolutions, 2m and 4m (Figures 168 – 173). Both grid resolution tests were performed with the Full Saint Venant equations. The grid resolution tests show that because of the use of the subgrid bathymetry, HEC-RAS can get almost the same results as the originally stated problem (2 meter grid) with a grid resolution twice as large (4 meter grid). Run times with the larger grid cell size are dramatically lower than with the smaller grid cell size. The HEC-RAS subgrid bathymetry capability provides a major advantage over other software that does not support using the detailed terrain within the cell and for the cell face properties.

Table 10. Benchmark Test 8A Specific Summary Information.

Version Number and Numerical Scheme	Version 5.0.4 Two-dimensional Implicit Finite Volume solution of the shallow water equations including: gravity, friction, pressure forces, inertial forces. Options for eddy viscosity and Coriolis effects were not included.
Specification of hardware used to undertake the simulation	Precision T5610 Intel Xeon E5-2687W processor 3.0 GHz to 3.4 GHz Turbo mode 8.0 CPU cores
Minimum recommended hardware specification	Refer to hardware details in Chapter 1
Time increment used	Variable: Full Eqs. (0.5 to 1s), Diff Wave (1 to 4s)
Grid resolution (or number of cells)	2 meters; 95,719 cells 4 meters x 4 meters; 23,760 cells
Total computational time	Full EQ: 59 min 36s Diff Wave: 27 min 51s 4 meter grid Full EQ: 6 min 18s 4 meter grid Diff Wave: 3 min 18s

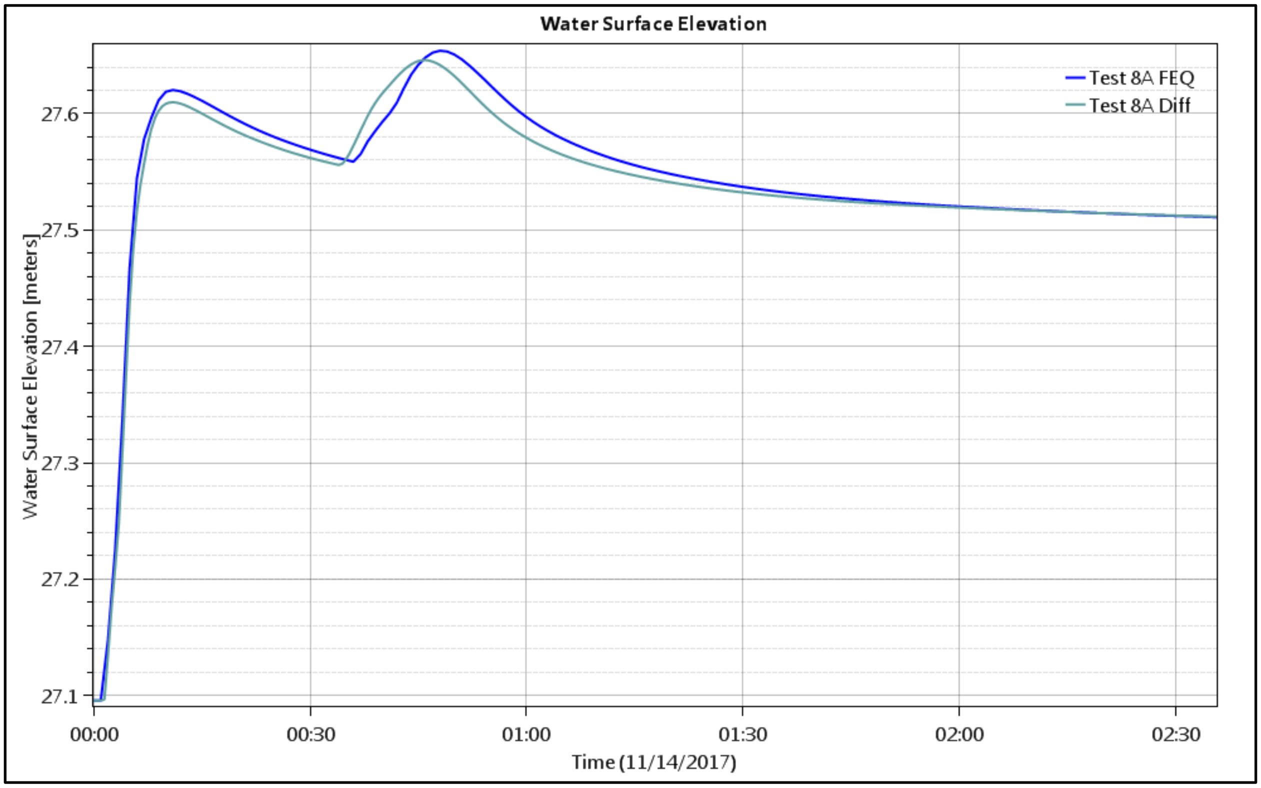


Figure 162. Test Point 1 - Water Level (depth) for Full Equations and Diffusion Wave.

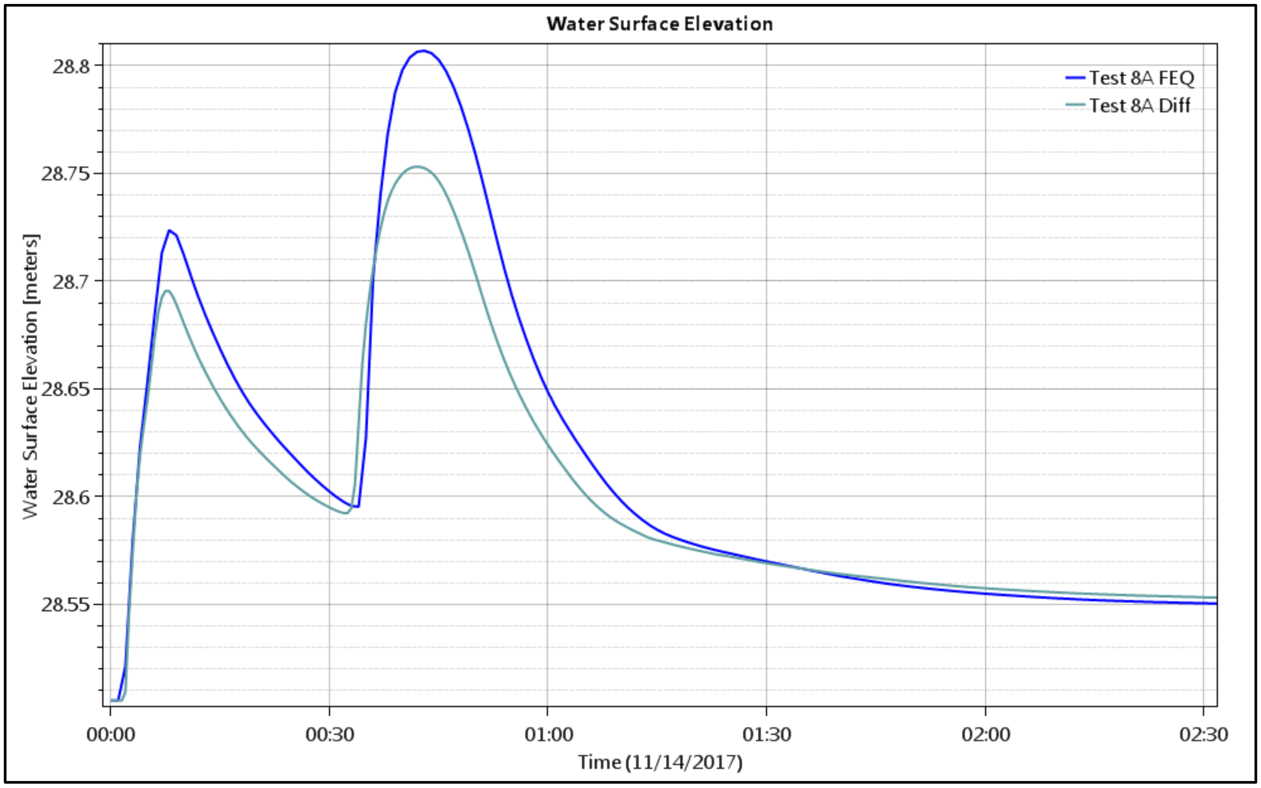


Figure 163. Test Point 2 - Water Level (depth) for Full Equations and Diffusion Wave.

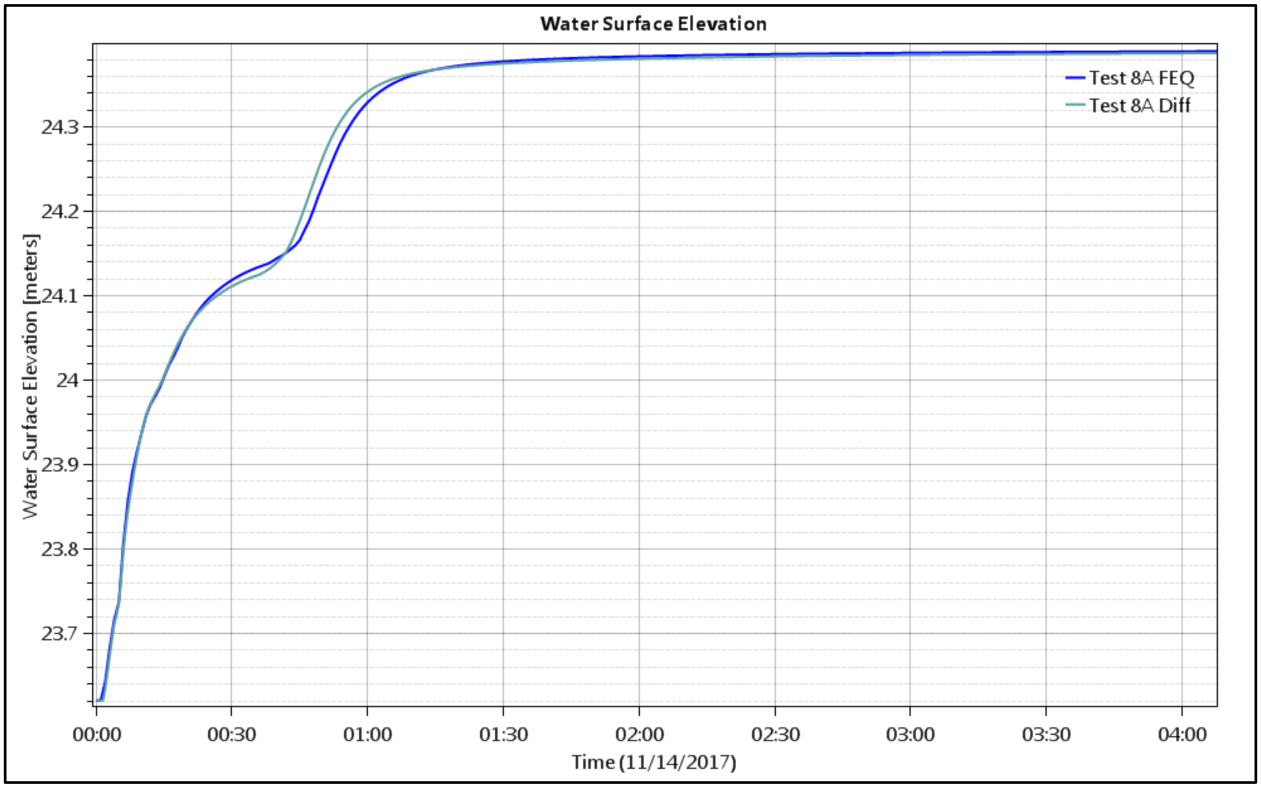


Figure 164. Test Point 3 - Water Level (depth) for Full Equations and Diffusion Wave.

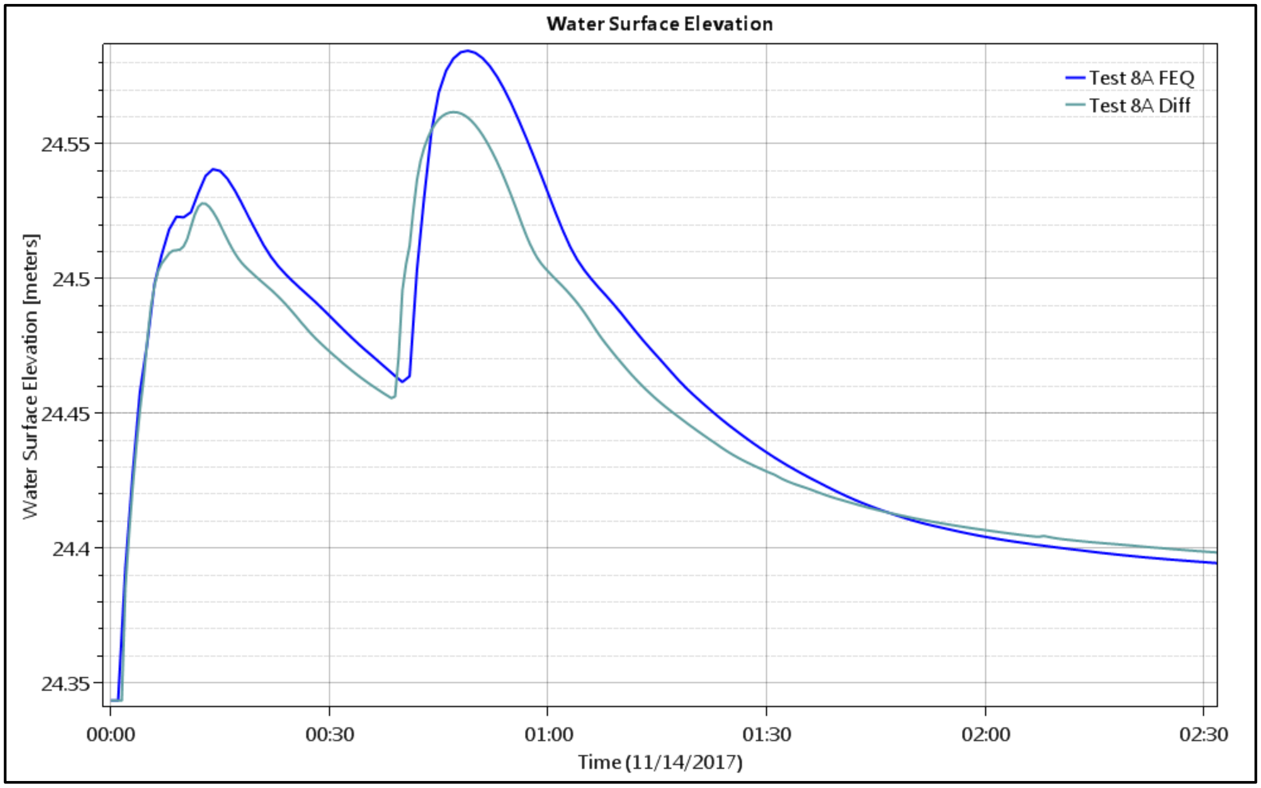


Figure 165. Test Point 4 - Water Level (depth) for Full Equations and Diffusion Wave.

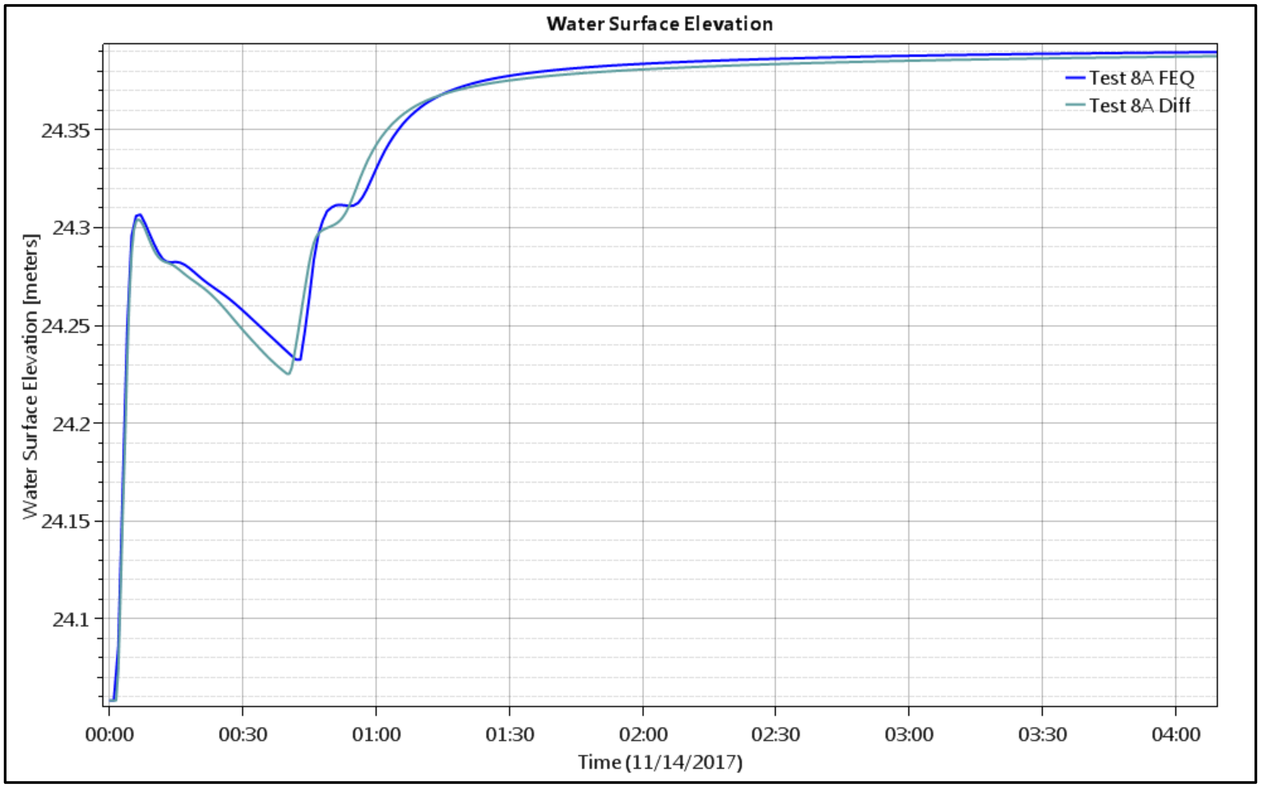


Figure 166. Test Point 5 - Water Level (depth) for Full Equations and Diffusion Wave.

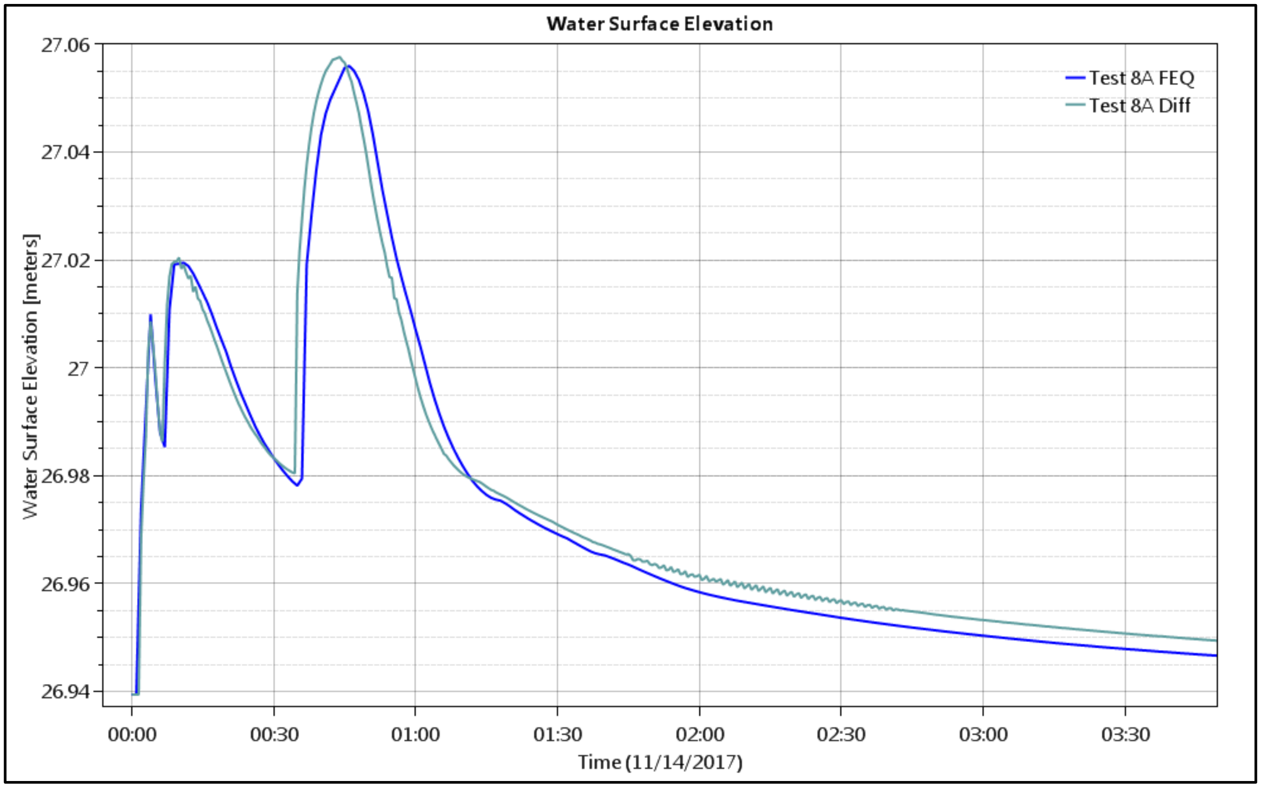


Figure 167. Test Point 6 - Water Level (depth) for Full Equations and Diffusion Wave.

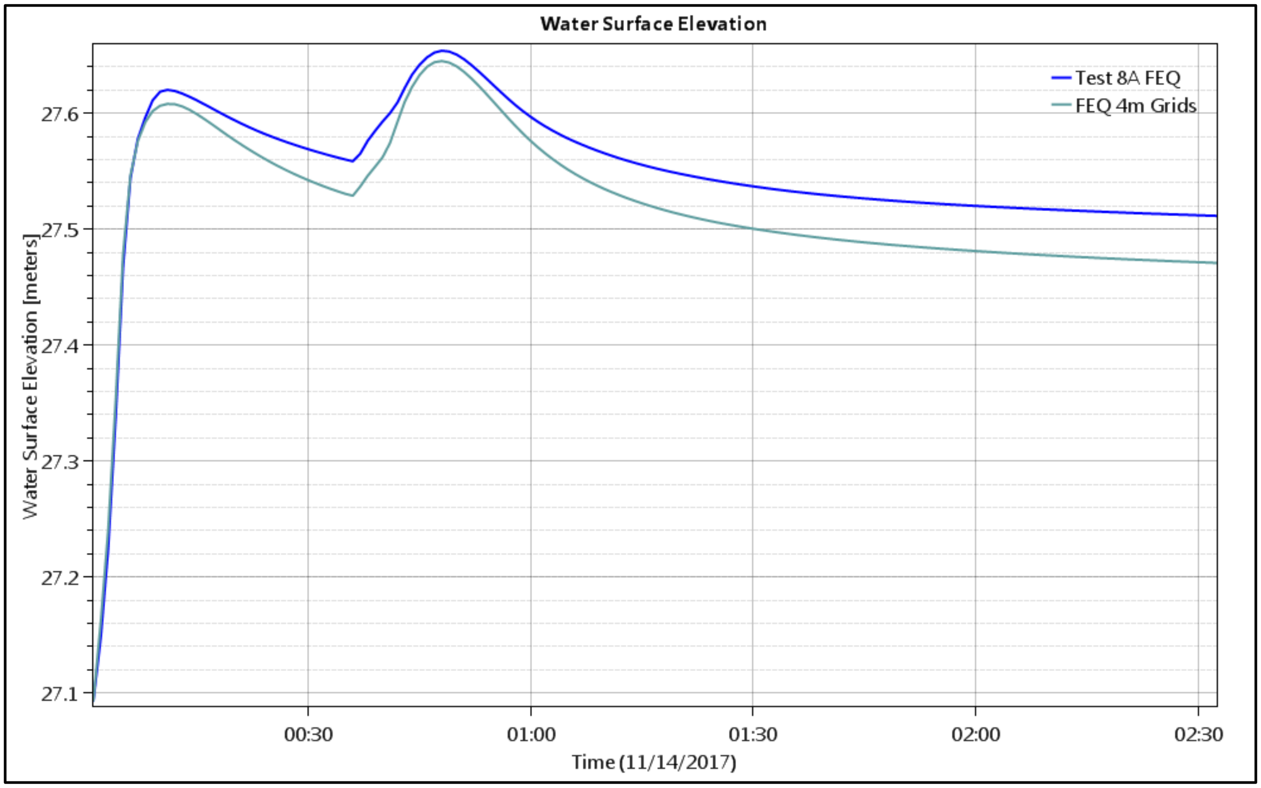


Figure 168. Test Point 1 - Water Level (depth) for Full Equations with 2m and 4m Grids.

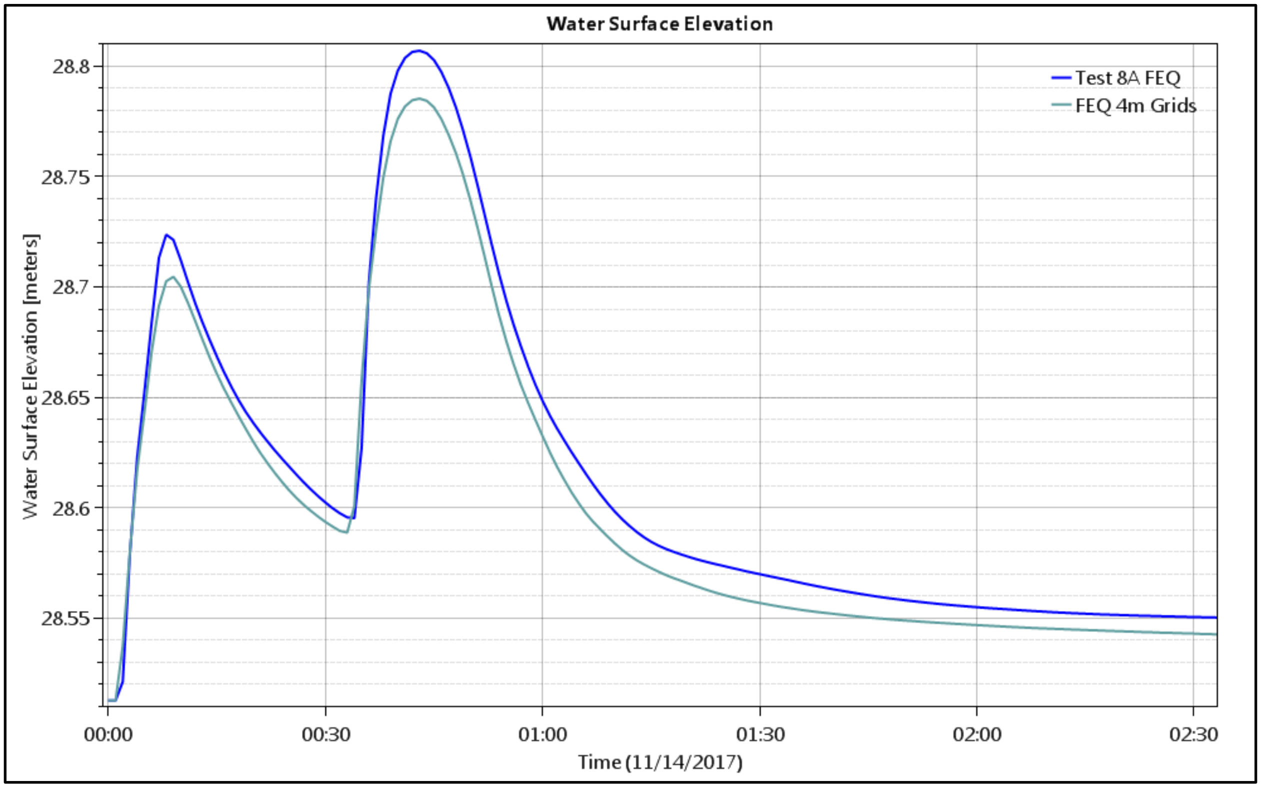


Figure 169. Test Point 2 - Water Level (depth) for Full Equations with 2m and 4m Grids.

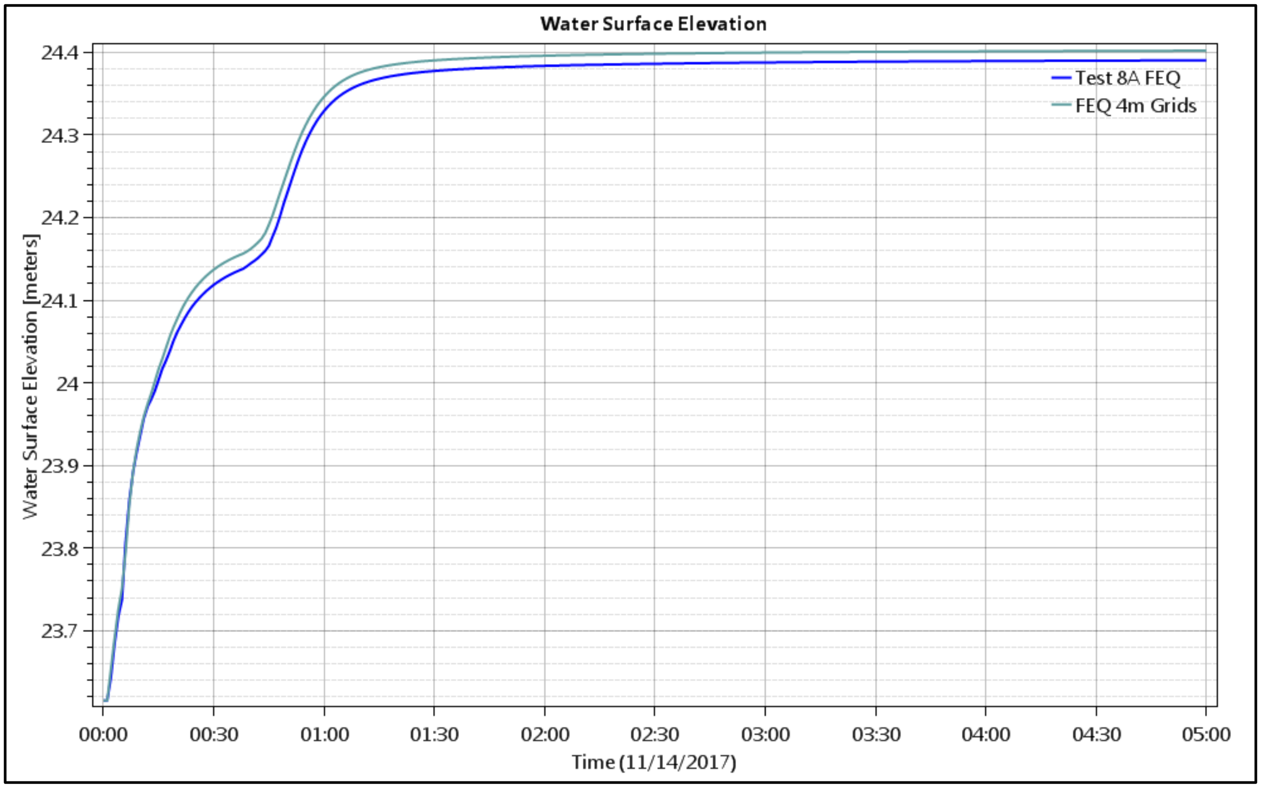


Figure 170. Test Point 3 - Water Level (depth) for Full Equations with 2m and 4m Grids.

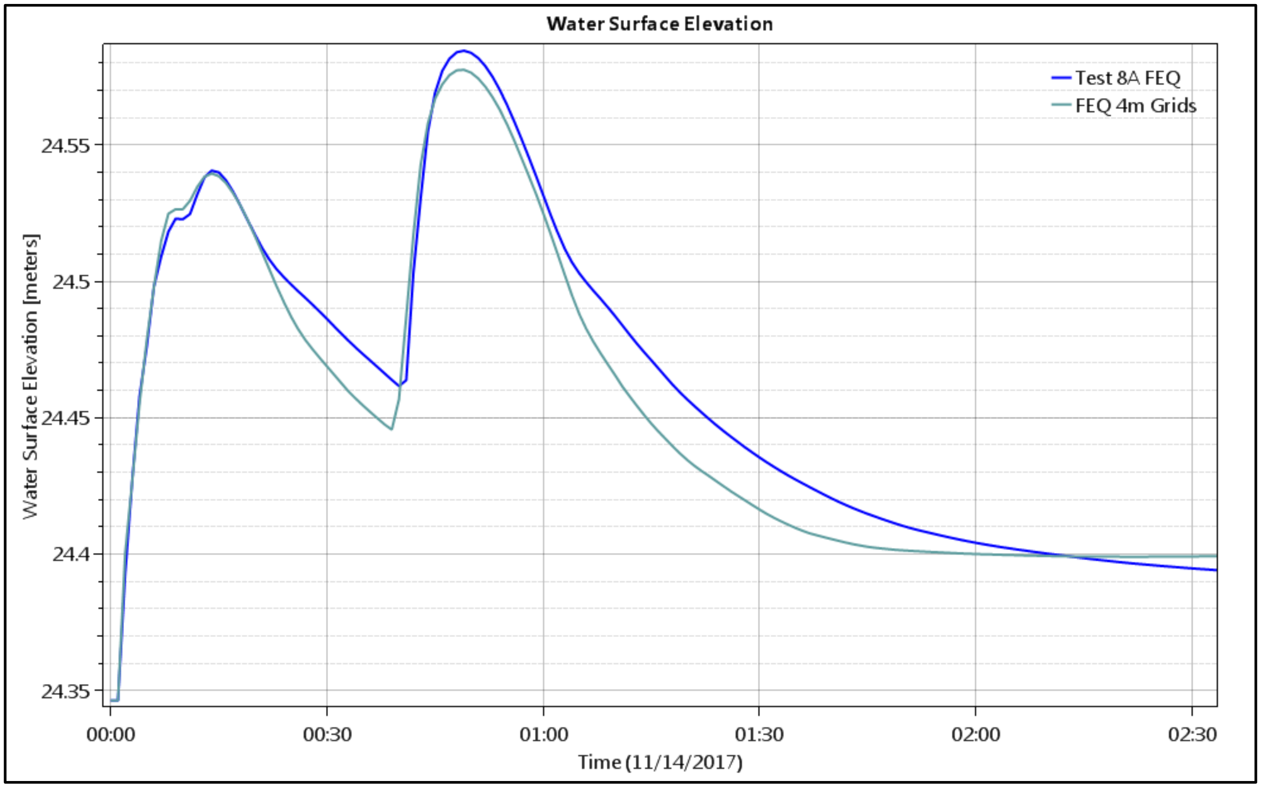


Figure 171. Test Point 4 - Water Level (depth) for Full Equations with 2m and 4m Grids.

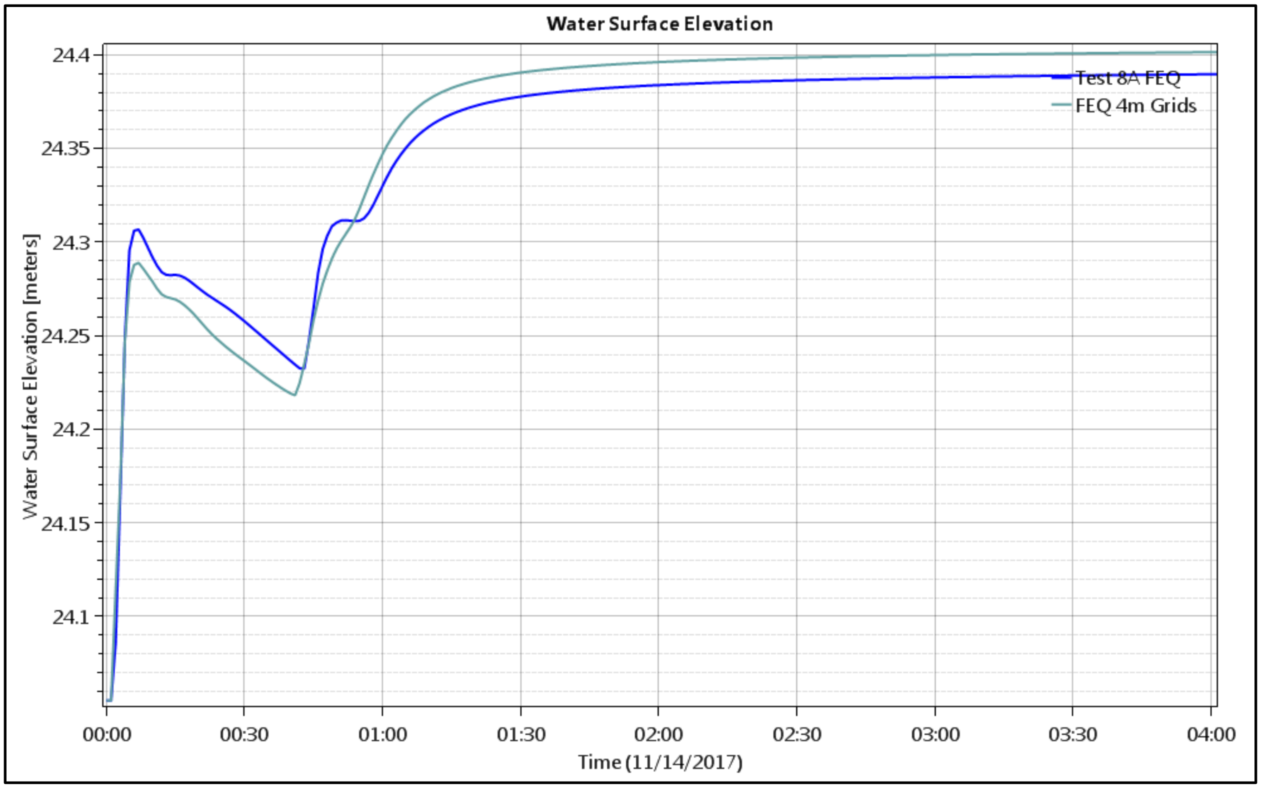


Figure 172. Test Point 5 - Water Level (depth) for Full Equations with 2m and 4m Grids.

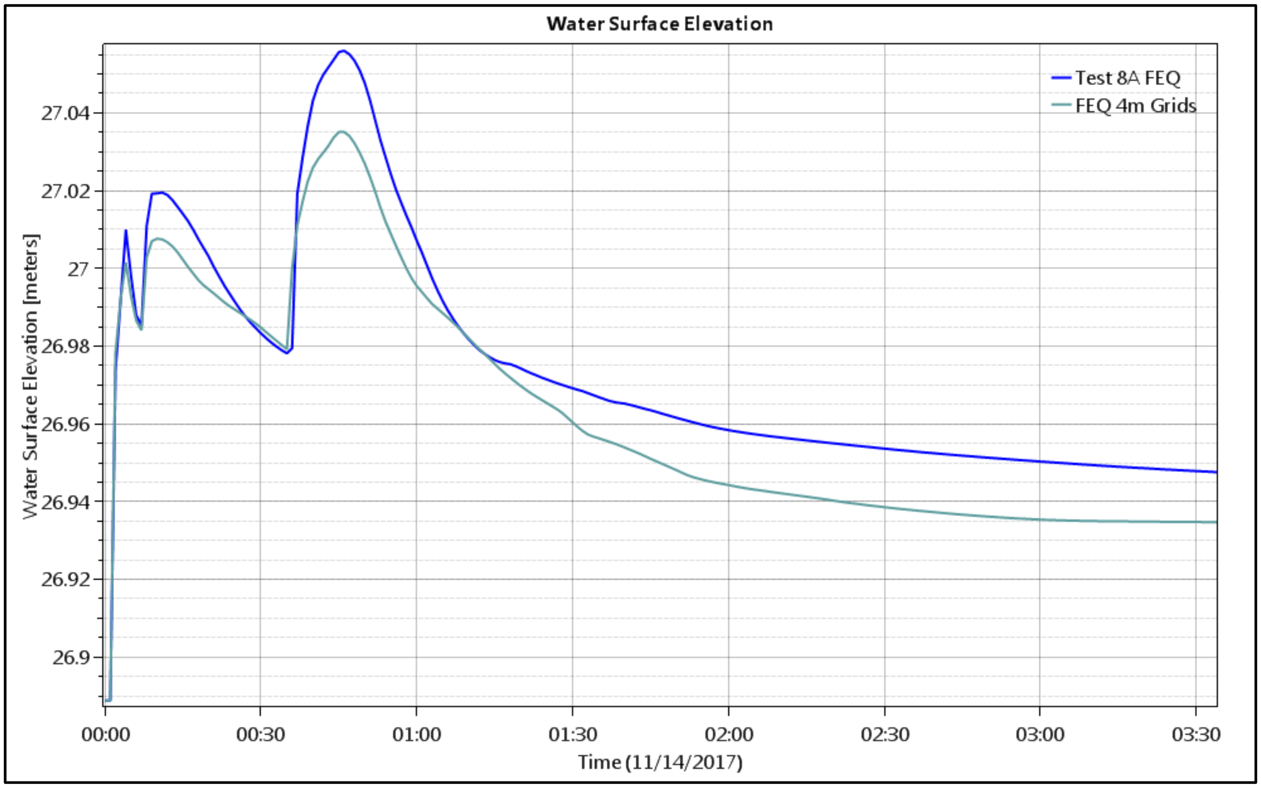


Figure 173. Test Point 6 - Water Level (depth) for Full Equations with 2m and 4m Grids.

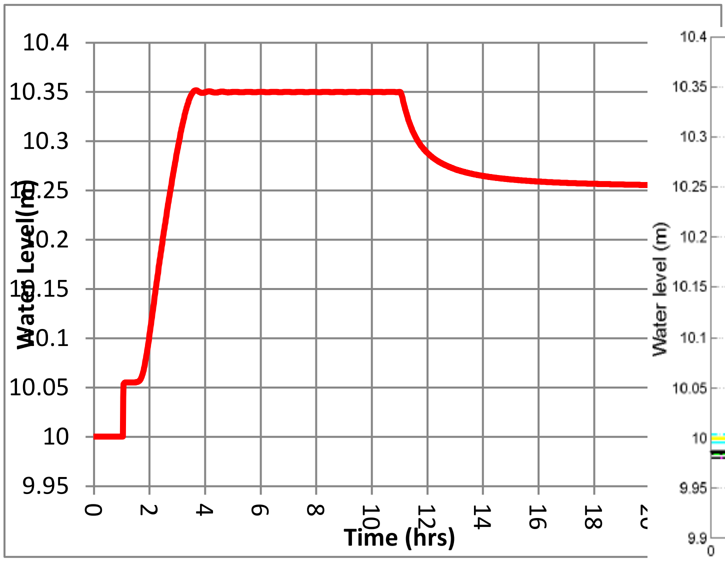
Appendix A
Comparison of HEC-RAS Results to Report Plots

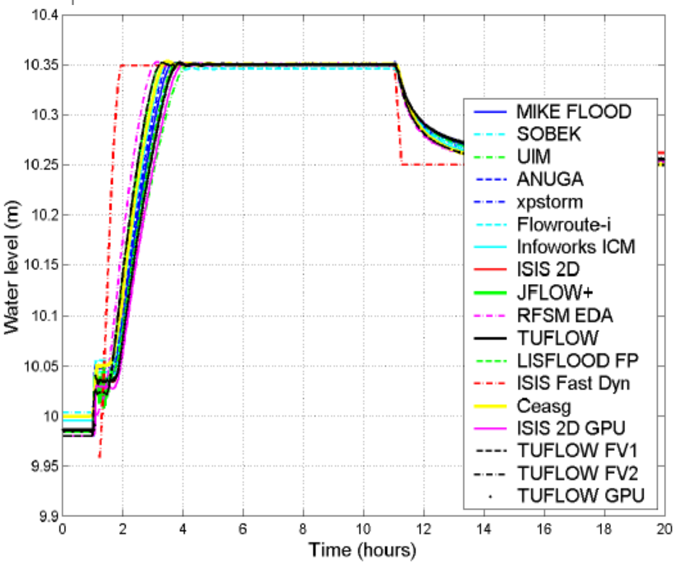
This appendix contains direct side by side comparisons of the HEC-RAS results to the results published in the report "Delivering Benefits through Evidence - Benchmarking the latest generation of 2D hydraulic modeling packages" (Report - SC120002), published in August 2013, by the United Kingdom's (UK) Joint Defra (Department for Environmental Food and Rural Affairs) Environment Agency.

Show below are the published results for each of the test that HEC-RAS was run for on the left side, and the documented results from multiple software packages documented by the study.

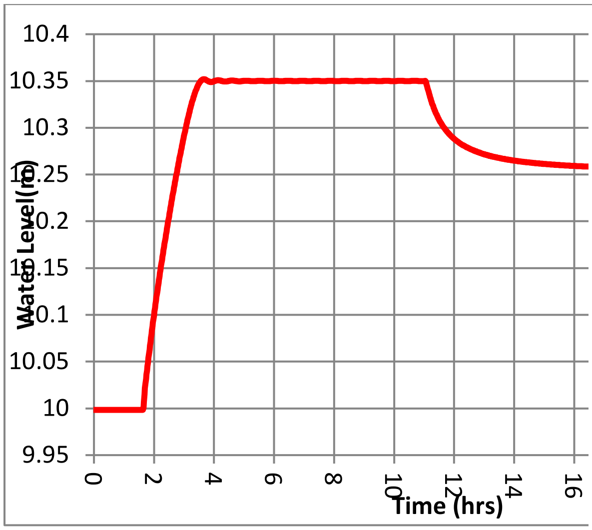
A.1 Benchmark Test 1 Results

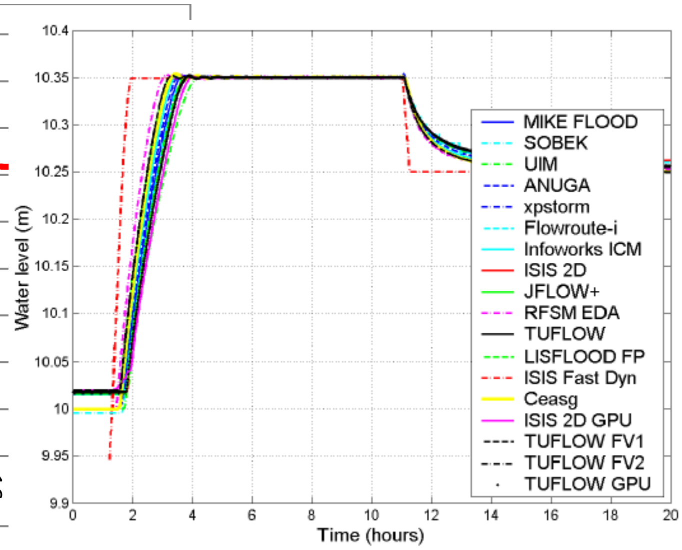
Location 1:





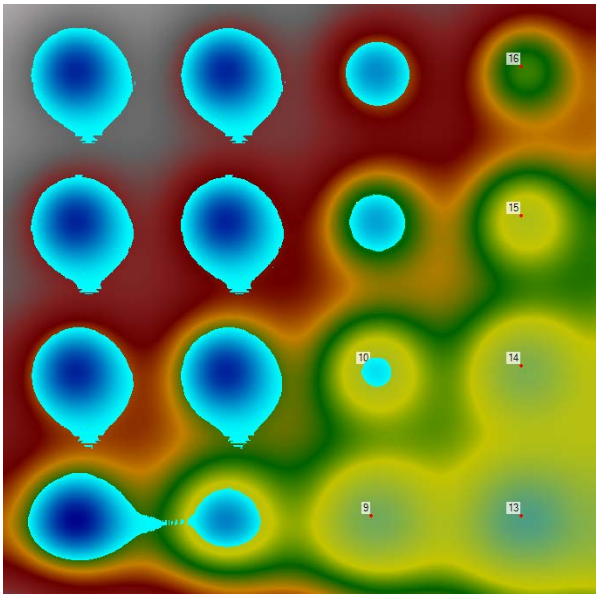
Location 2:

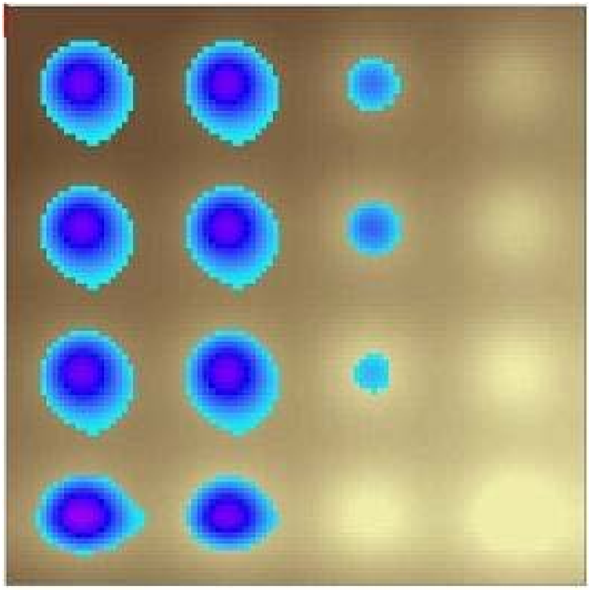




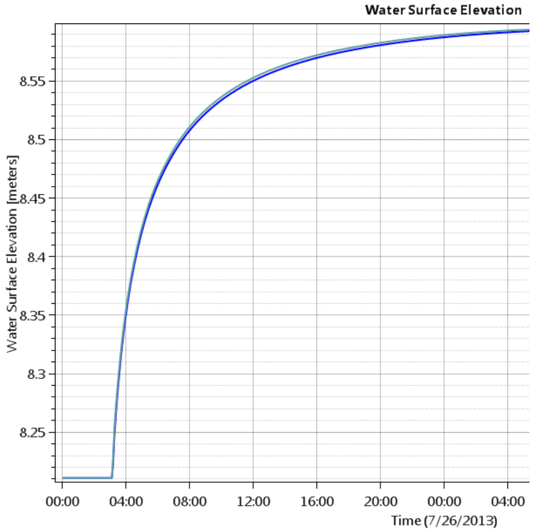
A.2 Benchmark Test 2 Results

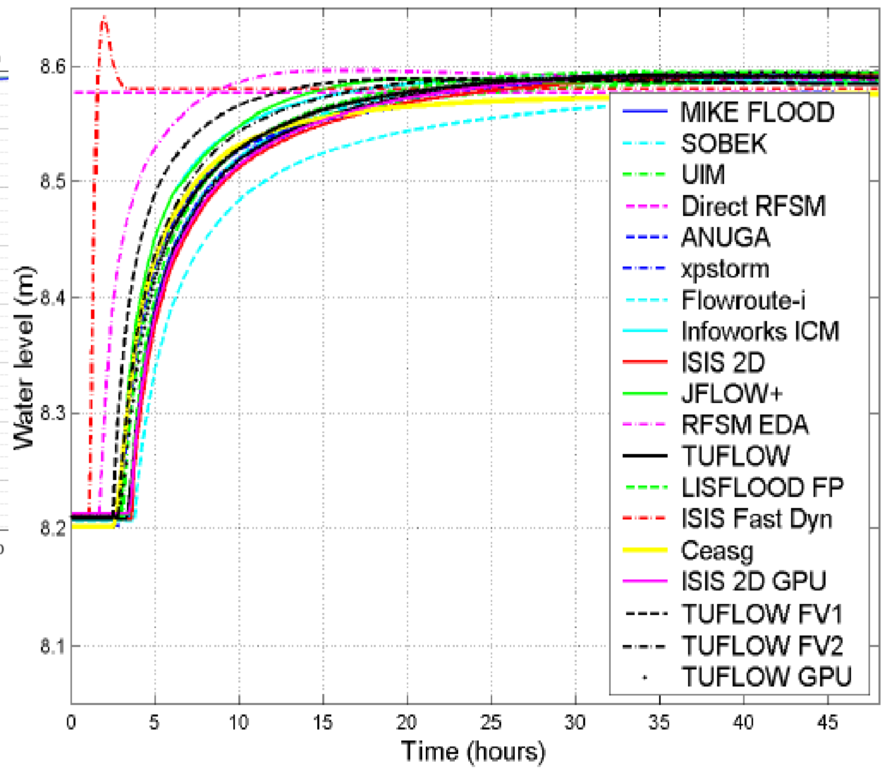
Final Water Depths:



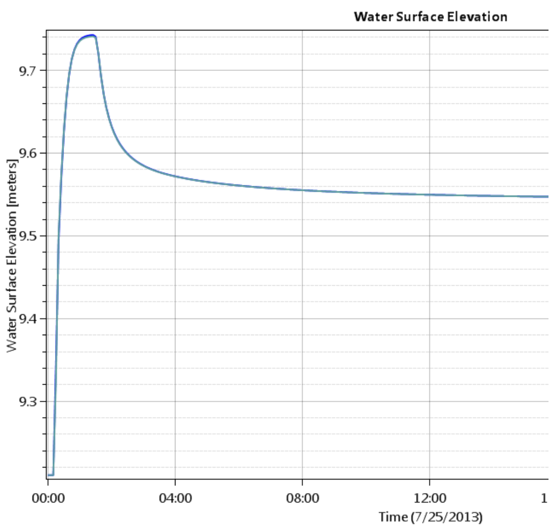


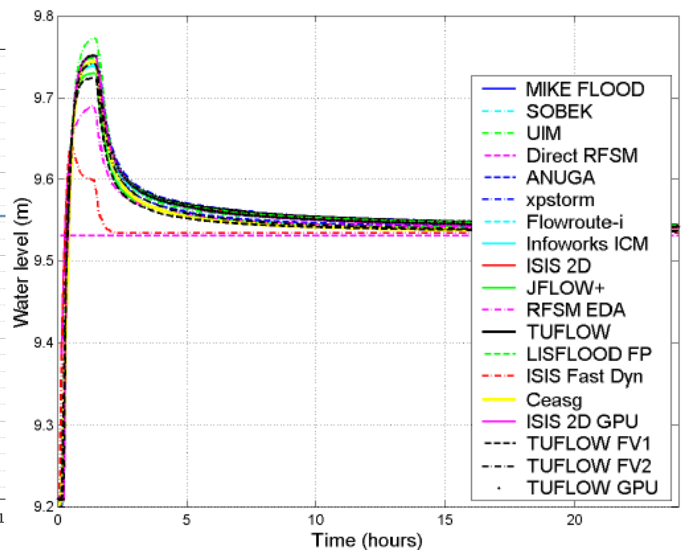
Location 1:



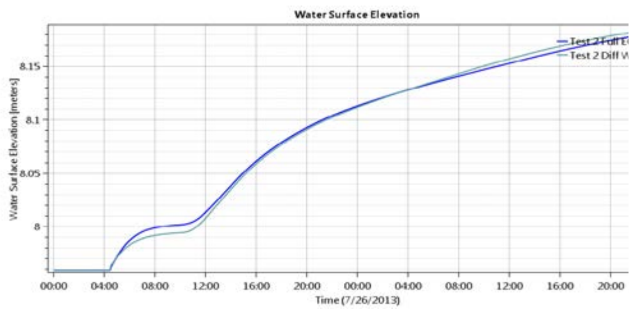


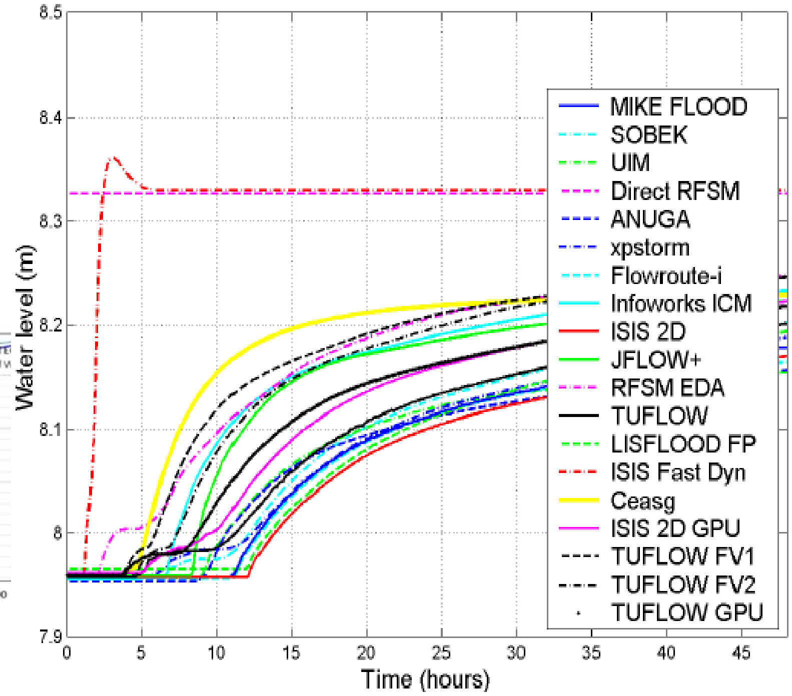
Location 4:



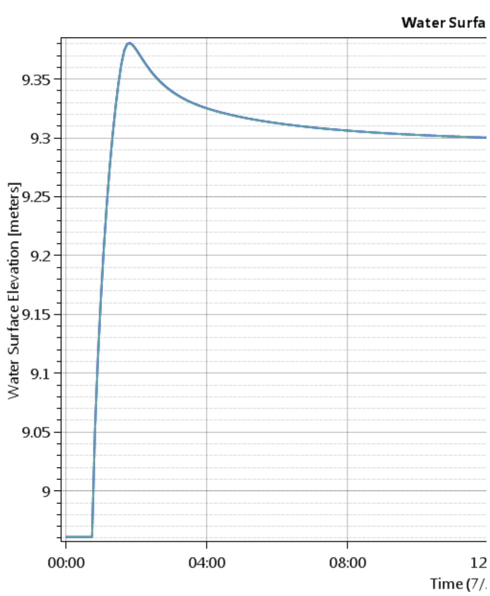


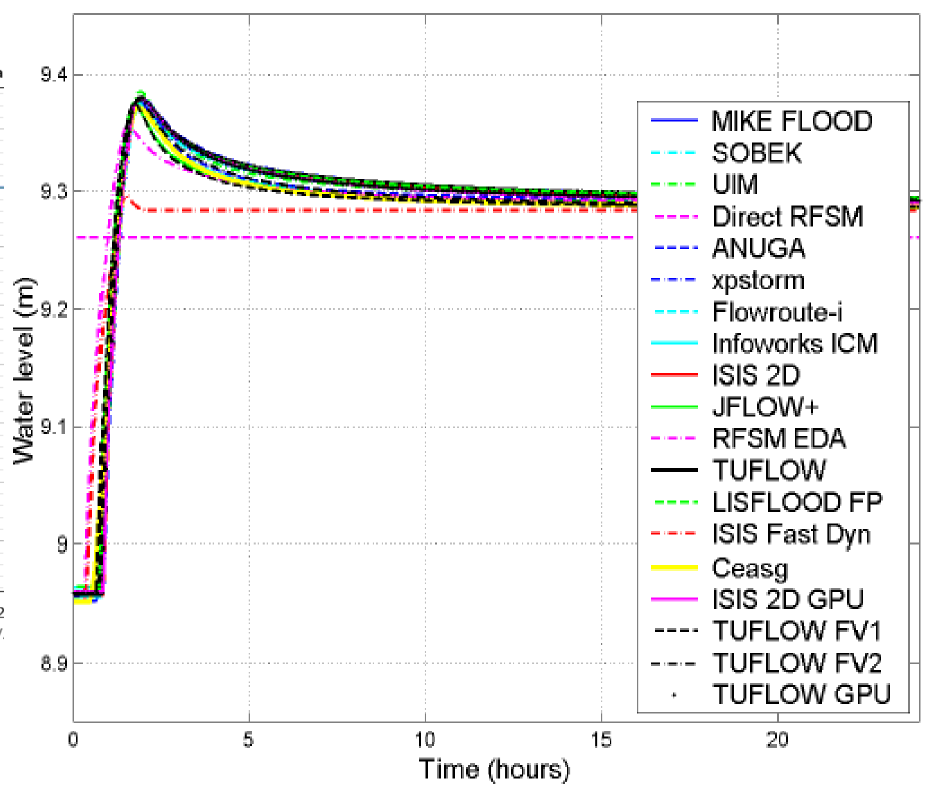
Location 5:



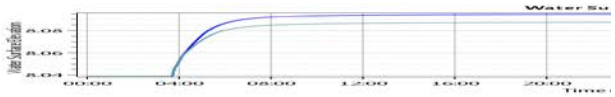


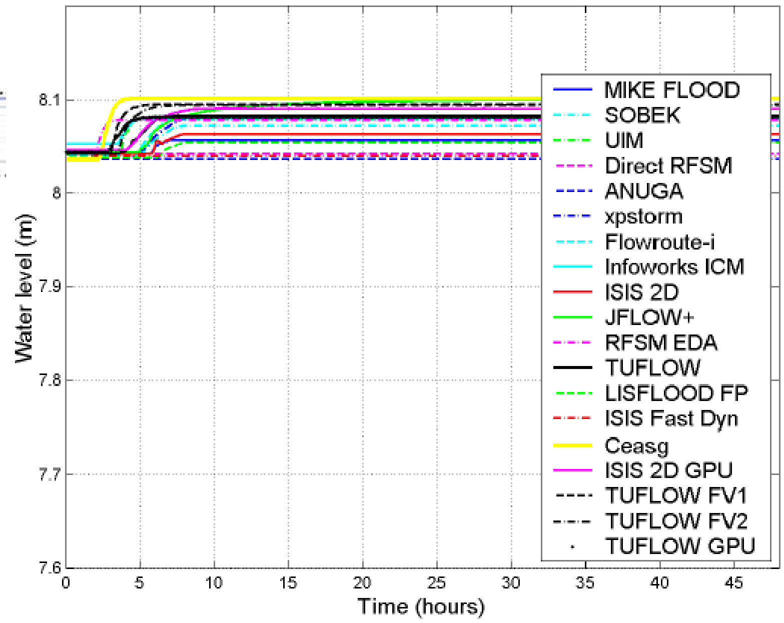
Location 8:



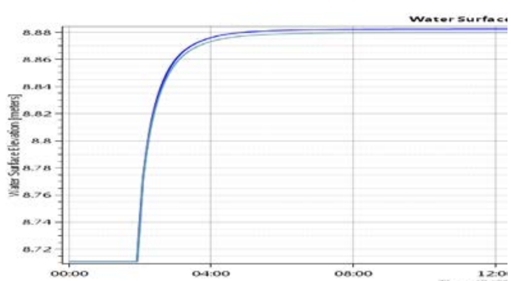


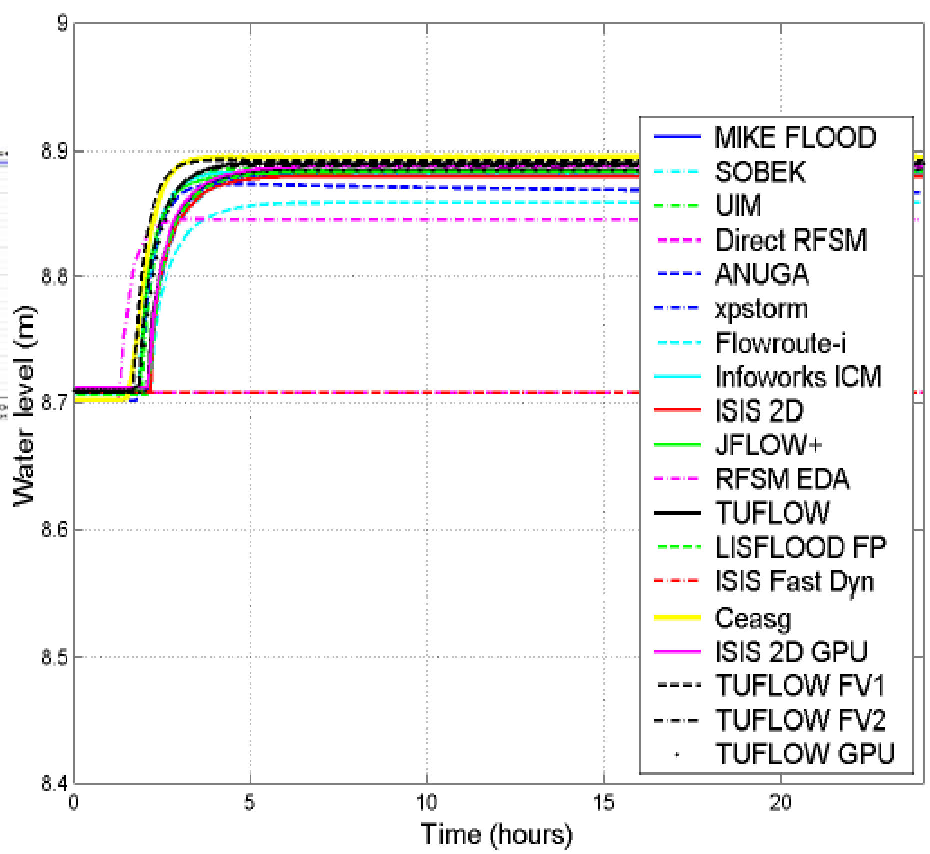
Location 10:





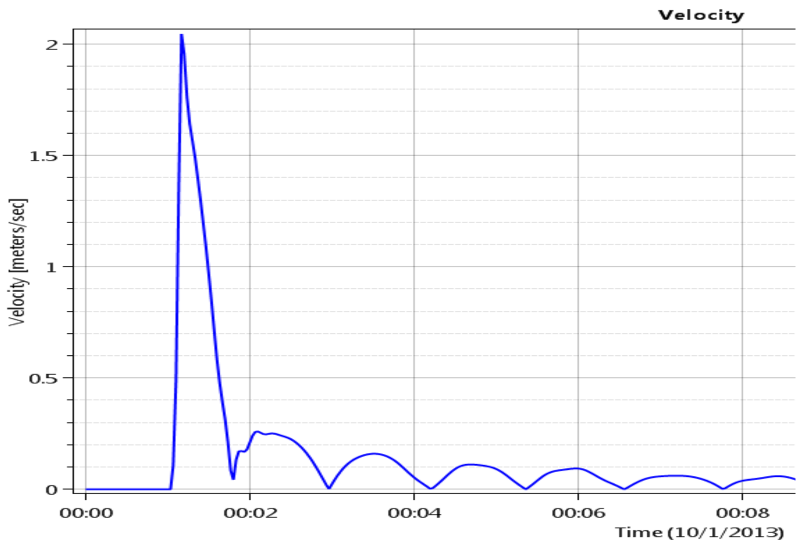
Location 12:

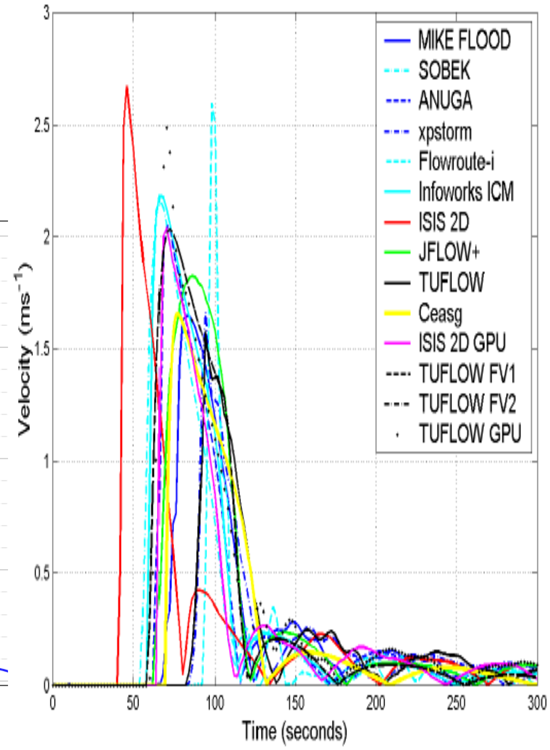




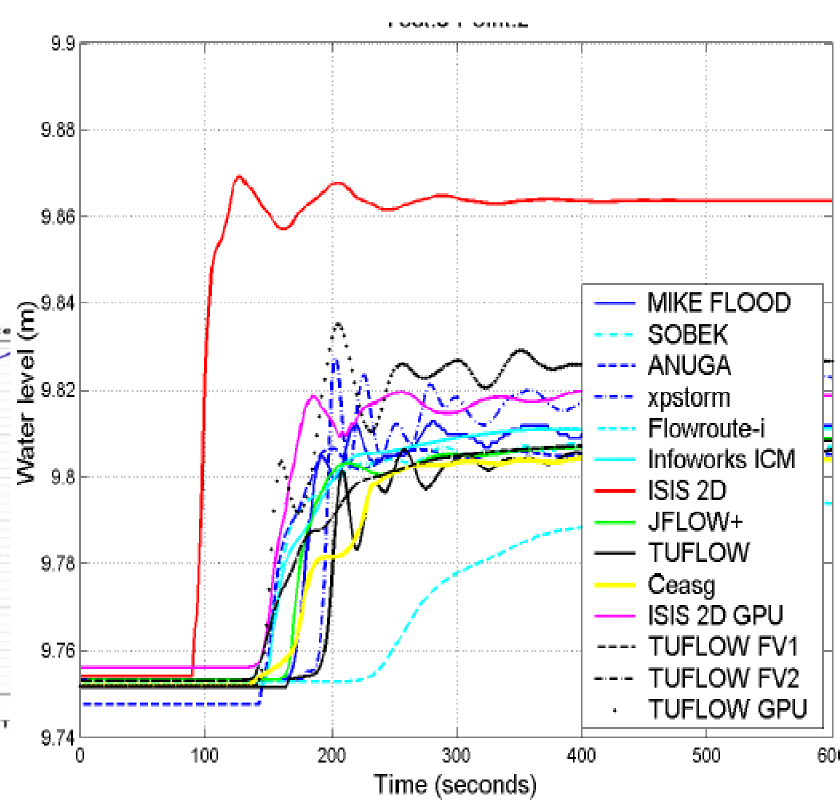
A.3 Benchmark Test 3

Location 1 Velocity:



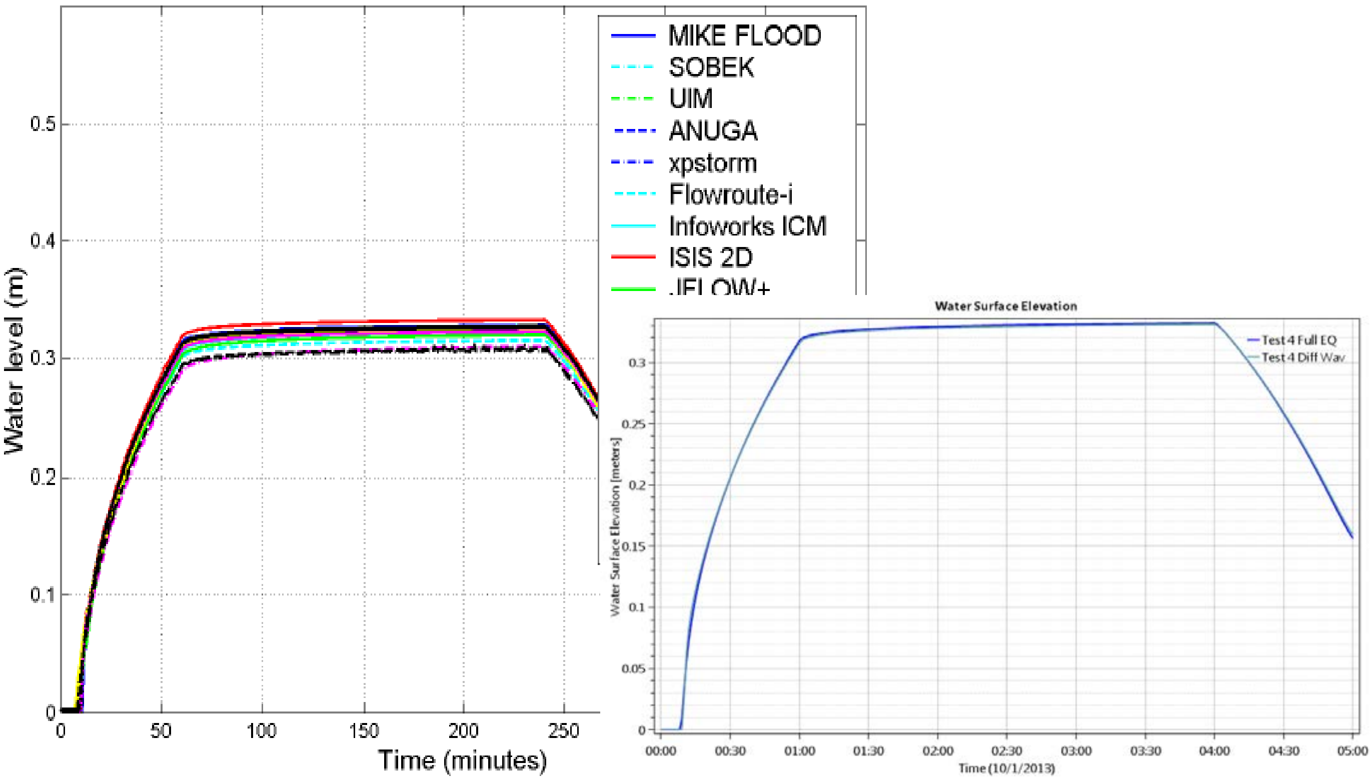


Location 2:

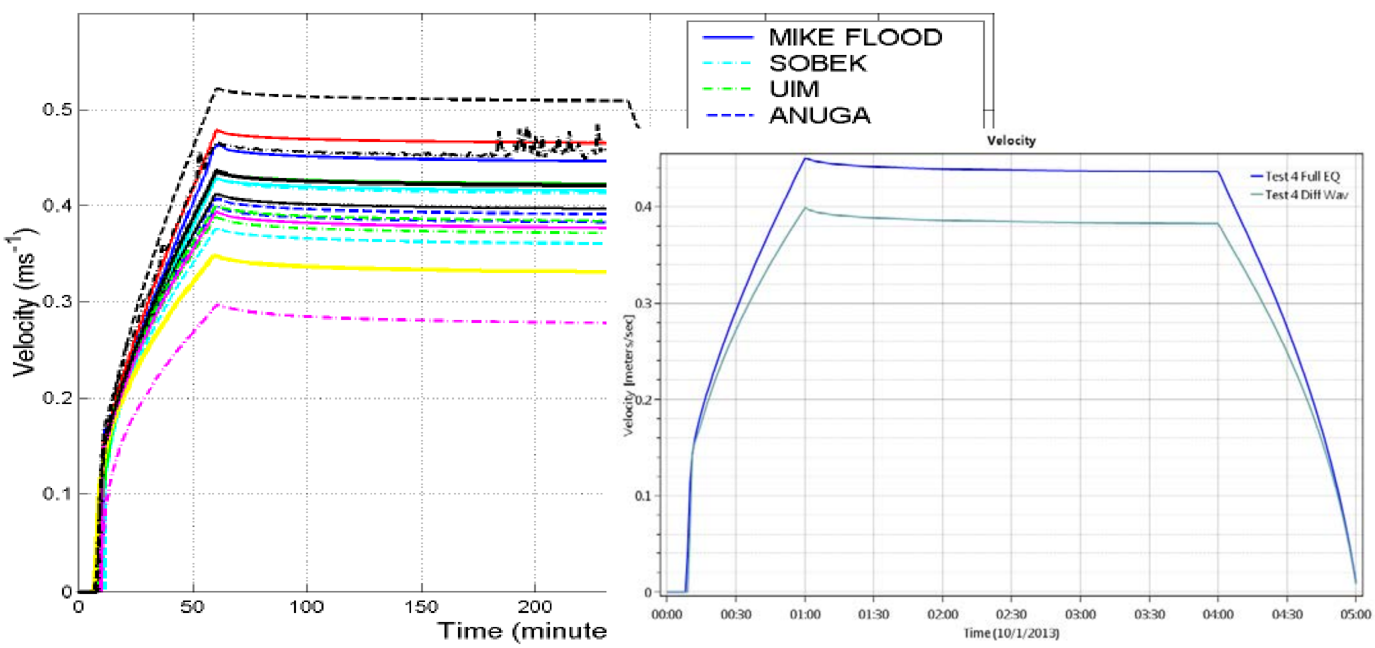


A.4 Benchmark Test 4

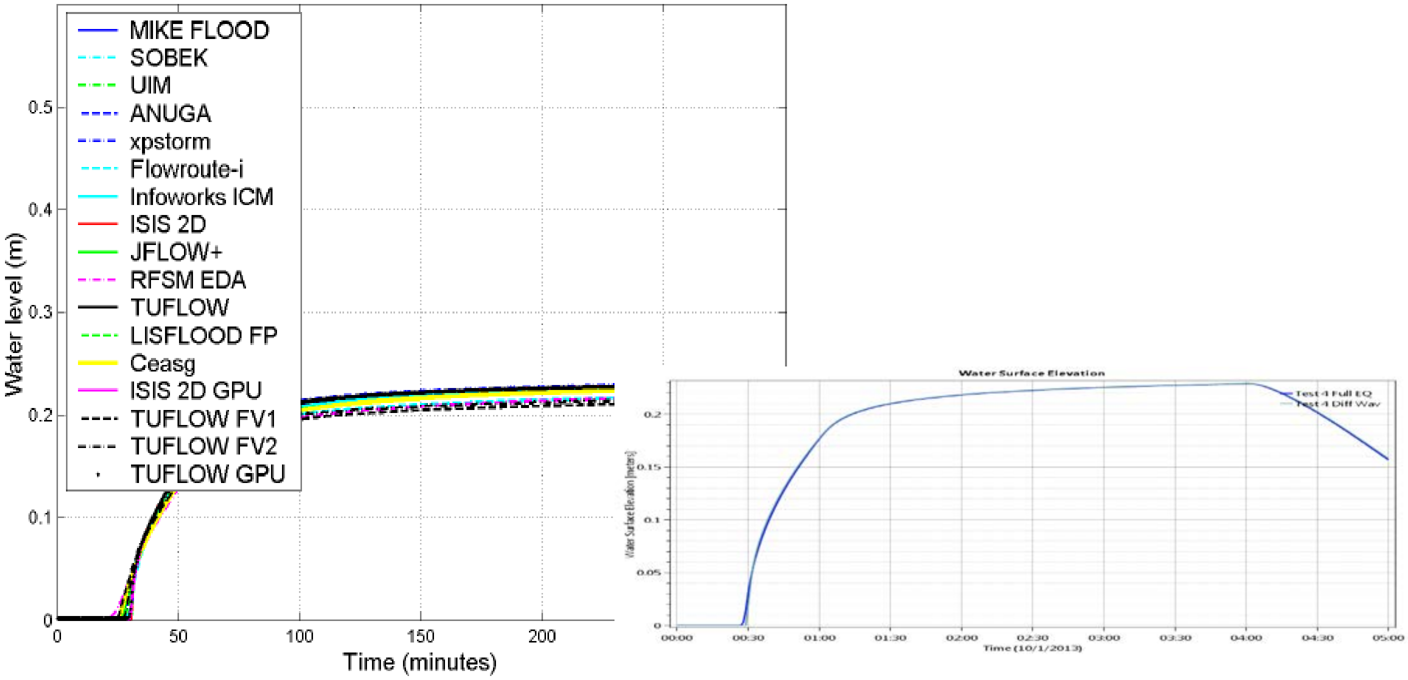
Location 1:



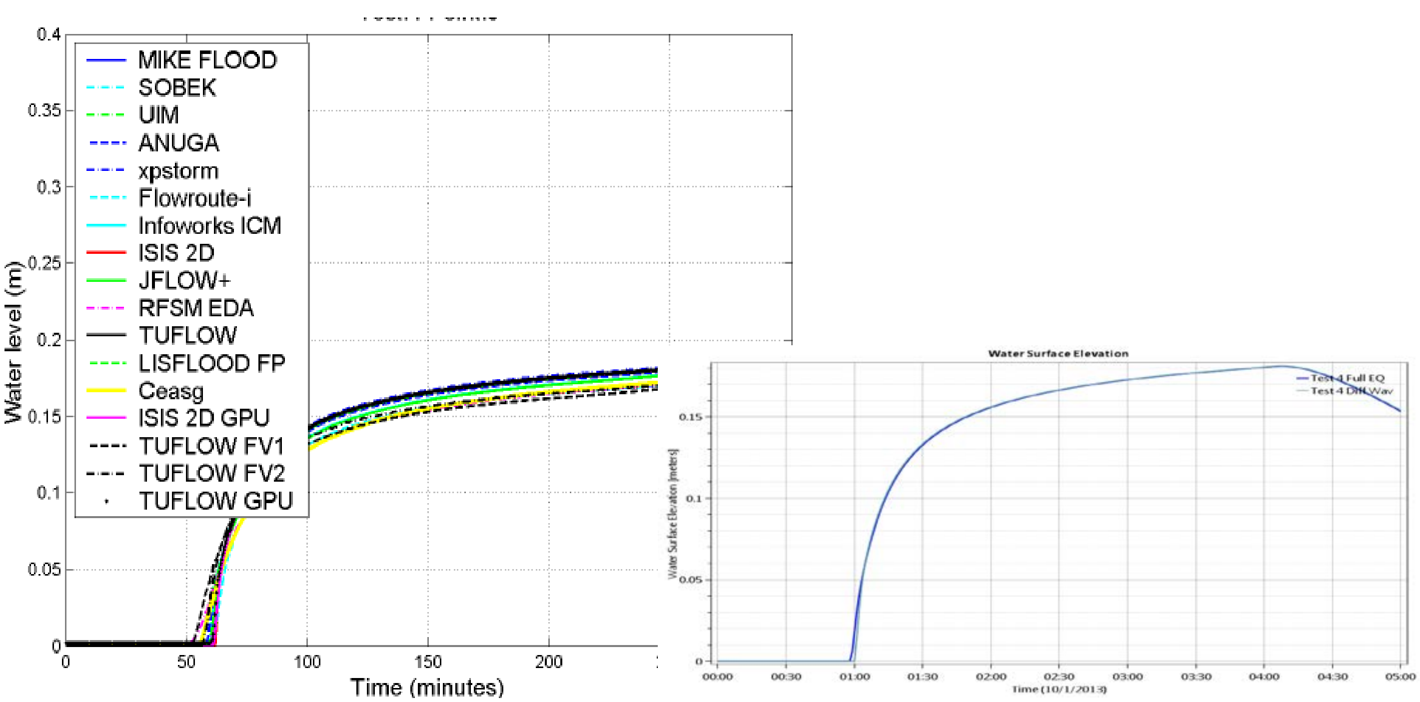
Location 1 Velocity:



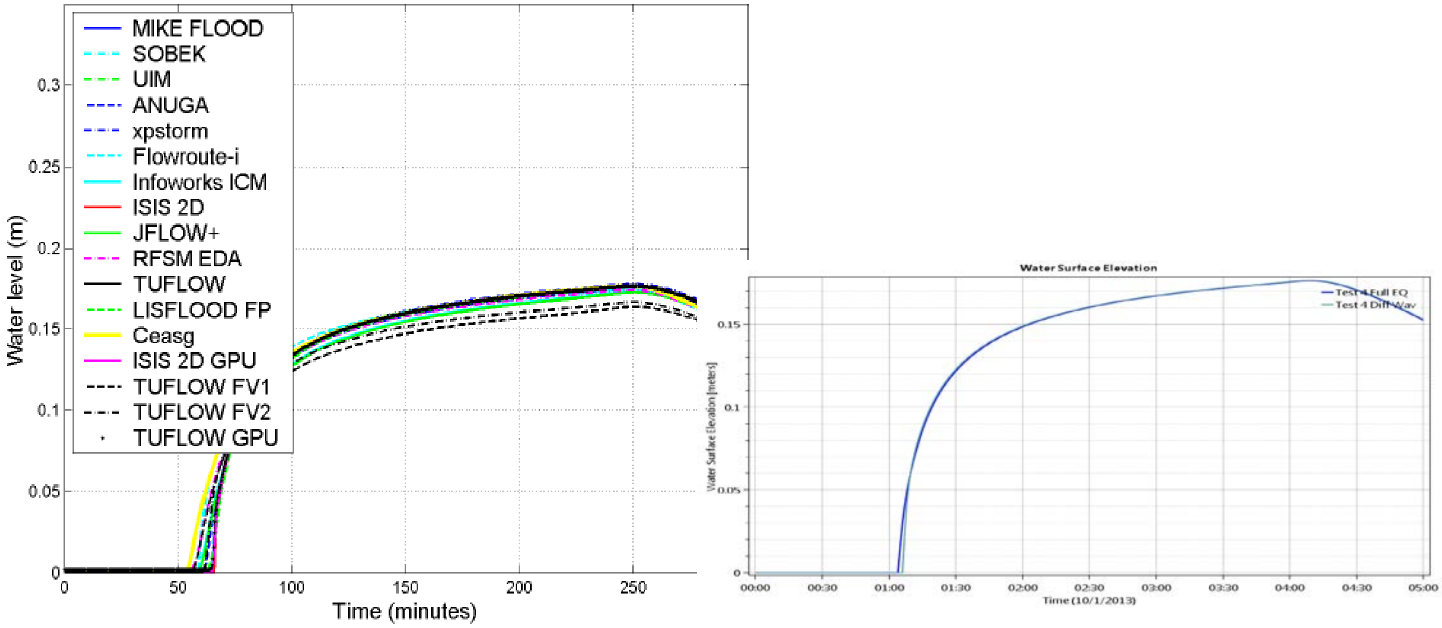
Location 3:



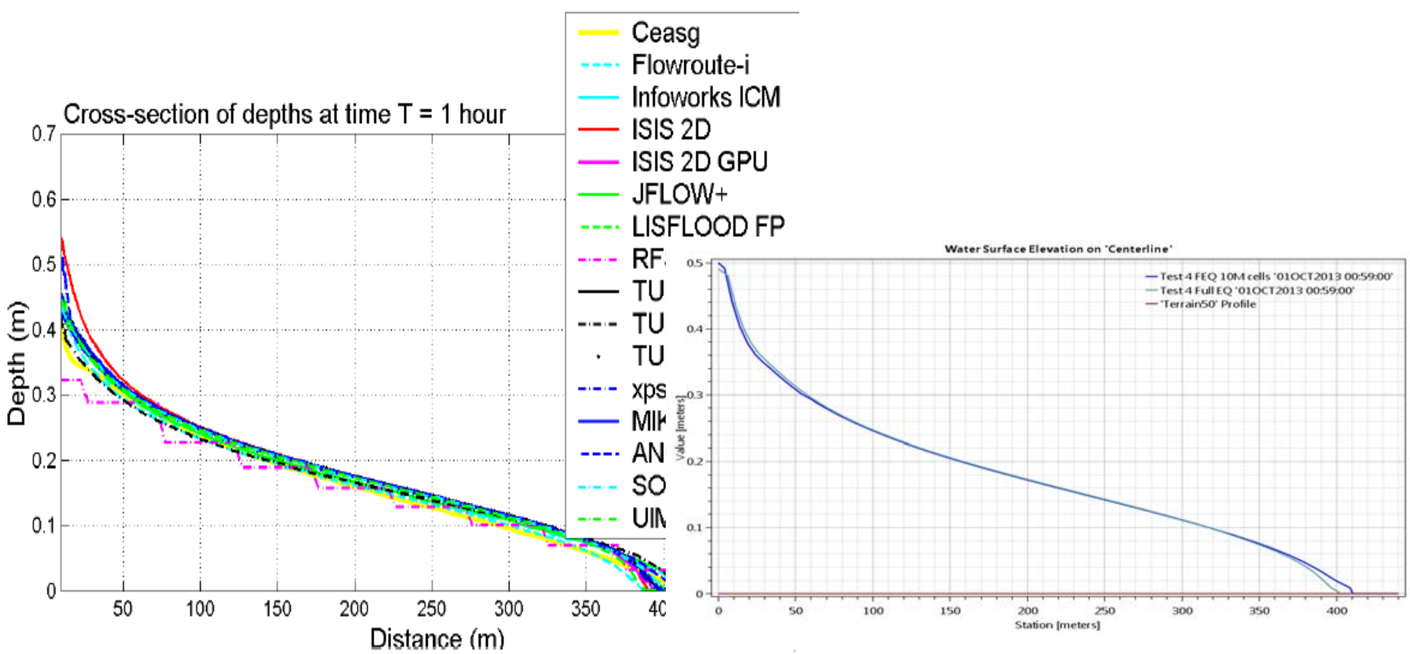
Location 5:



Location 6:

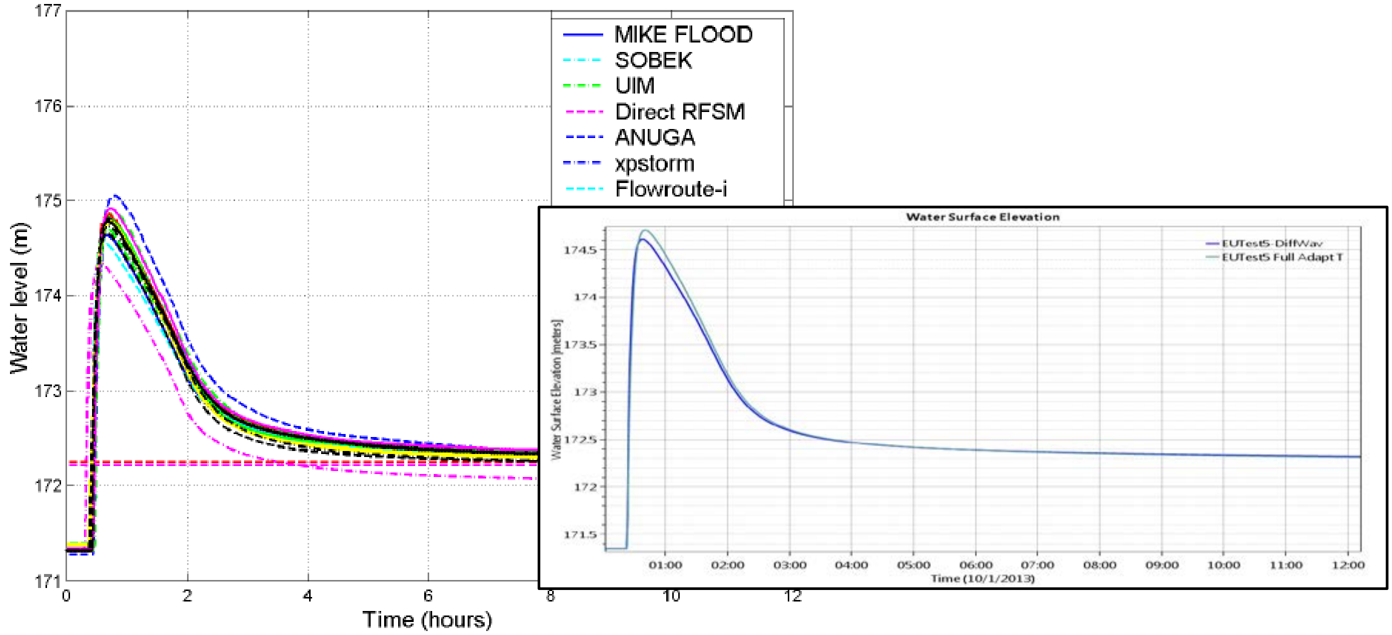


Centerline Profile:

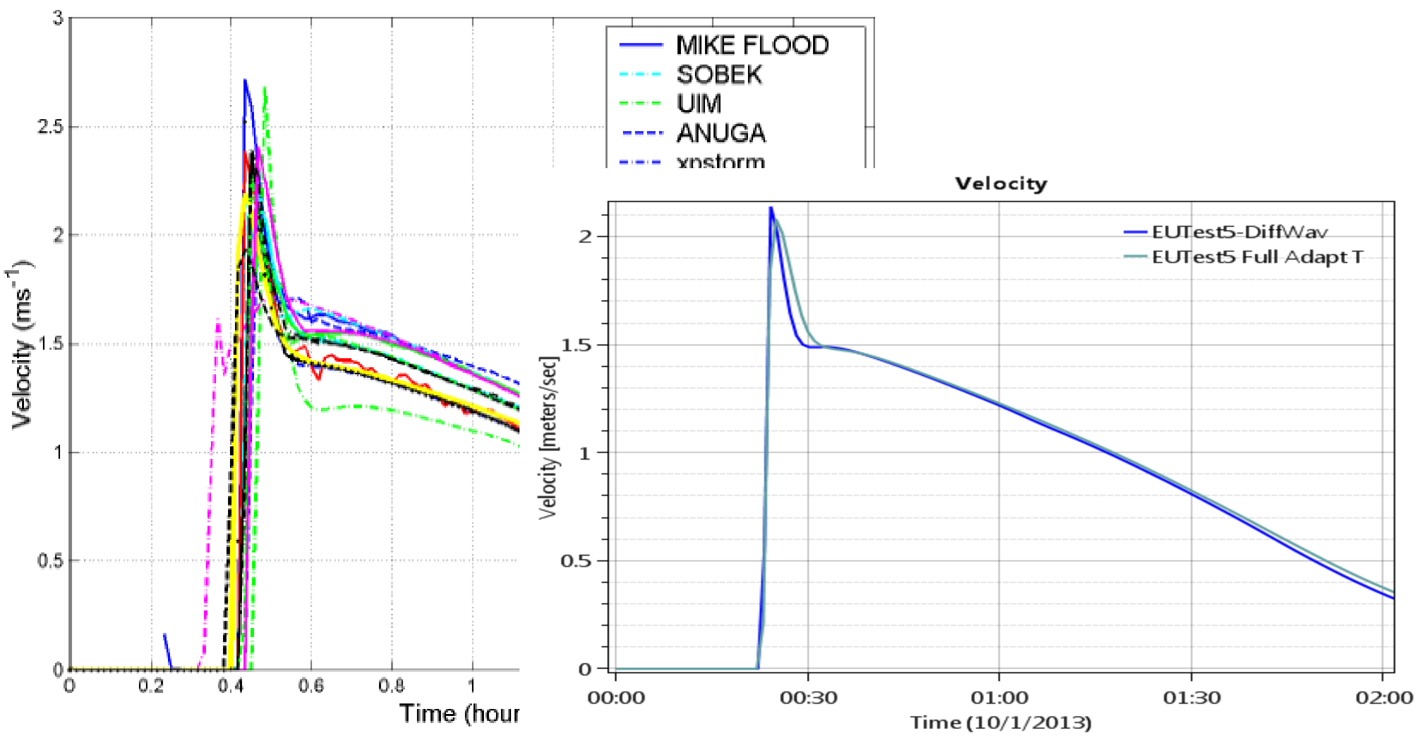


A.5 Benchmark Test 5

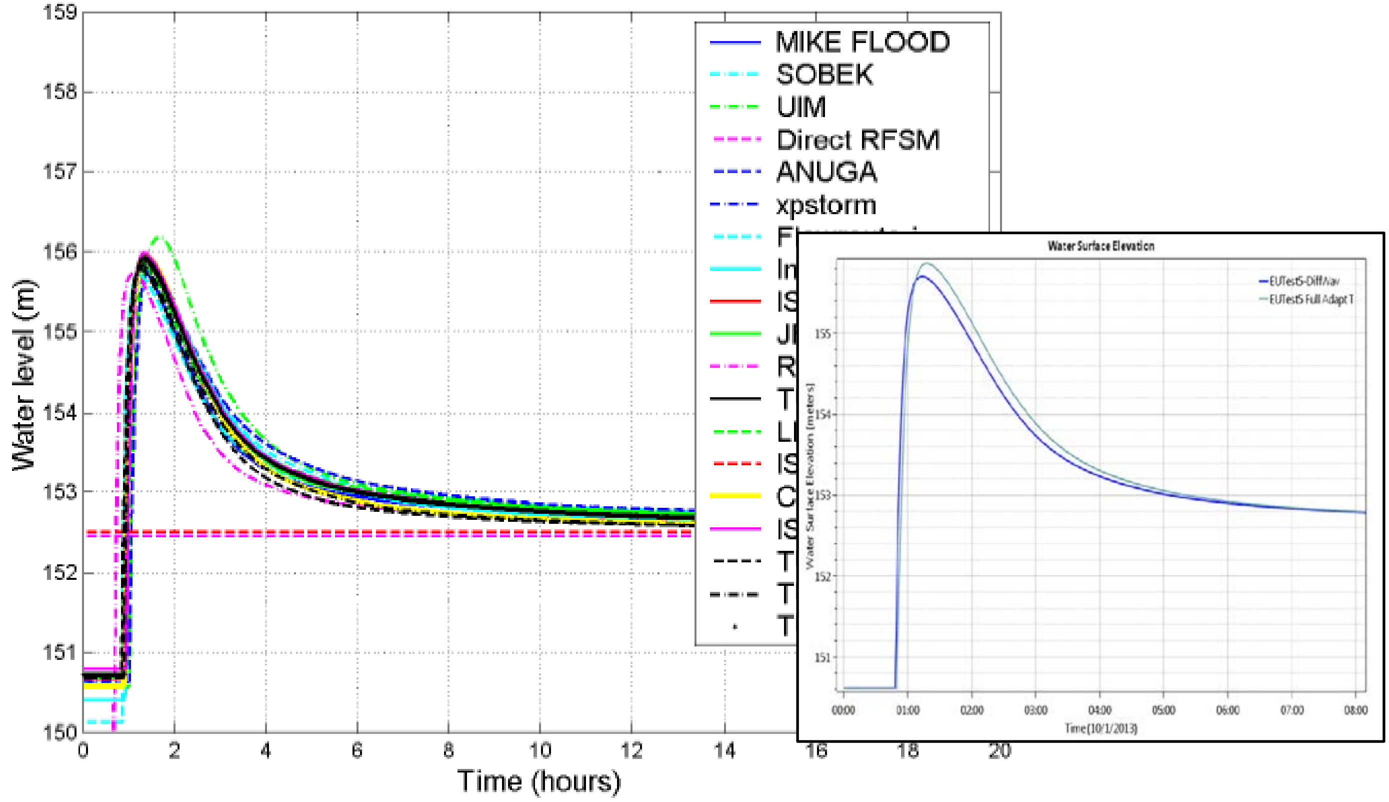
Location 1:



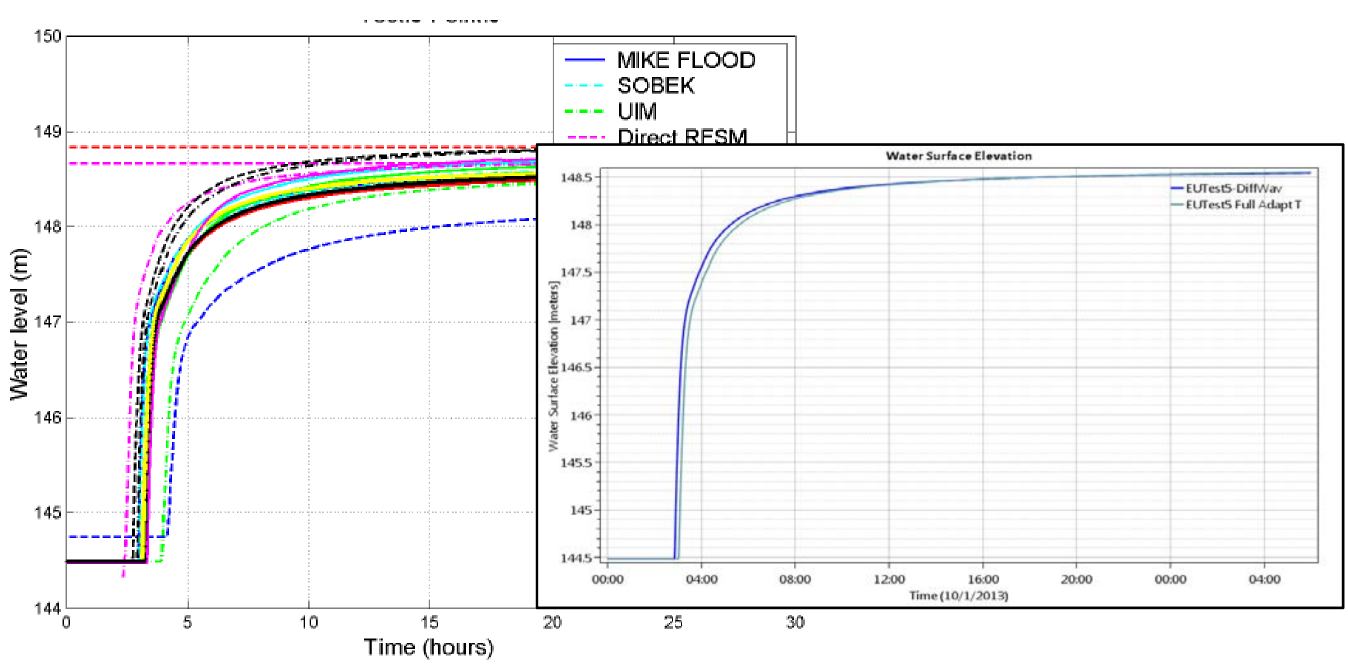
Location 1 Velocity:



Location 3:

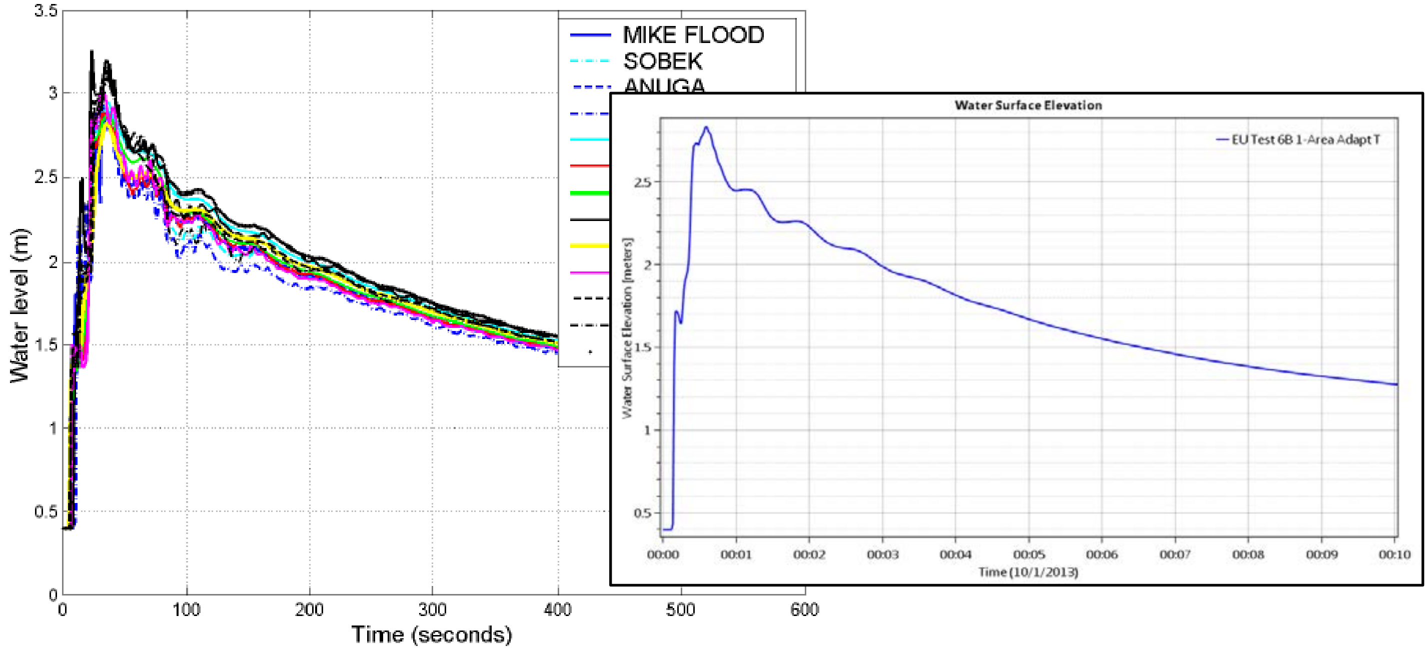


Location 5:

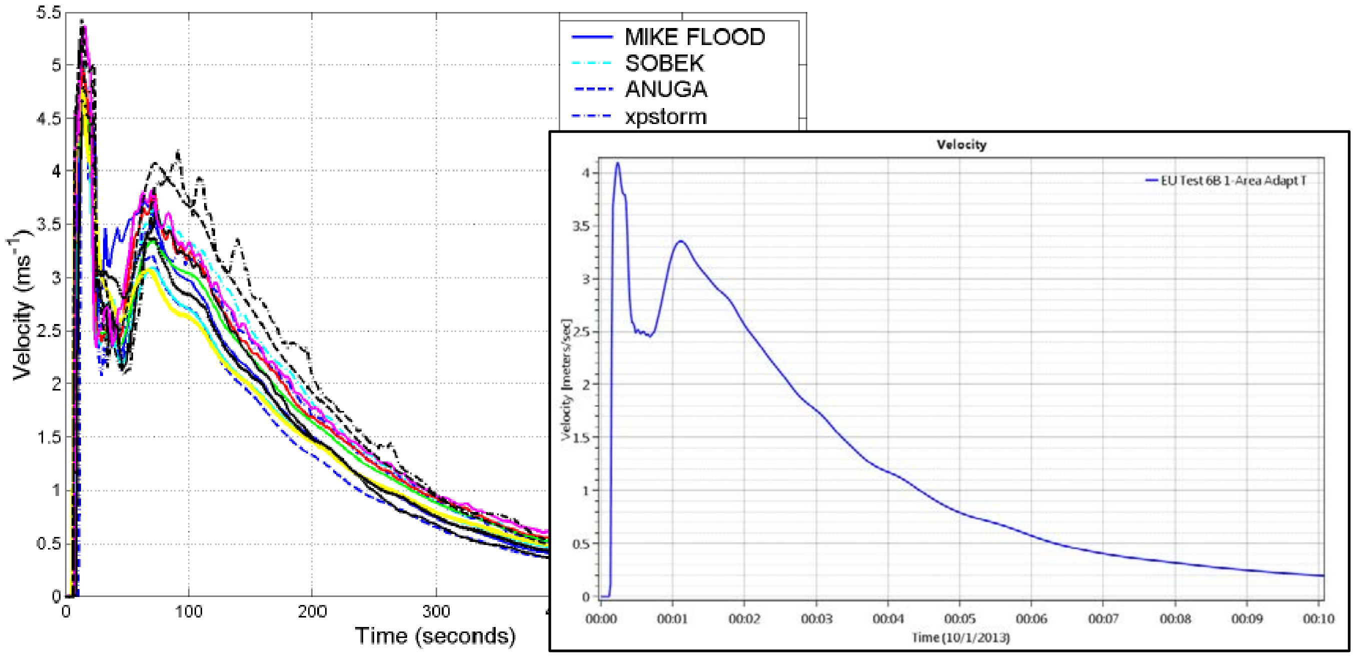


A.6 Benchmark Test 6

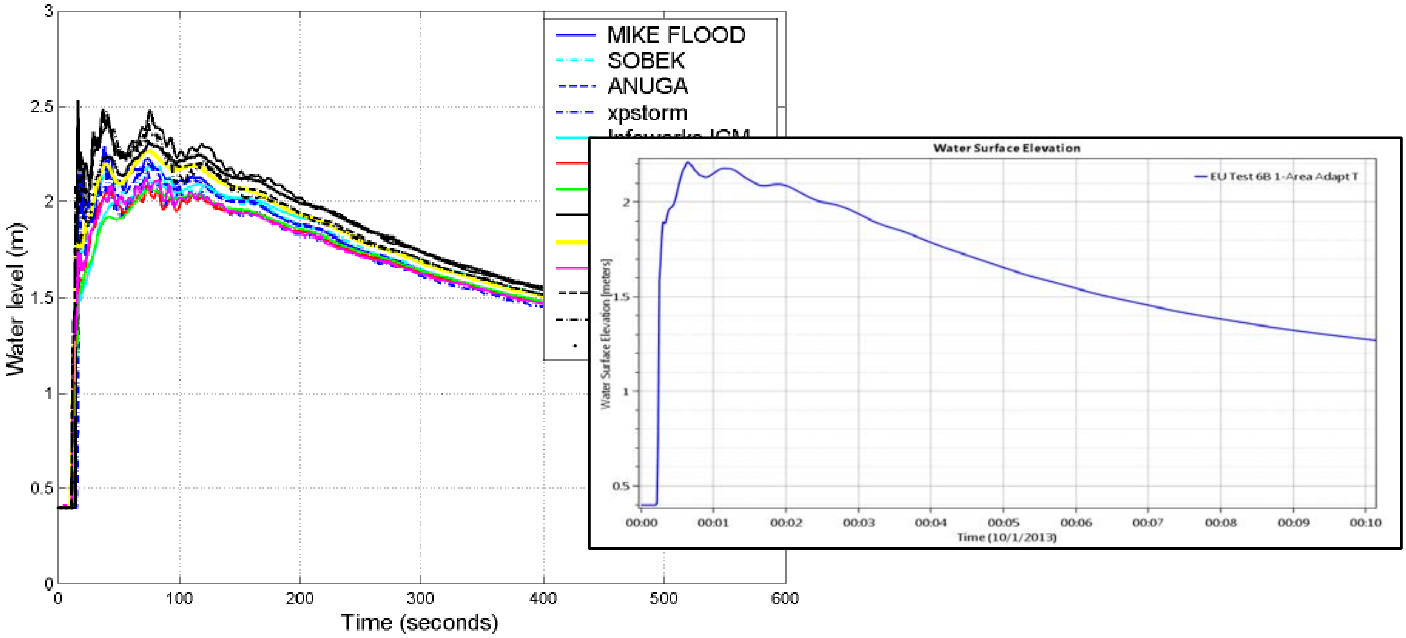
Location G2:



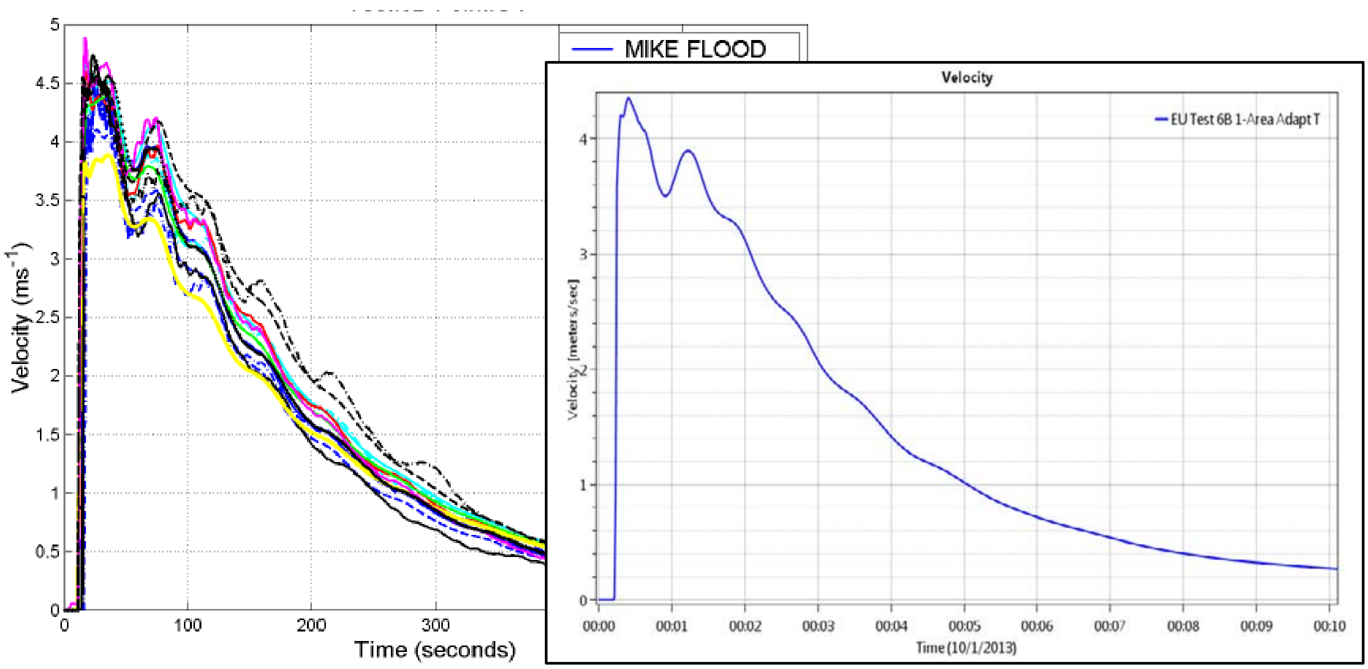
Location G2 Velocity:



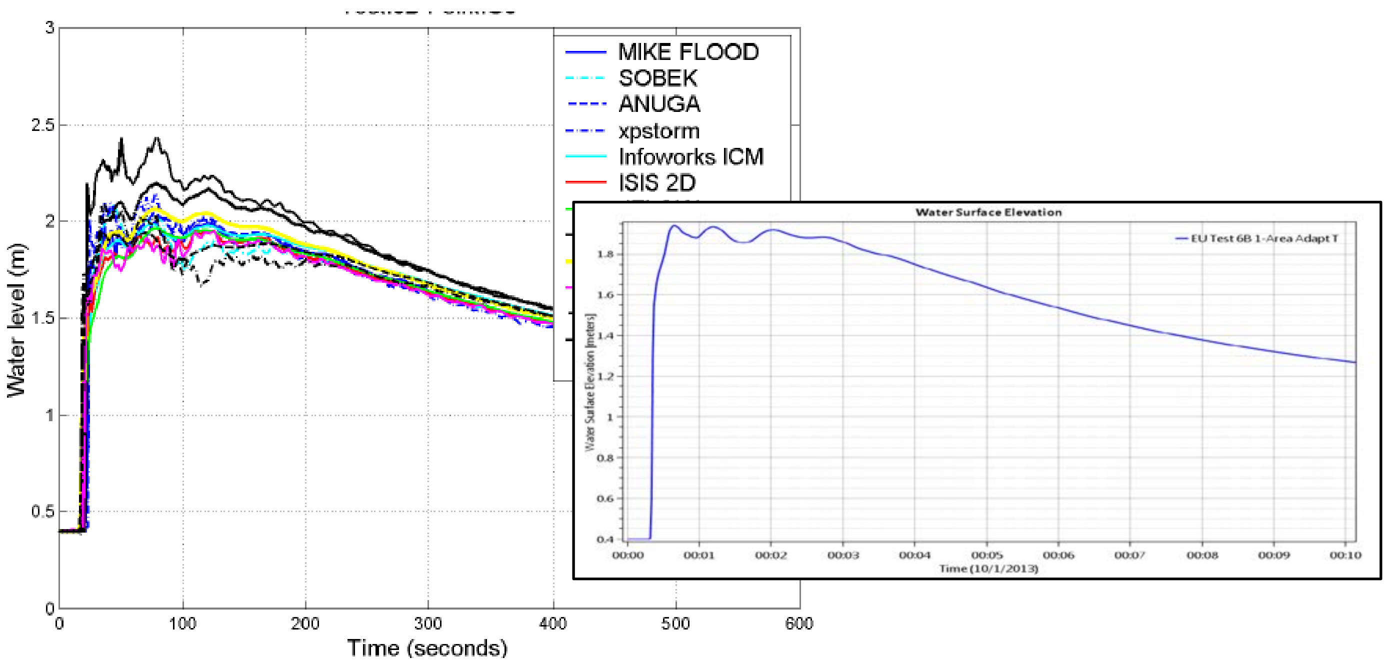
Location G4:



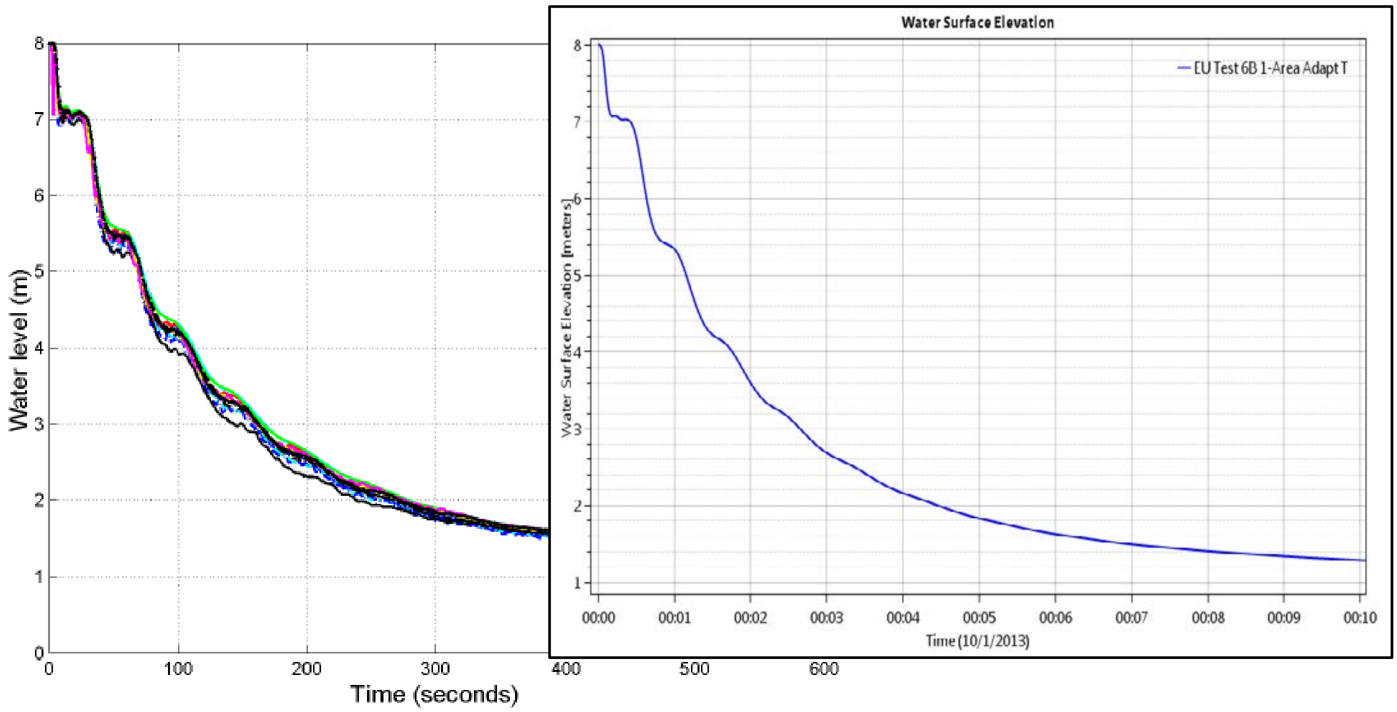
Location G4 Velocity:



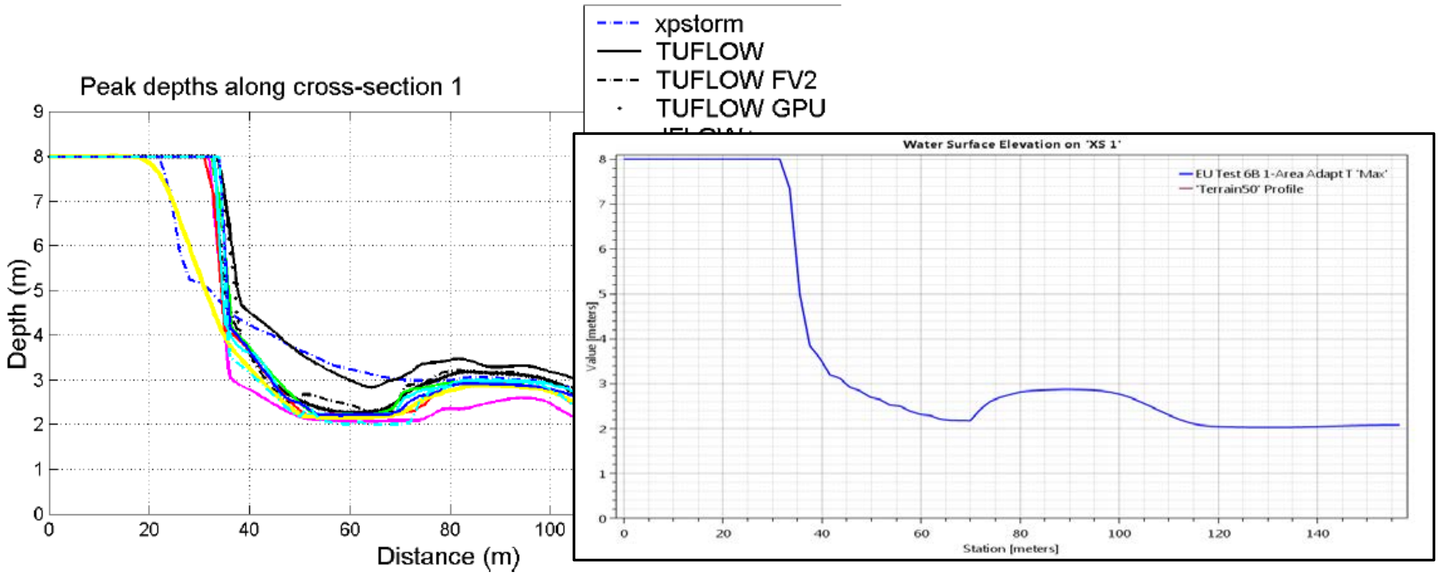
Location G5:



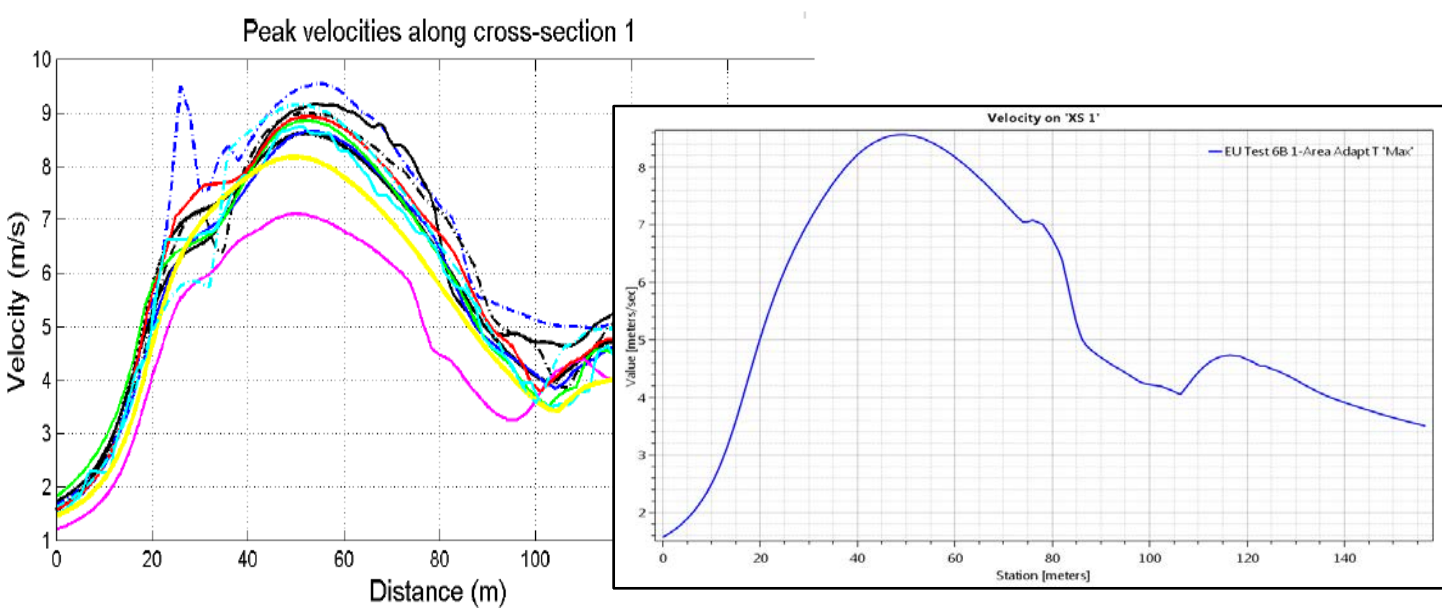
Location G6:



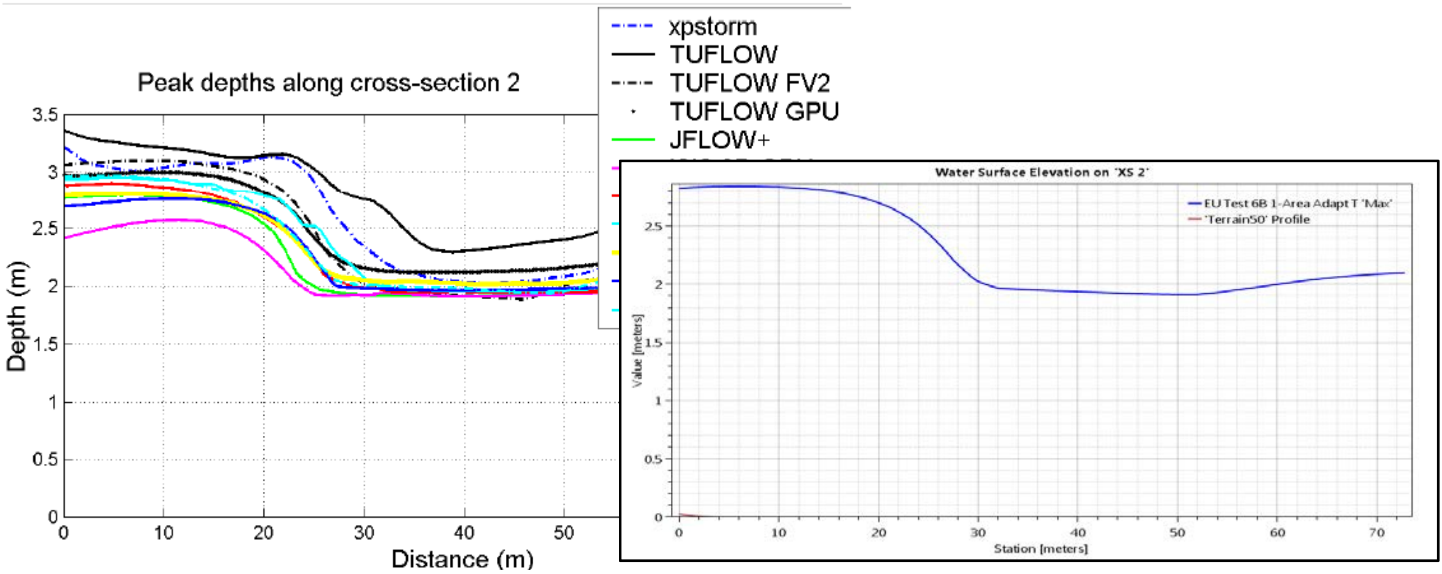
Cross Section 1 Water Surface:



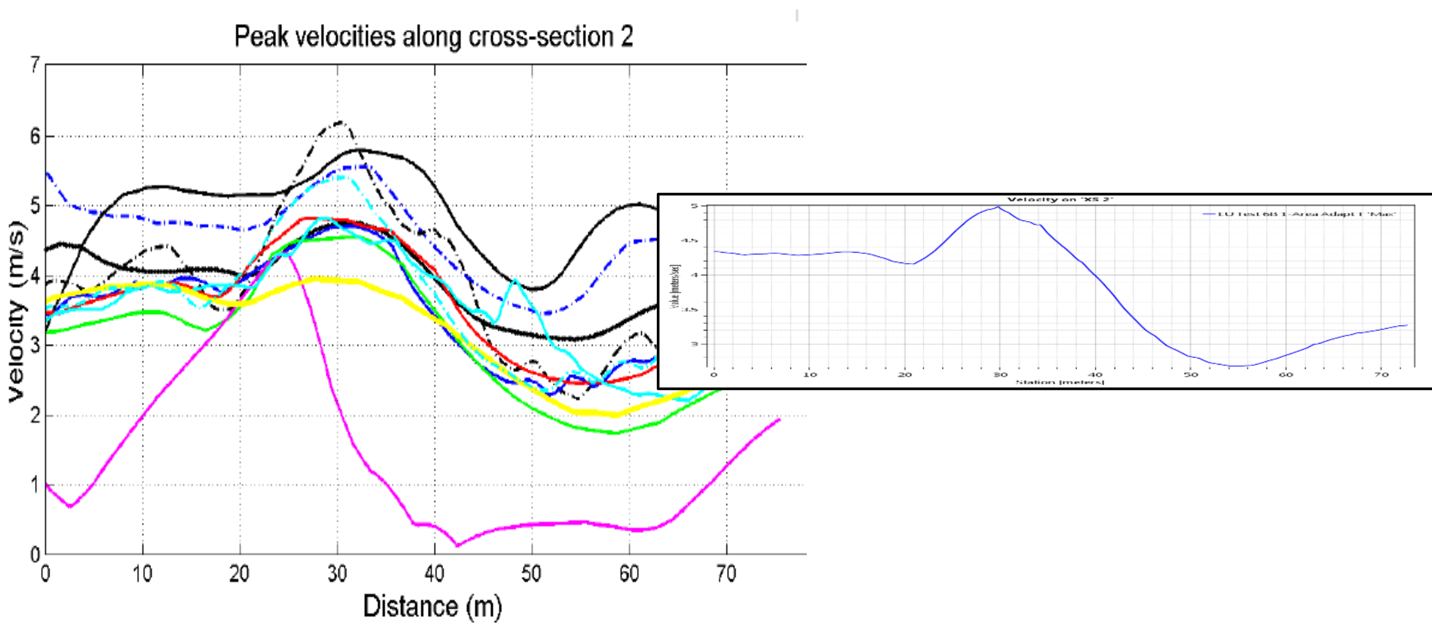
Cross Section 1 Velocity:



Cross Section 2 Water Surface:

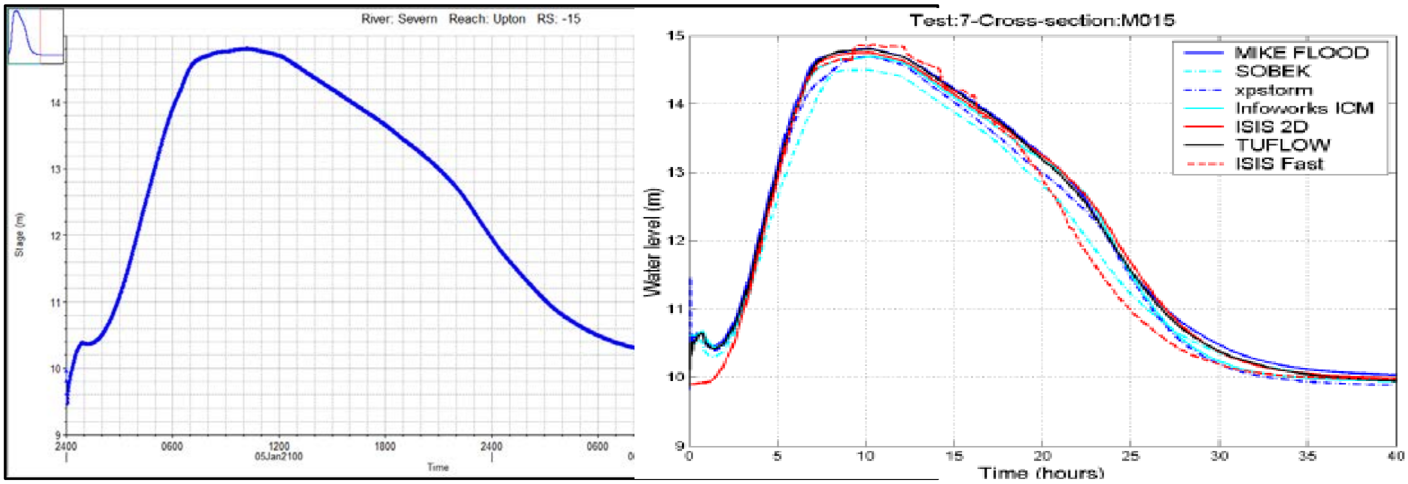


Cross Section 2 Velocity:

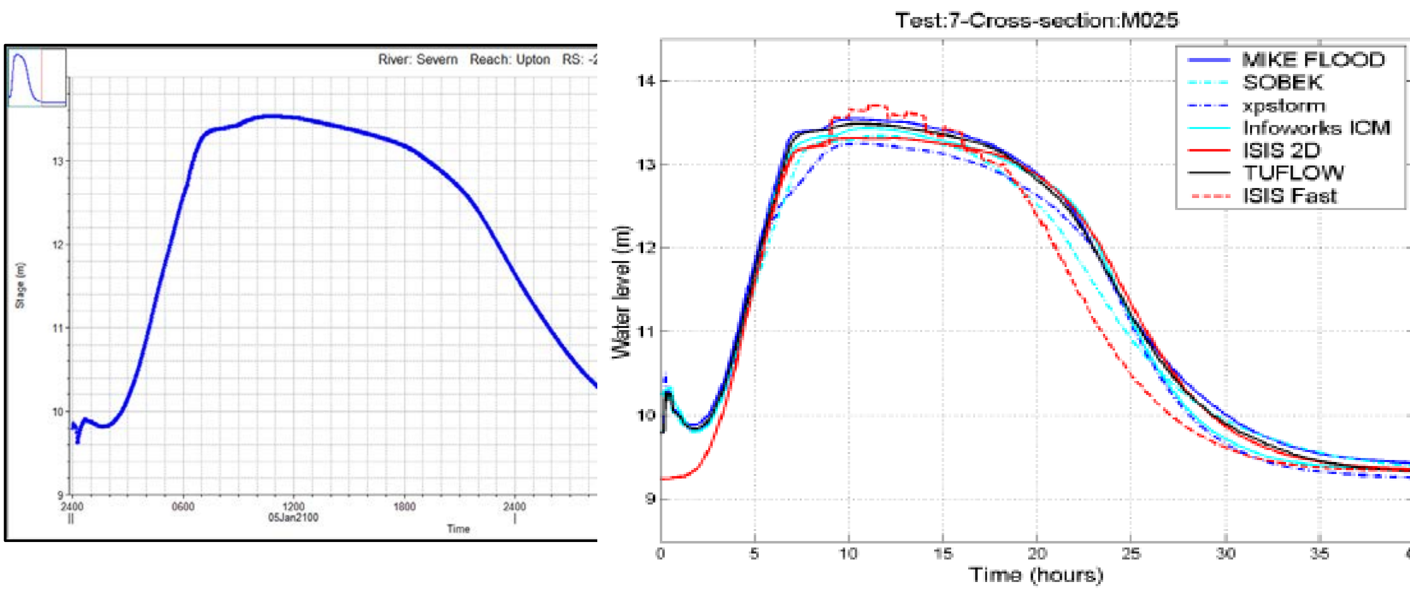


A.7 Benchmark Test 7

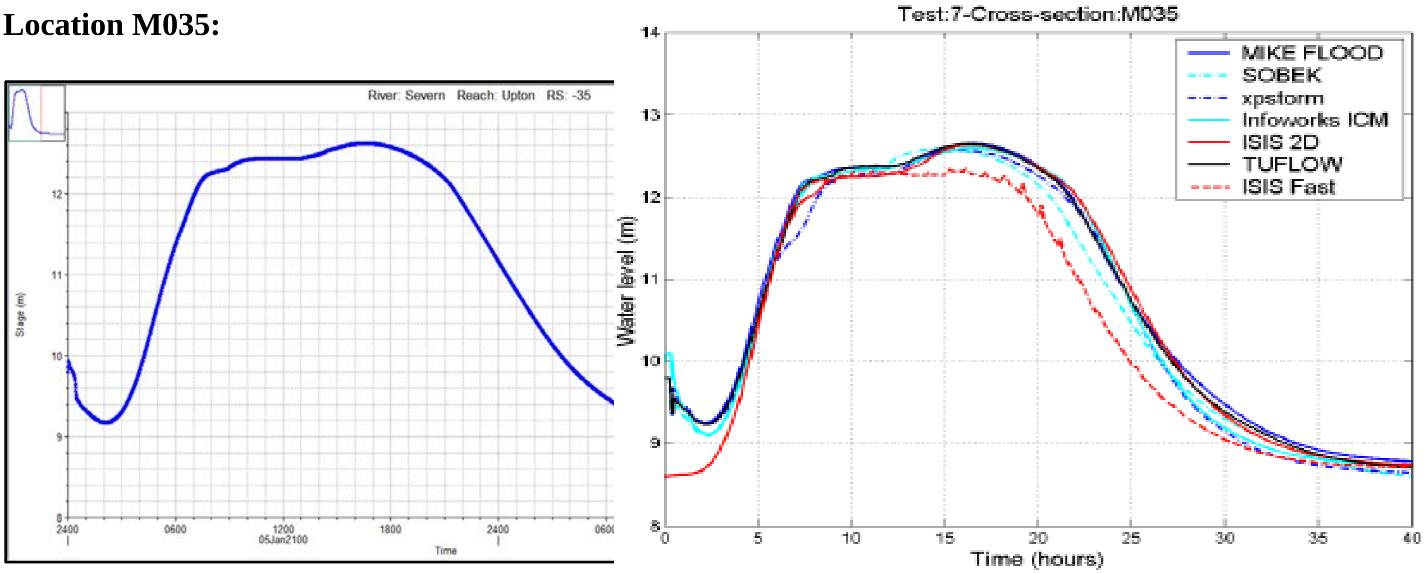
Location M015:



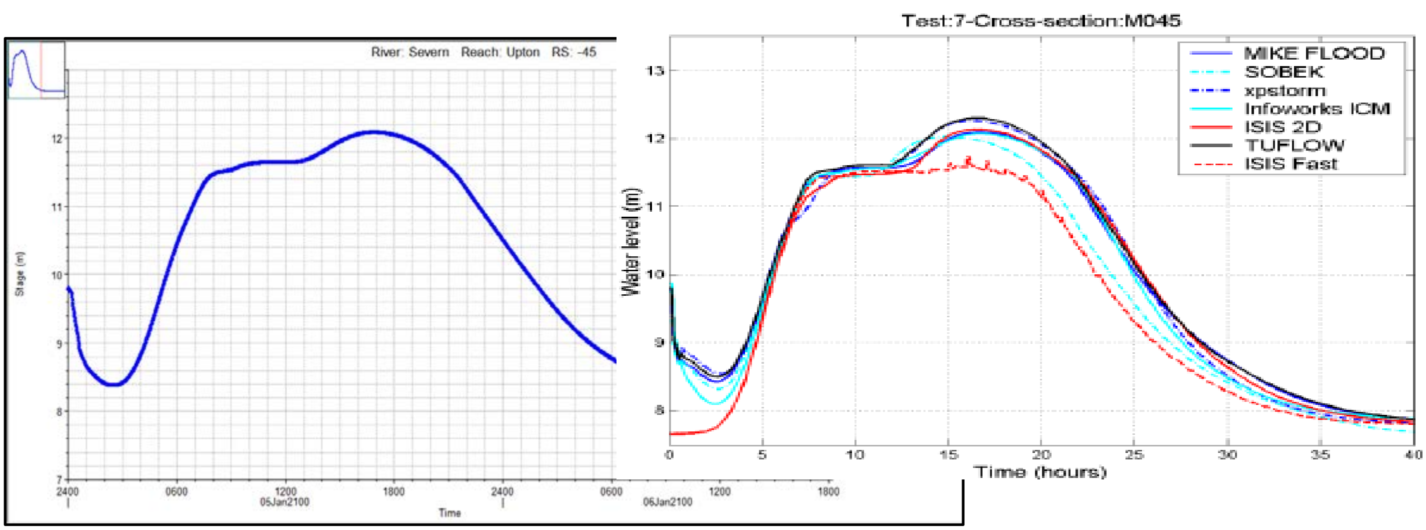
Location M025:



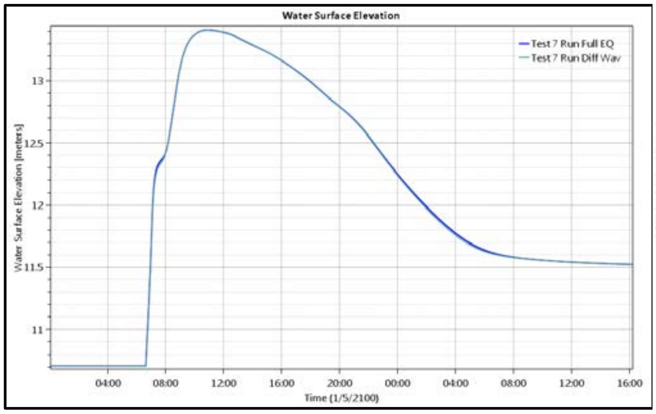
Location M035:

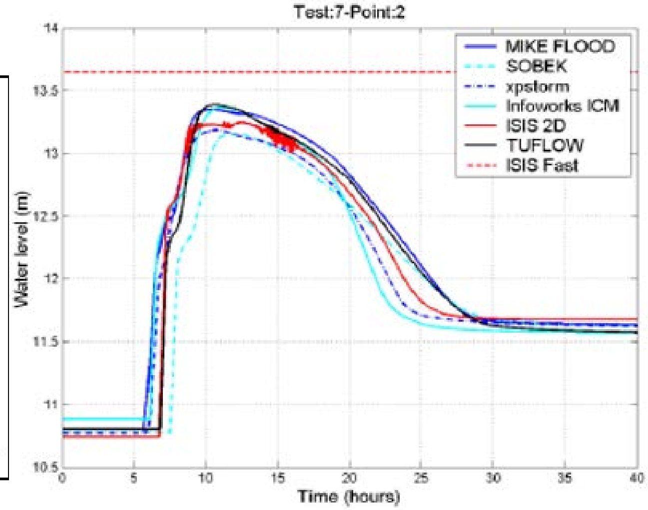


Location M045:

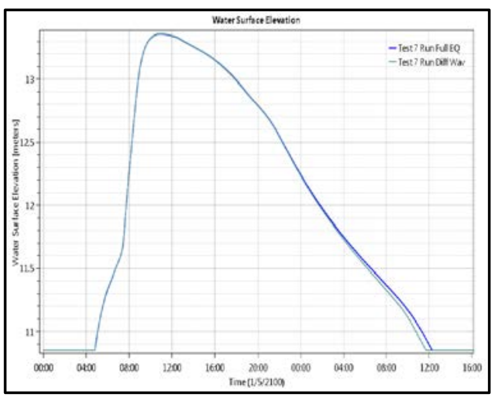


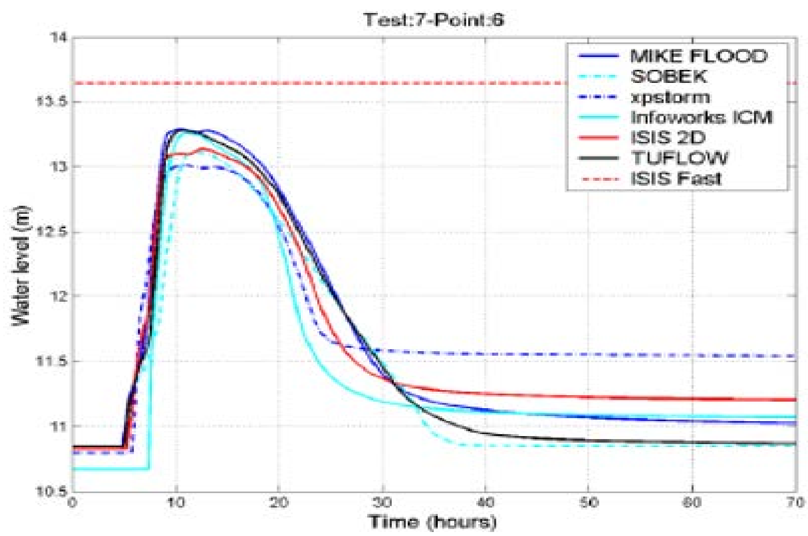
Floodplain 1, Location 2:



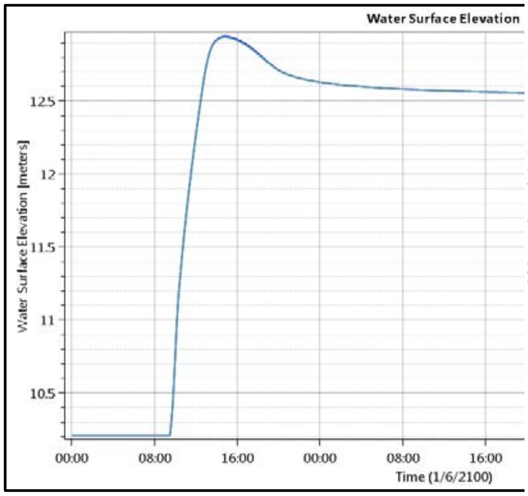


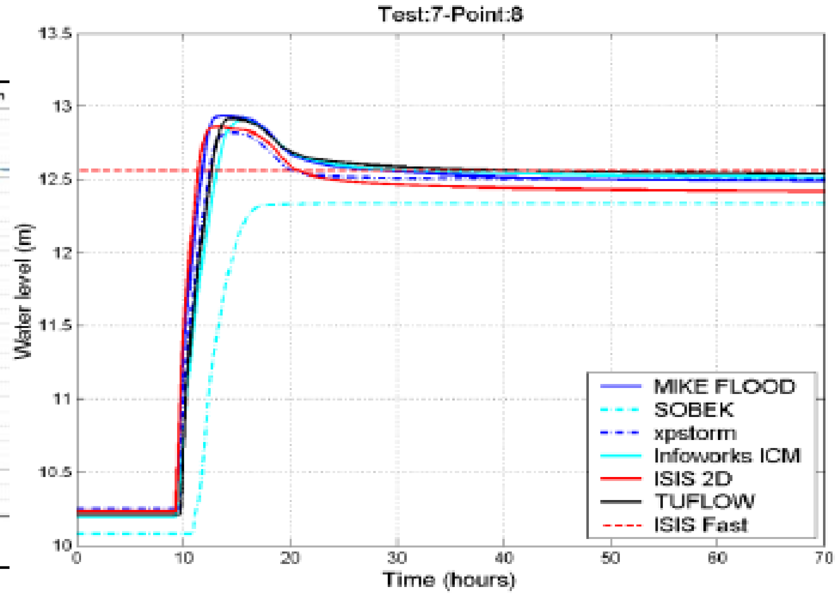
Floodplain 1, Location 6:



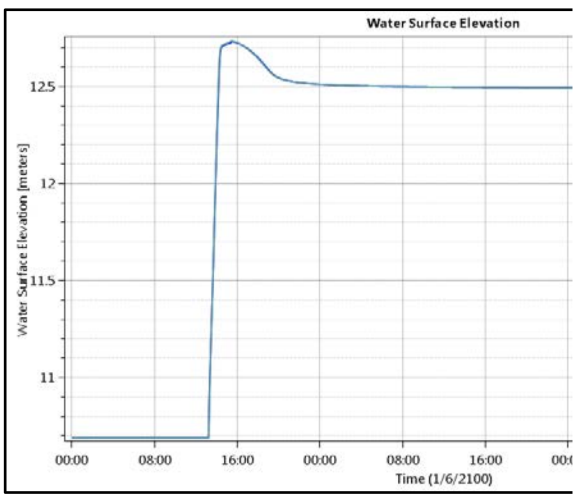


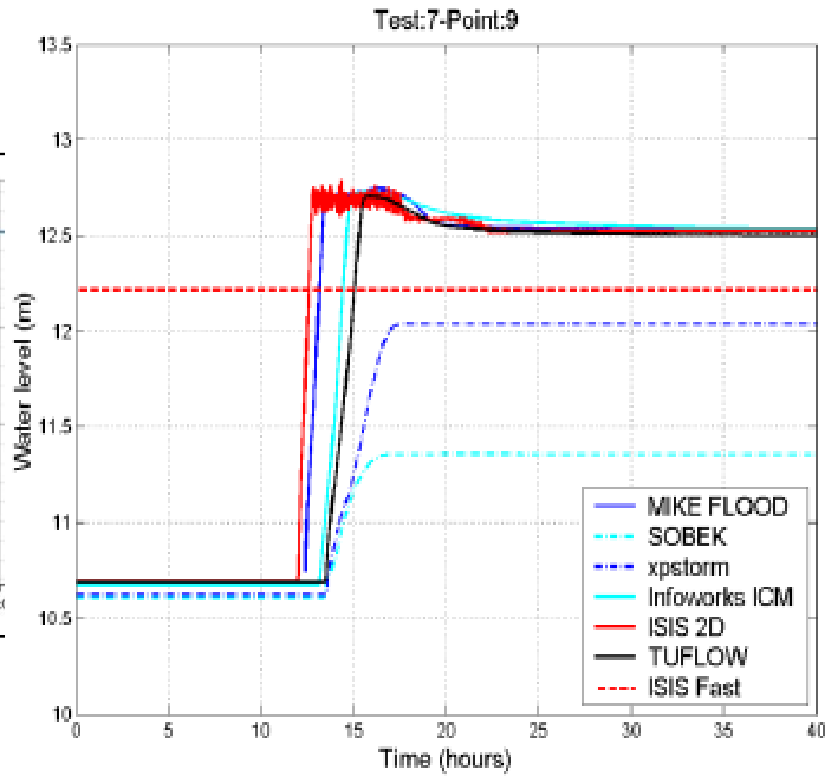
Floodplain 2, Location 8:



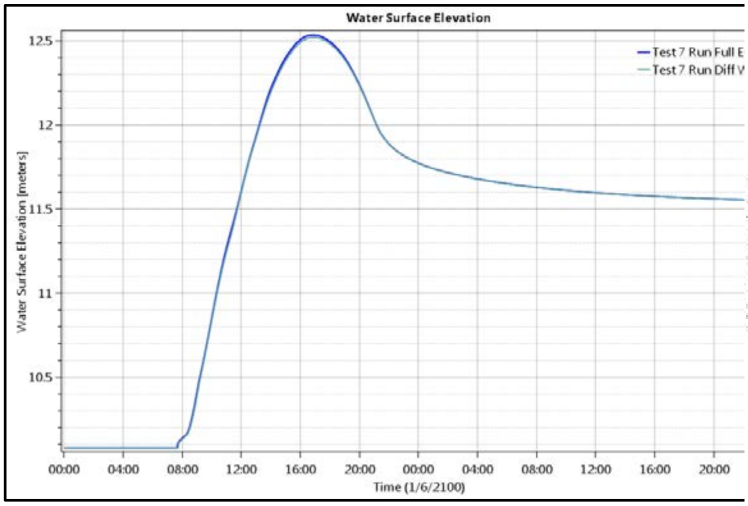


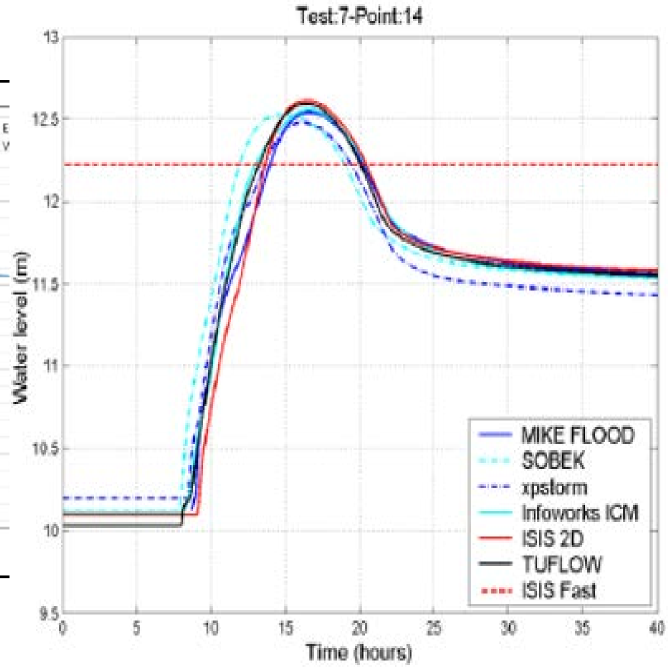
Floodplain 2, Location 9:



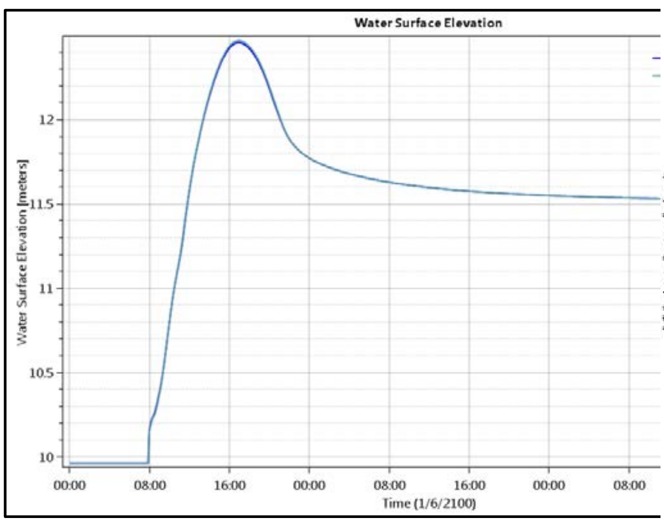


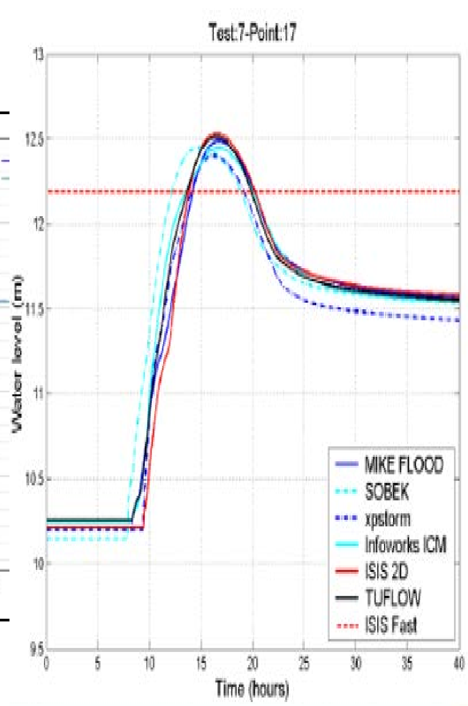
Floodplain 3, Location 14:



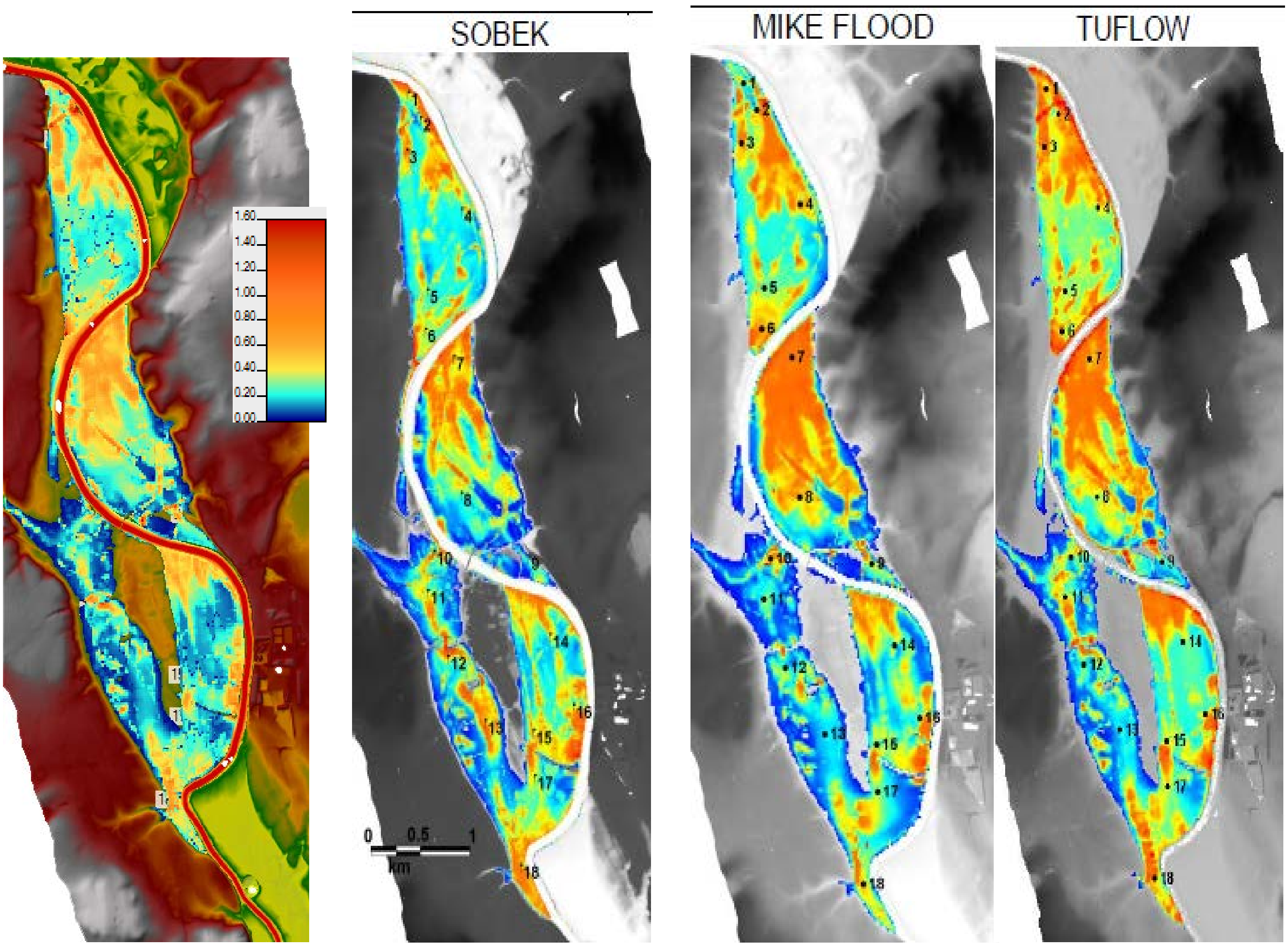


Floodplain 3, Location 17:

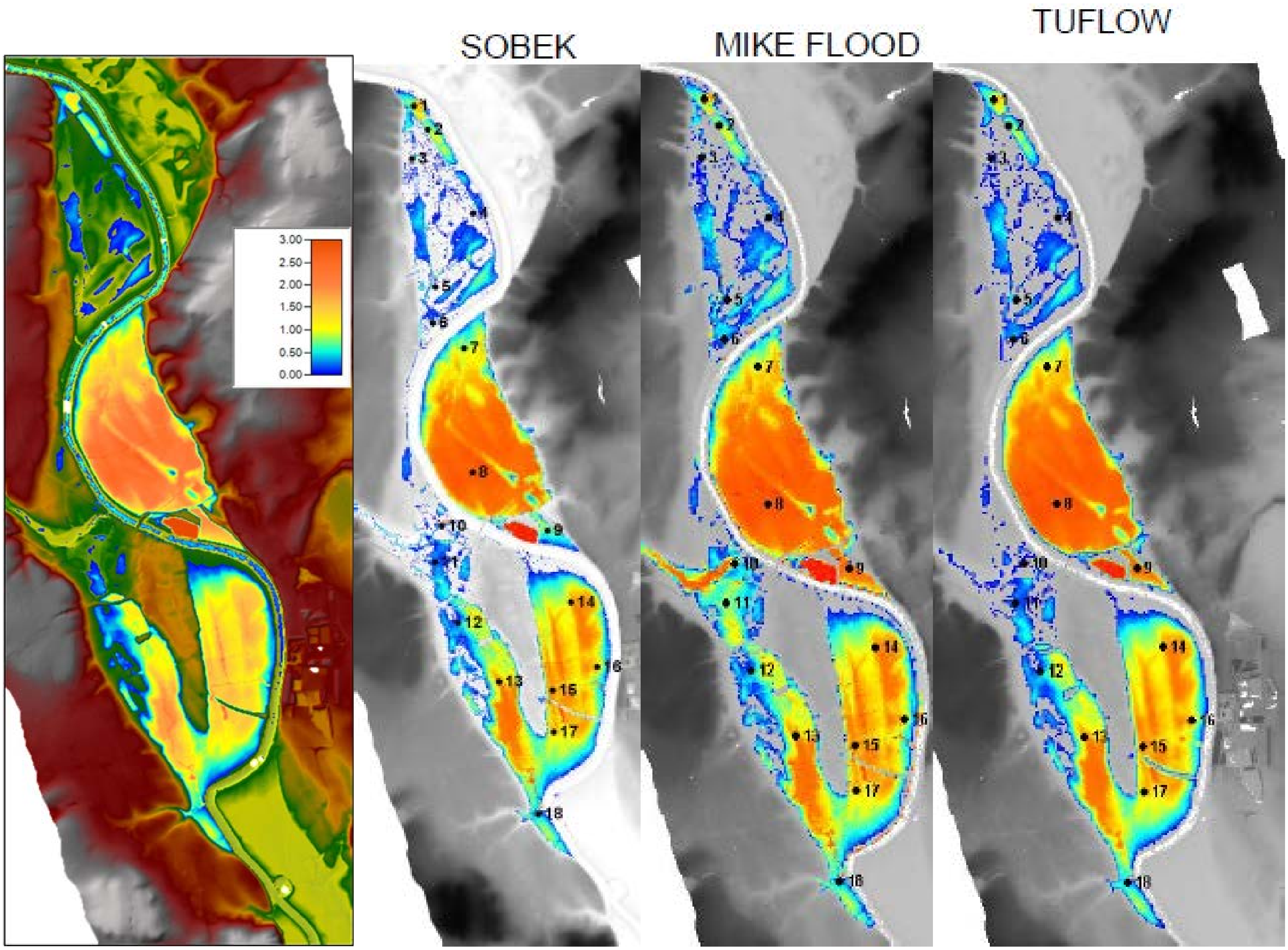




All Floodplains, Max Velocities:

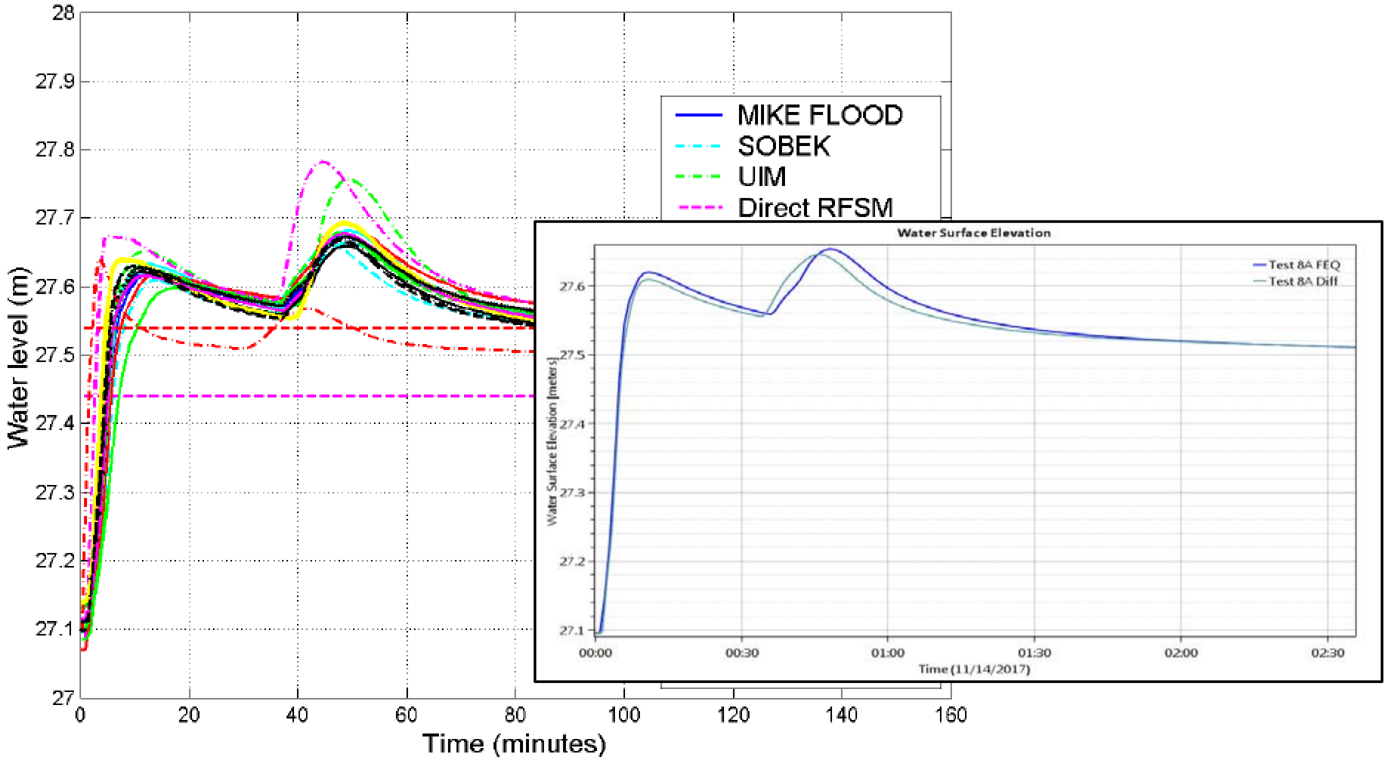


All Floodplains, Final Depths:

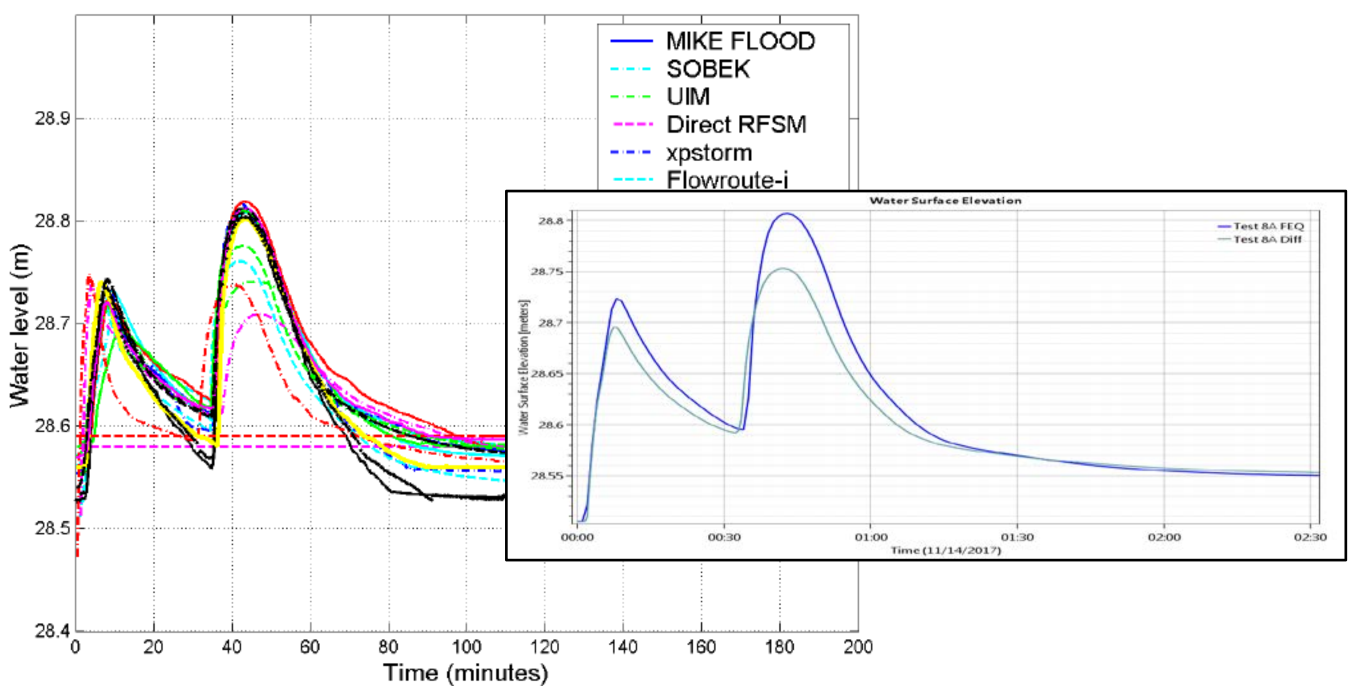


A.8 Benchmark Test 8A

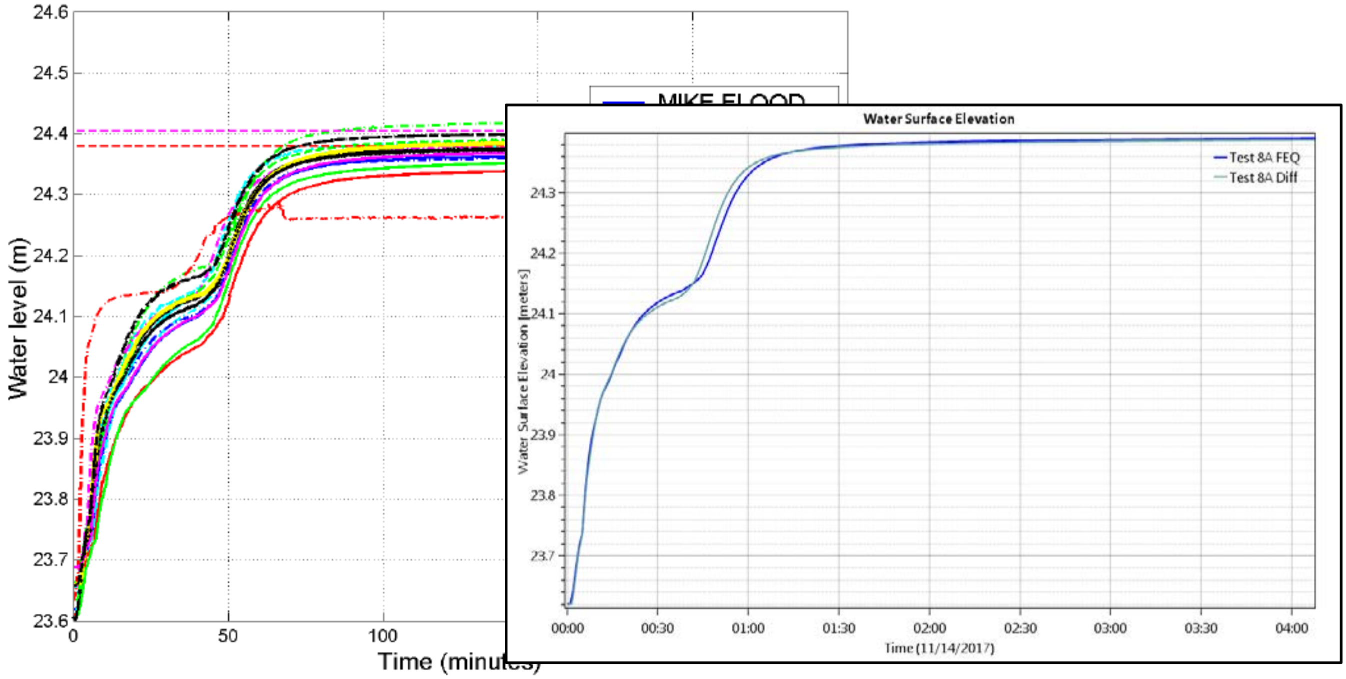
Location 1:



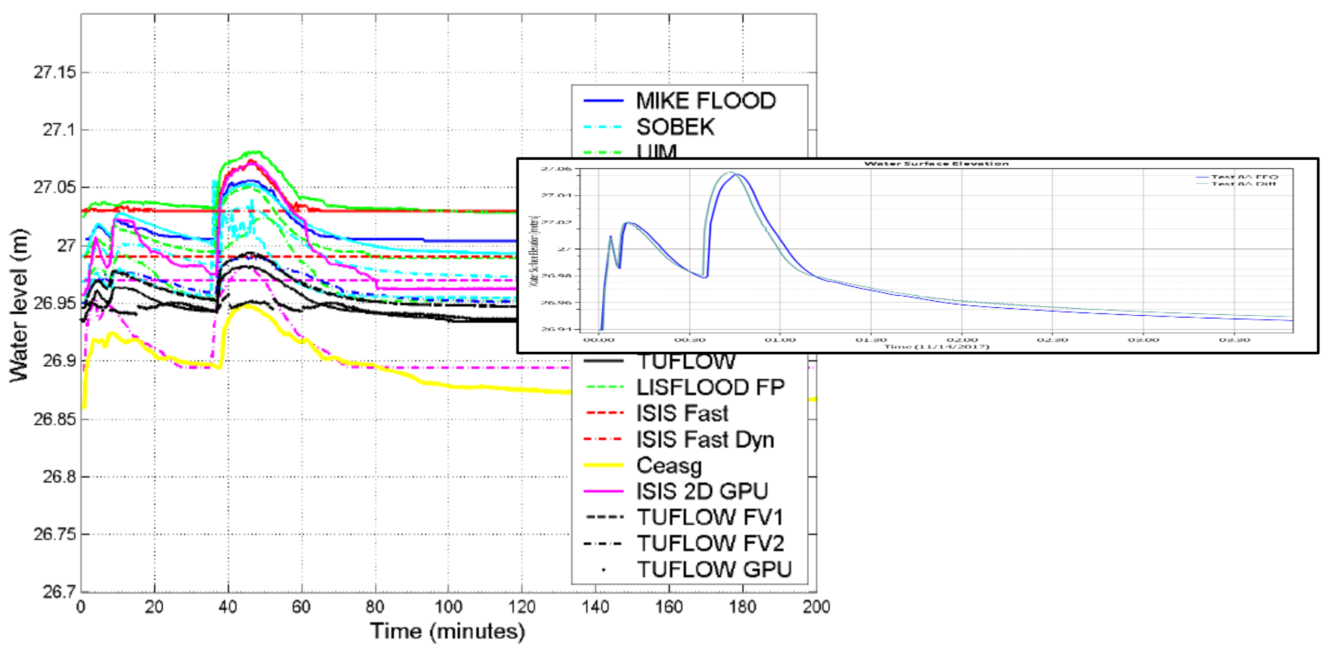
Location 2:



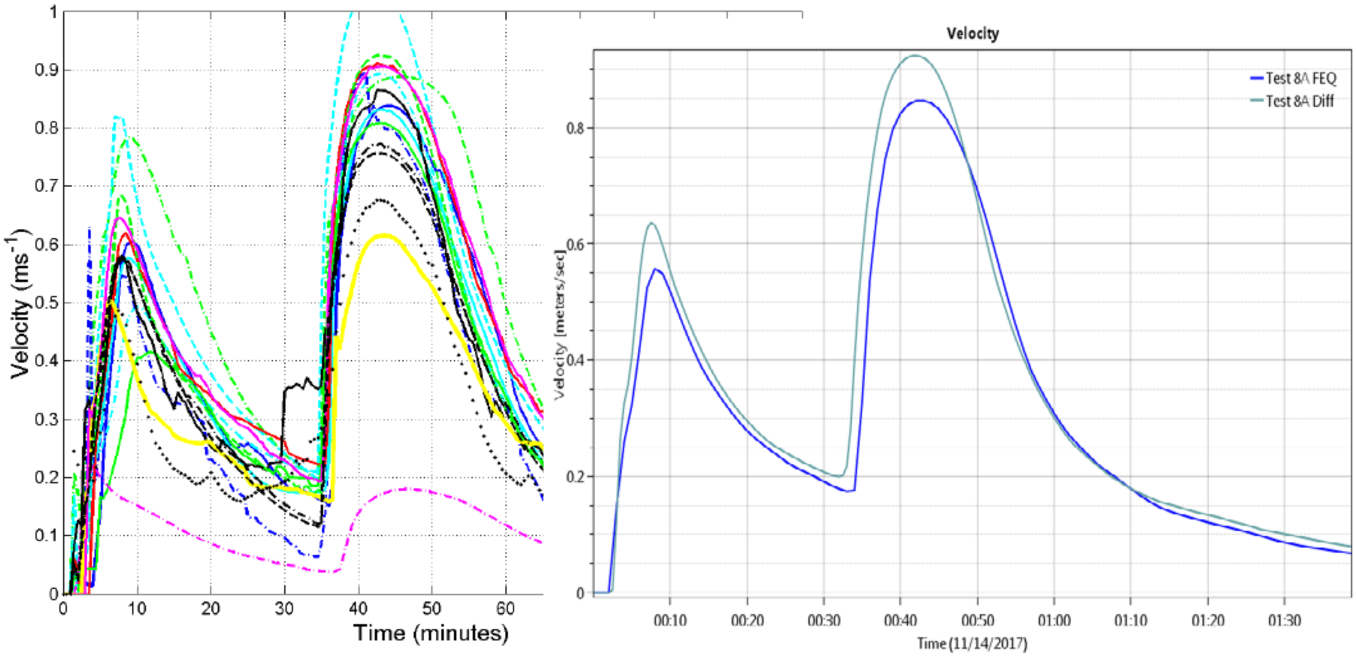
Location 3:



Location 6:



Location 2 Velocity:



Location 6 Velocity: