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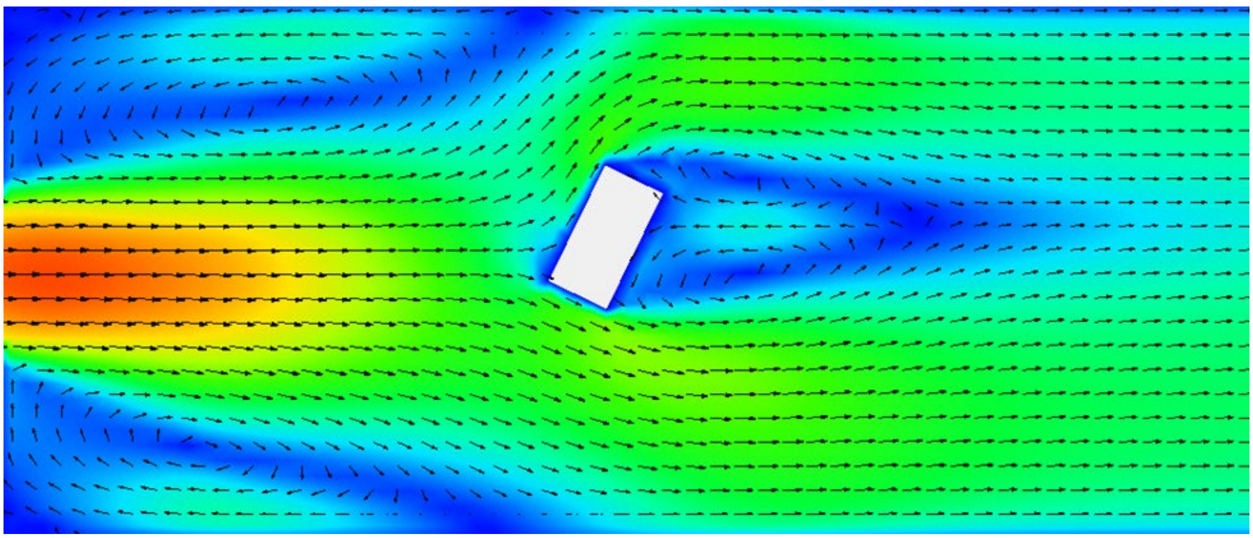
Benchmarking of SRH-2D



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16. Abstract
This document summarizes how the United States Bureau of Reclamation (Reclamation) Sedimentation and River Hydraulics – Two Dimension (SRH-2D) 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 SRH-2D is to demonstrate that the SRH-2D two-dimensional modeling capabilities can produce similar results to the two-dimensional models documented by the United Kingdom Environment Agency and the Hydrologic Engineering Center (HEC) River Analysis System (HEC-RAS) research reports.

The tests summarized in this document were run with SRH-2D Version 3.3.

17. Key Words SRH-2D, hydraulic modeling, hydraulic analysis, two-dimensional, research and development, United Kingdom, benchmarking, time steps, computational interval, grid/element resolution	18. Distribution Statement

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1 Introduction

1.1 Need for Modeling

The current generation of hydraulic modeling tools, primarily one-dimensional (1D) modeling, has been in use for over 40 years. In that period, the user interfaces and computational power have greatly improved, but the underlying techniques are the same.

Current 1D modeling techniques that are commonly used for hydraulic design apply simplifying assumptions that can lead to overly conservative, inadequate, or inaccurate results and conclusions. A significant assumption is that key hydraulic properties, such as velocity and water surface elevation, are averaged at cross-sections and therefore only vary in the longitudinal (upstream/downstream) direction. This simplification obscures valuable information about actual hydraulic behavior in many situations.

The next generation of hydraulic modeling tools, including two-dimensional (2D) models, represents the real world in a much more comprehensive way. 2D models allow more realistic variation of key hydraulic variables, including velocity and water surface elevation, at any given location in the modeled area.

As hydraulic designers and the users of 2D hydraulic model outputs have recognized their benefits, these tools are being applied more frequently. Recent developments in hydraulic modeling tools as well as 3D computer visualization provide engineers, scientists, and other users with a more comprehensive understanding of complex flow patterns that are commonly encountered at river crossings and in coastal environments. These tools help locate and illustrate patterns of flow, water surface elevations, depth, velocity, and shear stress. The proper use of these tools allows for a more realistic estimation of hydraulic conditions (e.g., scour); floodplain impacts (e.g., FEMA floodplain); aquatic and terrestrial habitat impacts; and climate change or extreme weather event scenarios.

Furthermore, these new technologies offer enhanced visualization tools to not only assist engineers in their understanding of hydraulic conditions, but also to help communicate those conditions to other disciplines within the project delivery process (i.e., planning, environmental, design, and construction), the public, resource agencies, and other stakeholders.

1.2 Every Day Counts: CHANGE Initiative

The Every Day Counts[1] (EDC) initiative, launched by FHWA in cooperation with American Association of State Highway and Transportation Officials (AASHTO), is a State-based model that identifies and deploys proven but underutilized innovations that improve efficiencies at the State and local levels. The purpose of the EDC is to identify new methods that save time and resources, with the goal of delivering more projects for the same amount of money. The

[1] https://www.fhwa.dot.gov/innovation/everydaycounts/about-edc.cfm

program is not just focused on economic efficiencies; it also seeks to reduce project timeframes, improve safety, and increase environmental sustainability. Throughout EDC's two-year programmatic cycles, information on new innovations is developed and disseminated broadly in order to speed up their implementation and deployment across the nation.

One of the priority areas identified in the fourth and fifth rounds of EDC programs is broadening the use of more sophisticated numerical modeling tools. The *Collaborative Hydraulics: Advancing to the Next Generation of Engineering*[2,3] (CHANGE) program focuses on advancing state-of-the-practice modeling of the complex interactions between river or coastal environments and transportation infrastructure, with the goals of improved project design and delivery. Although most hydraulic modeling to date has been performed using 1D models, the FHWA recognizes the benefits of 2D hydraulic modeling and has developed guidance and training opportunities to support its use (e.g., Two-Dimensional Hydraulic Modeling for Highways in the River Environment, HDS 7, FHWA-NHI-135095).

1.3 Overview

A wide range of 2D hydraulic modeling tools are available and are increasing with advances in technology. For these reasons, a set of 2D modeling benchmark tests were developed by the United Kingdom (UK) Joint Defra (Department for Environmental Food and Rural Affairs) Environment Agency. The results of their research are provided in Report SC120002, *Benchmarking the latest generation of 2D hydraulic modelling packages*, published in August 2013. Report SC120002 is the result of research commissioned by the Environment Agency and funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme. The Environment Agency states the following regarding the set of benchmark tests:

> The 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

This document summarizes how the United States Bureau of Reclamation's (Reclamation) two-dimensional (2D) hydraulic modeling software (SRH-2D) performed in the 2D benchmark tests. The authors of the Environment Agency Reports were contacted to determine if the data or plots developed in the report were available, such that tests conducted by SRH-2D could be directly compared with the other models tested. It was determined that the data was not available, therefore, in order to compare data, both text and figures were extracted from the Environment Agency report to allow for result comparisons. All research and analysis for

[2] https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/change.cfm
[3] https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/

Benchmarking the latest generation of 2D hydraulic flood modelling packages is available for use under the Open Government Licence, including Report SC120002. Copies of the report can be downloaded from the following website:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/290883/LIT_8570_a3d694.zip

Since the United Kingdom Environment Agency Report has been published, the US Army Corps of Engineers (USACE) has published a research document titled *Benchmarking of the HEC-RAS Two-Dimensional Hydraulic Modeling Capabilities* (USACE 2018). This research document summarizes how HEC-RAS 2D (version 5.0.4) performed in the 2D modeling benchmark tests that were developed in the UK Report (Report SC120002). The author of the USACE Research Document was contacted to determine if the data or plots developed in the report were available for public use, so that tests conducted by SRH-2D could be directly compared with HEC-RAS 2D. It was determined that the data was not available, therefore in order to compare data, the figures were extracted from the USACE report to compare results. Discussion of HEC-RAS 2D model results throughout this document are in reference to the 2018 report, referred to as RD-51.

The purpose of performing these tests with SRH-2D is to demonstrate that SRH-2D can produce similar results to the 2D models documented by the United Kingdom Environment Agency Report and the USACE Research Document. **The figures in this report containing results of the SRH-2D analyses are depicted in SI units, instead of US customary units, so that understandable comparisons can be made with the results figures extracted from the Report SC120002 and RD-51 documents, which are presented using SI units.**

To demonstrate model run times, various benchmark tests were run with varying time steps until the solutions converged to a similar result. Figures and summary tables contained throughout the report illustrate and provide the largest time step that results in a converged solution with SRH-2D.

The benchmark tests were run using SRH-2D Version 3.3 in 2021. The benchmark tests were configured and simulated by Natural Waters. Table 1-1 contains a description of the computer hardware used to run the benchmark tests. Table 1-2 contains a list and description of the benchmark tests ran using SRH-2D.

Table 1-1 Minimum Hardware Specifications

	Minimum recommended hardware specifications	Hardware specifications used to perform tests
Make	Windows based or compatible PC	Dell
Model	No restrictions	Precision 3431
Type	No restrictions	Tower Workstation
Processor	No restrictions	Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
CPU Cores	One required, but four or more recommended	8
RAM	2 GB	32 GB
Operating System	Windows 7	Windows 10 Pro
CPU Processing	32 bit or 64 bit	64 bit
Graphics Card	No restrictions	NVIDIA Quadro P1000

Table 1-2 Summary of United Kingdom Environment Agency Benchmark 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 dam break scenario	Yes
6B	Full scale dam break scenario	Yes
7	River and floodplain linking	No; SRH-2D does not currently have the option to perform modeling with a coupled 1D-2D model
8A	Rainfall and point source surface flow in urban areas	No; SRH-2D does not currently have the option to model a uniformly distributed rainfall hyetograph over a model domain
8B	Surface flow from a surcharging sewer in urban areas	No; SRH-2D does not currently have the option to model a 1D surcharging pipe

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2 Benchmark Test 1: Flooding a Disconnected Water Body

2.1 Objective

The objective of Benchmark Test 1 is to assess basic model 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 2-1. The modeled domain is rectangle in shape, measuring 700 meters by 100 meters (2,296.6 feet by 328.1 feet). A varying water level (Figure 2-2) is applied as a boundary condition along the entire length of the left-hand side of the rectangle, causing the water to rise to a level of 10.35 meters (34 feet). This elevation is maintained long enough for the water to fill the depression and become horizontal over the entire domain. It is then lowered back to its initial state, causing the water level in the pond to be at 10.25 meters (33.6 feet), the same elevation as the sill.

2.3 Boundary and Initial Conditions

- Varying water level with time is found along the dashed red line in Figure 2-1 (provided as part of the test input dataset).
- All other boundaries closed.
- Initial condition: Water elevation equals 9.7 meters (31.8 feet) and varies through time (Figure 2-2).

2.4 Parameter Values

- Manning's n equals 0.03 (uniform).
- Model grid resolution equals 10 meters (32.8 feet), or 700 nodes in modeled area.
- Time of end: Model is to be run until time T equals 20 hours.

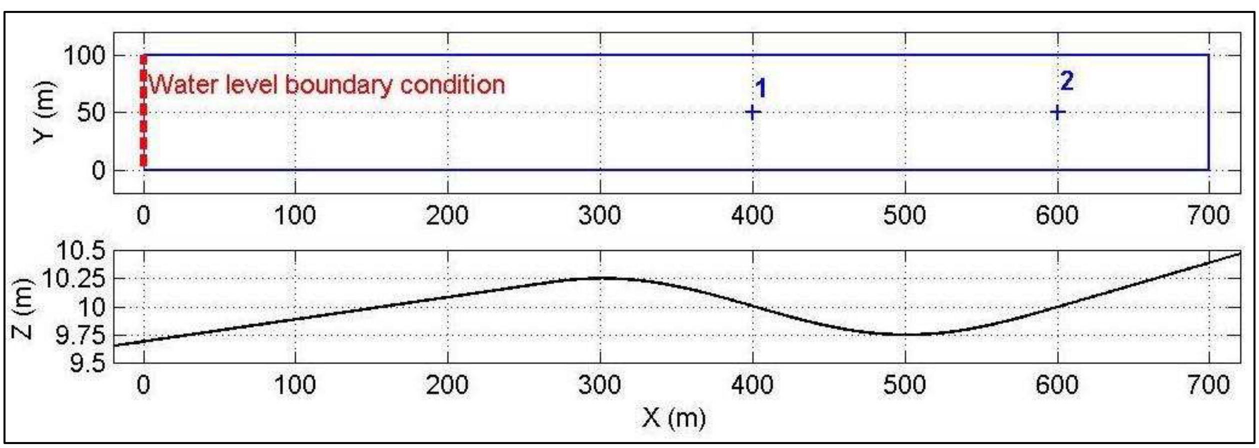

Figure 2-1 Plan (top) and profile (bottom) view of DEM (digital elevation model) used in Benchmark Test 1.

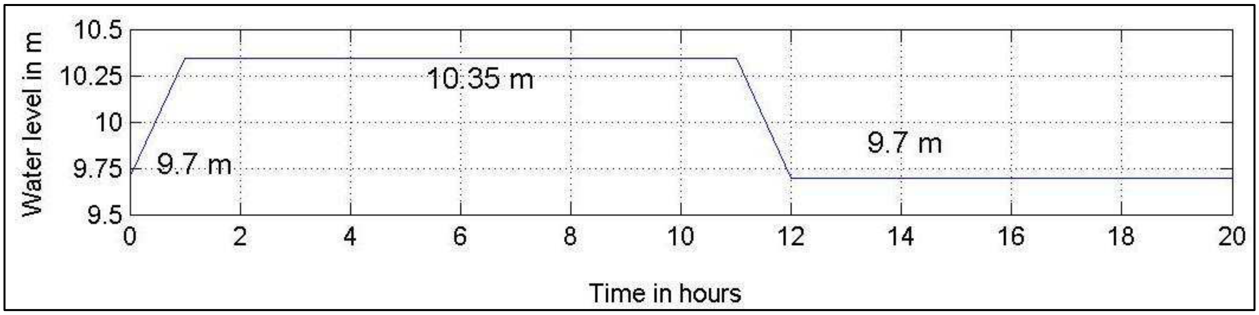

Figure 2-2 Water level hydrograph used as boundary condition.

2.5 Results

The results for Benchmark Test 1 were output at points 1 and 2 (Figure 2-1). SRH-2D water level versus time results, at a 60 second output frequency, are displayed in Figure 2-3 and Figure 2-6 for these locations. Table 2-1 provides information related to the modeling computer, grid resolution, number elements, computational timestep and total computational time. Table 2-2 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included.

SRH-2D performed well compared to the other 2D models from the original Benchmarking Study (Figure 2-5 and Figure 2-8). The results are also similar to the output from the HEC-RAS 2D RD-51 report (Figure 2-4 and Figure 2-7). Note the computational mesh in the SRH-2D model can start with dry elements. Because of this, the SRH-2D results (Figure 2-3 and Figure 2-6) differ from some of the other model results at the beginning of the test (Figure 2-4, Figure 2-5, Figure 2-7, Figure 2-8).

The rate of water level rise in the pond generally matches that of the other models. Consistent with the other models, the water level difference between test point 1 and 2 is negligible after 2 hours of simulation time. The final water surface elevation at both points of 10.25 meters (33.6 feet) is consistent with the results of the other models.

Table 2-1 Benchmark Test 1 Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	10 meters (32.8 feet); 700 elements
Computational time increment used	60s
Total computational time	10.7s

Table 2-2 Benchmark Test 1 Model Parameters Adapted from Table 4.2 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time
ANUGA	1.1beta_7501	No	714 Elements	Adaptive	205s
Ceasg	1.12	Yes - GPU	10m	0.5s	1s
Flowroute-i™	3.2.0	Yes - 4 CPUs	10m	Adaptive	5s
HEC-RAS 2D	5.0.4	Yes	10m	Adaptive	3s
InfoWorks ICM	2.5.2	Yes - GPU	714 Elements	60s	9s
ISIS 2D	3.6 (ADI)	Partial	10m	10s	1.7s
ISIS 2D GPU	1.17	Yes	10m	Adaptive	22s
ISIS Fast Dynamic	3.6	Partial	10m	2.5s	13.8s
JFLOW+	2	Yes - GPU	10m	Adaptive Average 2.12s	28s
LISFLOOD-FP	5.5.2	Yes	10m	Adaptive	1.8s
MIKE FLOOD	2012.00	Yes - 8 CPU Cores	10m	20s	1.9s
RFSM EDA	1.2	No	18 Elements	Adaptive (7-9s)	1.9s
SOBEK	2.13	No	10m	15s	17s
SRH-2D	3.3	No	10m	60s	10.7s
TUFLOW	2012-05-AA Single Precision	No	10m	Adaptive (15-60s)	2.1s
TUFLOW GPU	2012-05-AA	Yes - 448 GPU Cores	10m	Adaptive (1.7-2.1s)	15s
TUFLOW FV	2012.000b First Order and Second Order	12 CPU Cores	10m	Adaptive (~1.9s)	4.4s (6.7s)
UIM	2009.12	OMP	10m	0.1s	349s
XPSTORM	2011 2010-10-AB-iDP-w32	No	10m	5s	7.8s

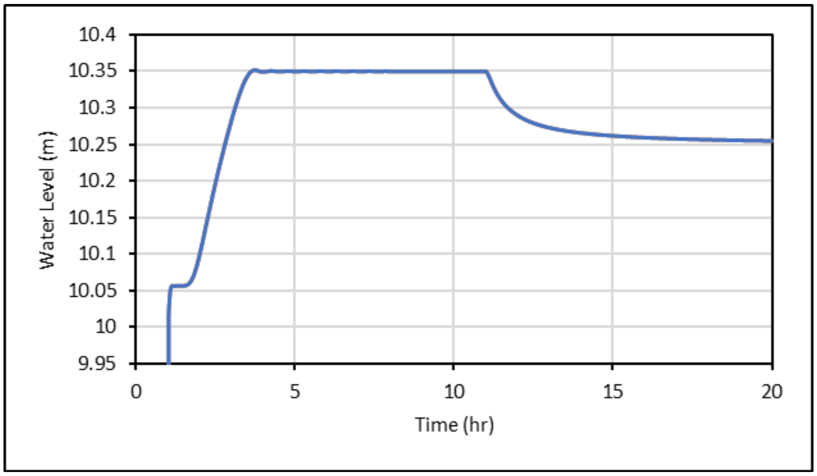

Figure 2-3 Test Point 1 – Water Level versus Time from SRH-2D

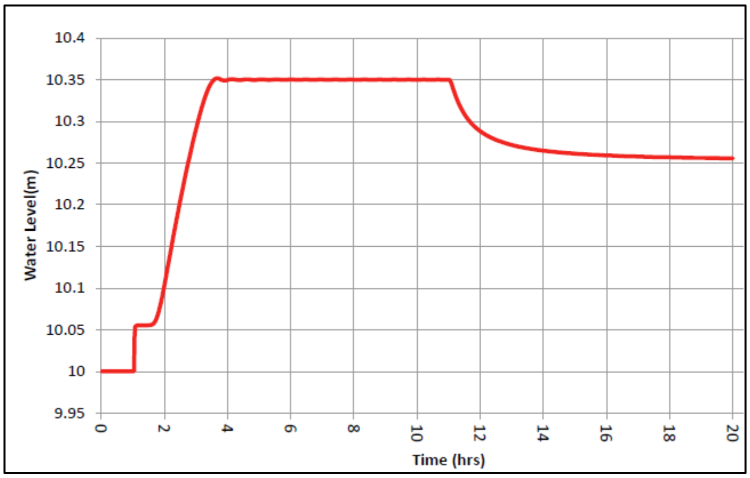

Figure 2-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

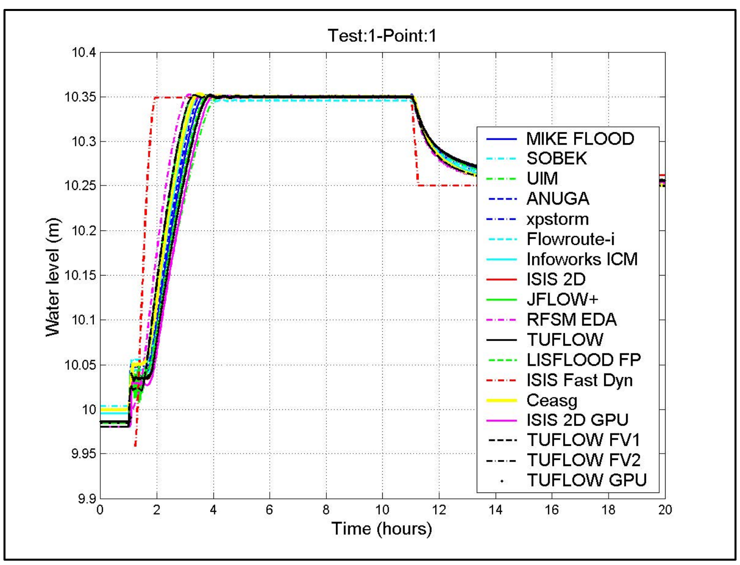

Figure 2-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

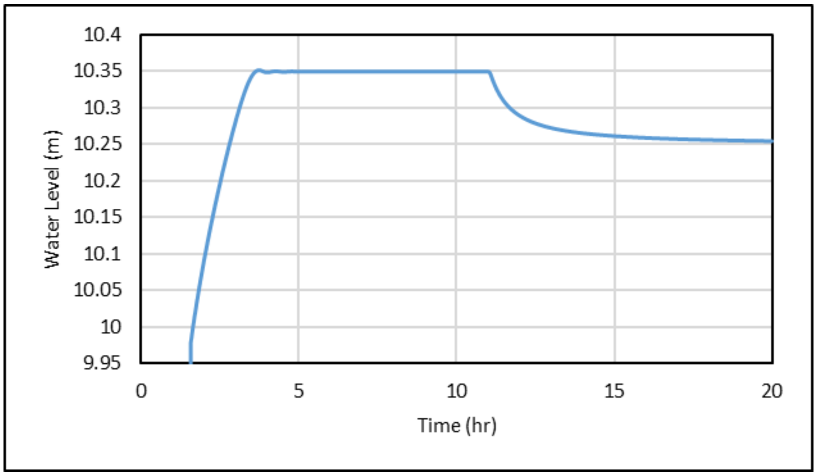

Figure 2-6 Test Point 2 – Water Level versus Time from SRH-2D

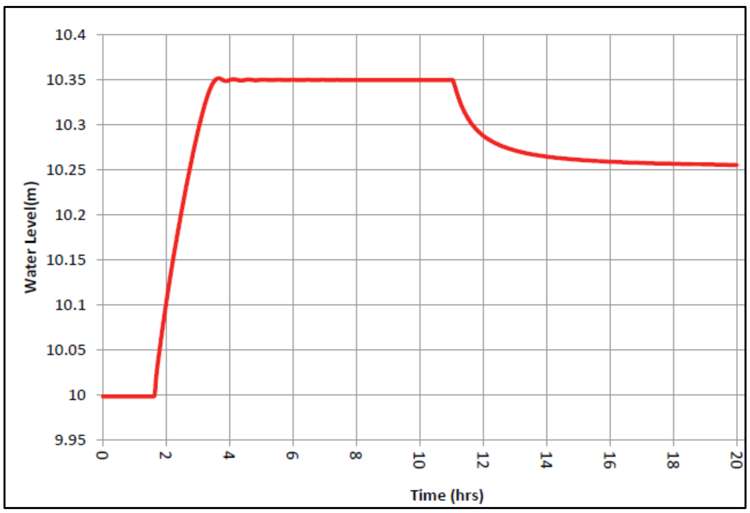

Figure 2-7 Test Point 2 –Water Level versus Time from RD-51 (2018)

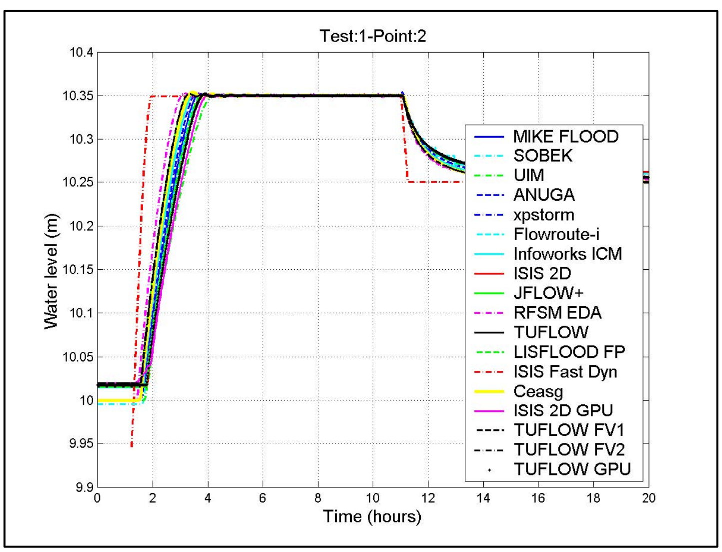

Figure 2-8 Test Point 2 – Water Level versus Time from Report SC120002 (2013)

Additional testing was performed with SRH-2D on Benchmark Test 1 to evaluate how varying the computational time increment impacts the computed results and total computational time. Table 2-3 depicts the computational time increments modeled as well as the total computational time for each model run. The computational timestep was varied from 2 seconds up to 60 seconds. Instructions for Benchmark Test 1 indicated that the results should be output at a 60 second frequency. Therefore, the computational timestep was not increased beyond this limiting time interval.

The sensitivity analysis in SRH-2D indicated that the computational time increment did not have a significant impact on the results of the hydraulic model for the various timesteps modeled. However, total computational time was reduced by raising the computational time increment. The water surface elevations were nearly identical and primarily only differed in the thousandths decimal place (Table 2-3).

Table 2-3 Benchmark Test 1 Computational Time Increment Analysis Summary

Computational Time Increment (seconds)	Computational Time (seconds)	Point 1 Water Surface Elevation (m) at End of Simulation	Point 2 Water Surface Elevation (m) at End of Simulation
2	49.3	10.254	10.254
5	25.5	10.254	10.254
10	18.8	10.254	10.254
20	14.4	10.255	10.255
30	13.0	10.255	10.255
40	11.7	10.255	10.255
50	11.1	10.255	10.255
60	10.7	10.255	10.255

In conclusion, SRH-2D performed well compared to the other 2D models from the original Benchmarking Study, as well as HEC-RAS 2D (Figure 2-3 to Figure 2-8). SRH-2D was able to correctly predict the final state of inundation in a case involving the filling of a depression and subsequent dewatering. This resulted in a horizontal water surface in the depression, at the elevation of the lowest point separating the depression from the origin of the flooding.

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3 Benchmark Test 2: Filling of Floodplain Depressions

3.1 Objective

Benchmark Test 2 has been designed to evaluate the capability of a 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 3-1, is a 2,000-meter by 2,000-meter (6,561.7 feet by 6,561.7 feet) square and consists of a 4 by 4 matrix of approximately 0.5 meter (1.6 feet) deep depressions with smooth topographic transitions. The digital elevation model (DEM) was obtained by multiplying sinusoids in the north to south and west to east directions, and the depressions are all identical in shape. An underlying average slope of 1:1,500 exists in the north to south direction, and of 1:3,000 in the west to east direction, with an approximately 2 meter (6.6 feet) drop in elevation along the northwest to southeast diagonal. The inflow boundary condition is applied along a 100-meter (328.1 feet) line running south from the northwest corner of the model domain (as depicted in Figure 3-1). A flood hydrograph with a peak flow of 20 cubic meters per second (21,134 cubic feet per second) is used (Figure 3-2). The model is run for 48 hours to permit the inundation to settle.

3.3 Boundary and Initial Conditions

- Inflow (Figure 3-2) along the red line in Figure 3-1 (location and tables provided as part of dataset).
- All other boundaries closed.
- Initial condition: Dry bed.

3.4 Parameter Values

- Manning's n equals 0.03 (uniform).
- Model grid resolution equals 20 meters (65.6 feet), or 10,000 nodes in modeled area.
- Time of end: Model is to be run until time T equals 48 hours.

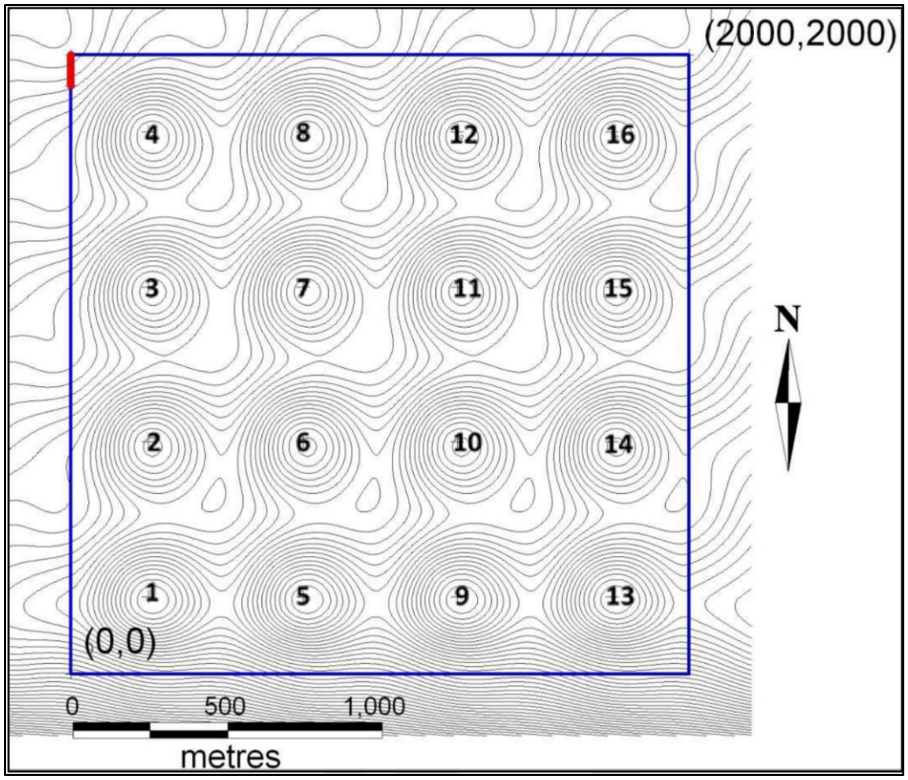

Figure 3-1 Map of the DEM showing the location of the upstream boundary condition (red line), ground elevation contour lines every 0.05 meters, and output point locations (numbers).

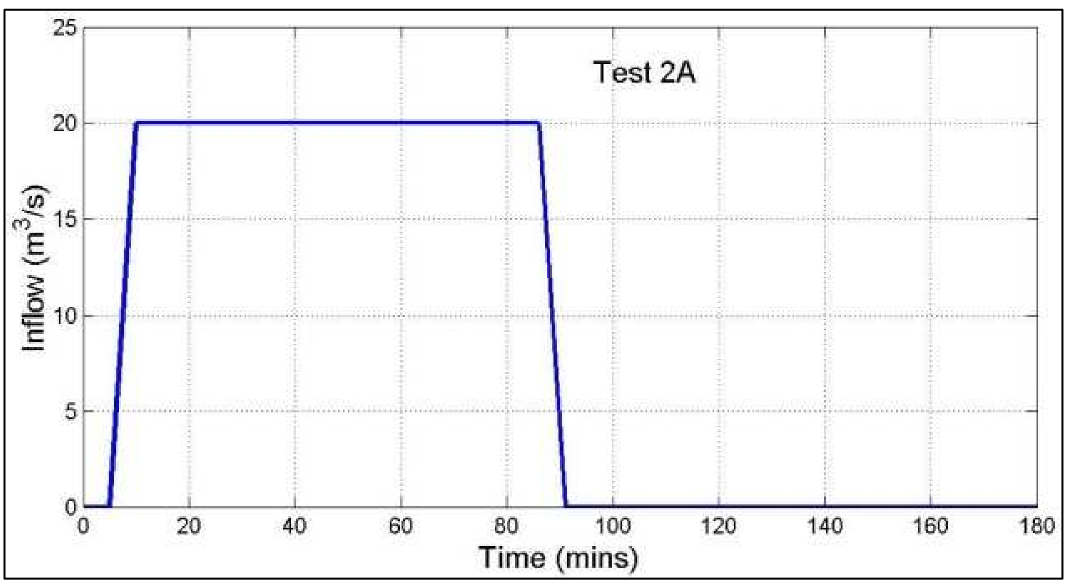

Figure 3-2 Inflow hydrograph used as upstream boundary condition.

3.5 Results

The results for Benchmark Test 2 were output at the center of each inundated depression within the model domain, represented by points 1 through 16 in Figure 3-1. Water level versus time, at a 300 second output frequency and 2 second timestep, is displayed for the SRH-2D results starting with Figure 3-3, and every third figure thereafter. Note that points 9, 13, 14, 15, and 16 all remained dry throughout the simulation time, therefore no figures are provided at these points. Table 3-1 provides information related to the modeling computer, grid resolution, number elements, computational timestep, and total computational time. Table 3-2 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included.

The SRH-2D results at the output point locations were comparable in terms of timing and magnitude to the other 2D models from the original Benchmarking Study (every third figure in this section starting at Figure 3-5). The results are also similar to the output from the HEC-RAS 2D model (every third figure in this section starting at Figure 3-4).

The results from SRH-2D, at the output point locations, are consistent with the UK Benchmark test models that solve the shallow water equations, as discussed in Report SC120002 (2013). After the initial inundation of the model domain from the inflow hydrograph, water first settles into the depressions near the inflow boundary condition. When the water level rises higher than the depression's surrounding sill elevations it flows over before eventually dropping to the elevation of the lowest adjacent sill. This behavior was observed at the depression containing points 2, 3, 4, 6, 7, and 8. The results indicate that the depressions containing points 1, 5, 10, 11, and 12 did not fill up enough to spill into the adjacent depressions.

The timing of the flooding of the depressions from SRH-2D is similar to those documented in Report SC120002 (2013) and RD-51 (2018). The depressions that received little inflow throughout the simulation time (see results for points 5 and 10), however, exhibit slightly larger differences in the timing.

The final water surface levels calculated by SRH-2D at the output point locations are similar (within several centimeters) to those determined by the other 2D models. A slightly larger range of final water surface levels and timing occurred at the depressions where limited inflow occurred during the simulation (points 5 and 10). Upon further examination of the variations in final water surface elevations and water volumes, a sensitivity analysis on timestep was assessed. For all points, except points 5 and 10, a ten second timestep provided a converged solution, however for points 5 and 10 a two second timestep was required. For these reasons, two different run times and final water volumes are reported below and in Table 3-2.

The final volume of water on the mesh at the end of the simulation from SRH-2D was 96,915 cubic meters (3,422,520.9 cubic feet) for the ten second timestep and 96,963 cubic meters (3,424,216.0 cubic feet) for the two-second timestep. Similar to some of the other model results, SRH-2D had a small fraction (< 1%) of the total inflow volume lost (see table 3-2).

In conclusion, SRH-2D performed well compared to the other 2D models from the original Benchmarking Study, as well as HEC-RAS 2D (Figure 3-3 to Figure 3-35). After modification to the default wet/dry threshold, the final volume of water on the mesh at the end of the simulations was less than other models (< 1%), however SRH-2D was still able to provide similar water level results to the other models.

Table 3-1 Benchmark Test 2 Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	20 meters (65.6 feet); 10,000 elements
Computational time increment used	10s (2s)
Total computational time	231s (983.5s)

Table 3-2 Benchmark Test 2 Model Parameters Adapted from Table 4.3 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time	Final Volume (m^3)
ANUGA	1.1beta_7501	No	10,088 elements	Adaptive	1130s	97223.15
Ceasg	1.12	Yes - GPU	20m	2.5s	15s	97200
Flowroute-i™	3.2.0	Yes - 4 CPUs	20m	Adaptive	6s	95584
HEC-RAS 2D, Full EQ (Diff Wav)	5.0.4	Yes	20m	Adaptive	30s (17s)	NA
InfoWorks ICM	2.5.2	Yes - GPU	9,997	60s	11s	97200
ISIS 2D	3.6 (ADI)	Partial	20m	15s	22s	96275.61
ISIS 2D GPU	1.17	Yes	20m	Adaptive	22s	97204
ISIS Fast Dynamic	3.6		20m	5s	2s	97200.0
JFLOW+	2	Yes - GPU	20m	Adaptive Average 5.17s	10s	97200
LISFLOOD-FP	5.5.2	Yes	20m	Adaptive	7.2s	97162
MIKE FLOOD	2012	Yes - 8 CPUs	20m	25s	9.6s	97252
RFSM (Direct)	3.5.4	No	16 Elements	N/A	1s	97200
RFSM - EDA	1.2	No	16 Elements	Addaptive Typically 60s	11s	97200
SOBEK	2.13	No	20m	15s	100s	97200
SRH-2D	3.3	No	20m	10s (2s)	231s (983.5s)	96,915 (96,963)
TUFLOW	2012-05-AA Single Precision	No	20m	Adaptive (5-120s)	7.3s	97195
TUFLOW GPU	2012-05-AA	Yes - 448 GPU Cores	20m	Adaptive (4-5s)	16s	97200
TUFLOW FV	2012.000b First Order (and Second Order)	Yes - 12 CPU Cores	20m	Adaptive (~5s)	26s (41s)	97189
UIM	2009.12	OMP	20m	1s	712s	97200
XPSTORM	2011; 2010-10-AB-iDP-w32	No	20m	10s	12.1s	97393

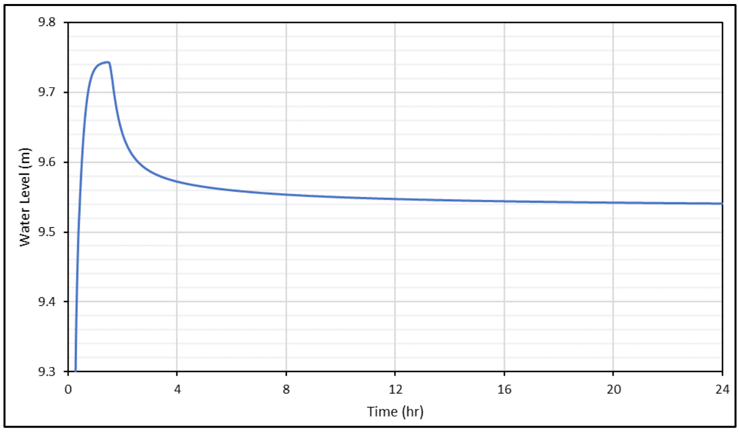

Figure 3-3 Test Point 4 – Water Level versus Time from SRH-2D

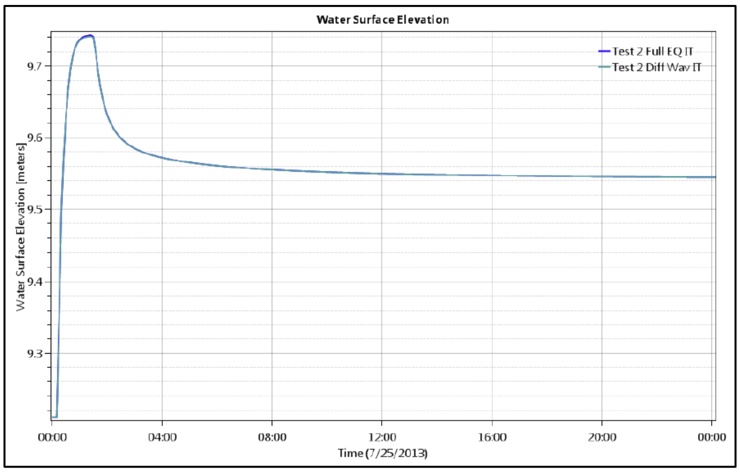

Figure 3-4 Test Point 4 – Water Level versus Time from RD-51 (2018)

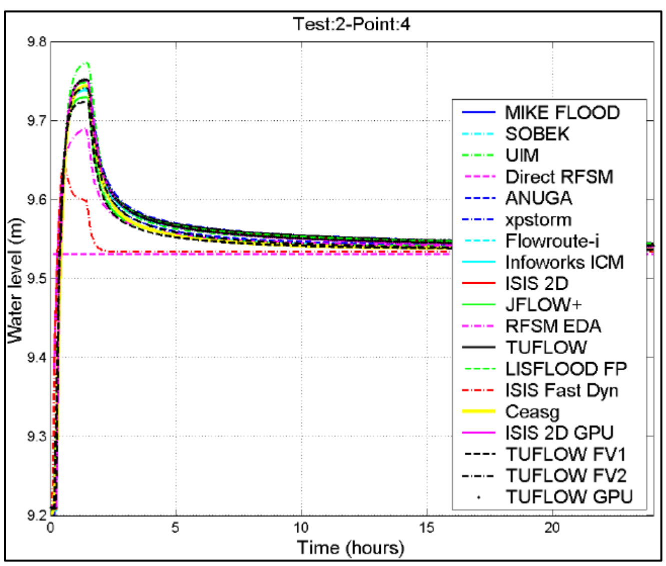

Figure 3-5 Test Point 4 – Water Level versus Time from Report SC120002 (2013)

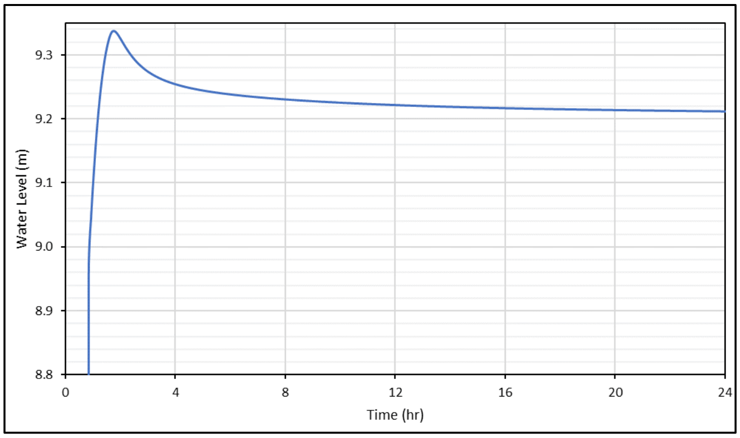

Figure 3-6 Test Point 3 – Water Level versus Time from SRH-2D

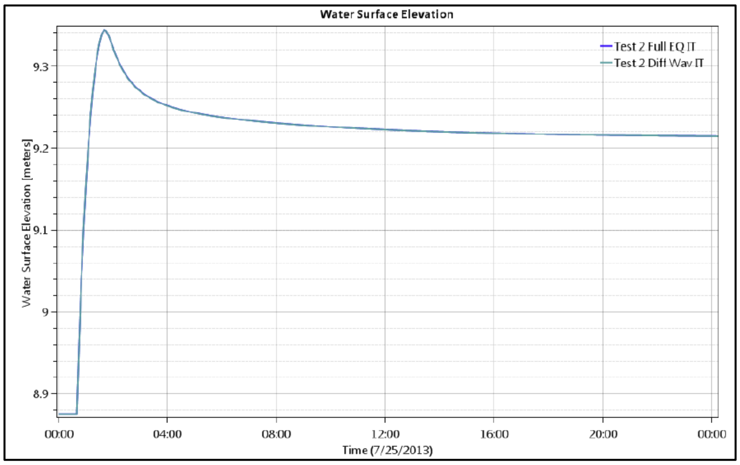

Figure 3-7 Test Point 3 – Water Level versus Time from RD-51 (2018)

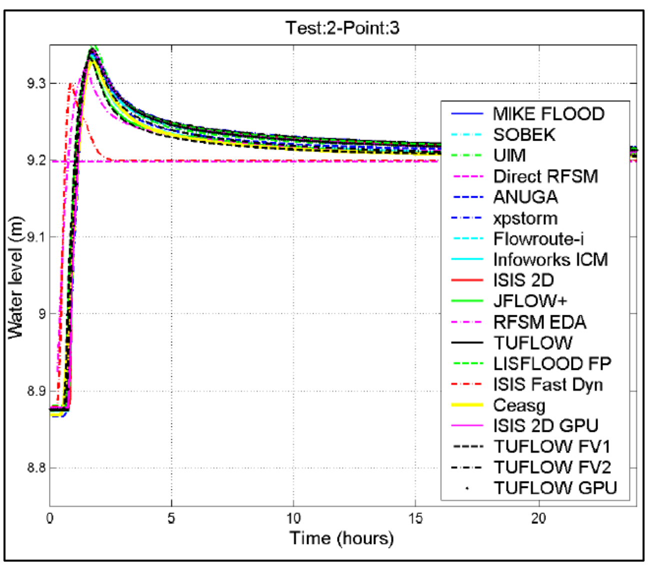

Figure 3-8 Test Point 3 – Water Level versus Time from Report SC120002 (2013)

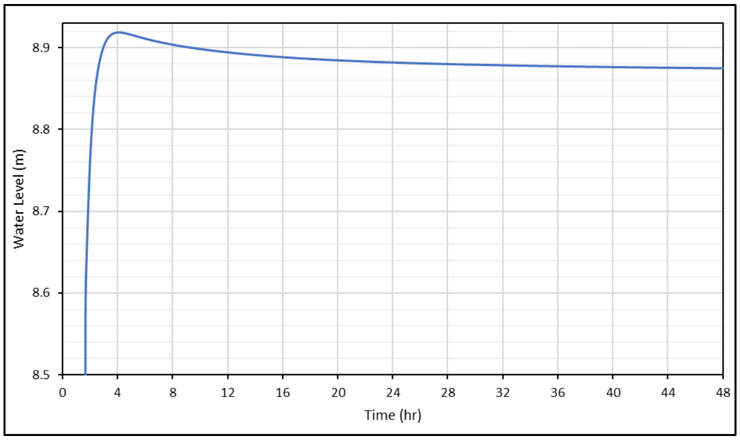

Figure 3-9 Test Point 2 – Water Level versus Time from SRH-2D

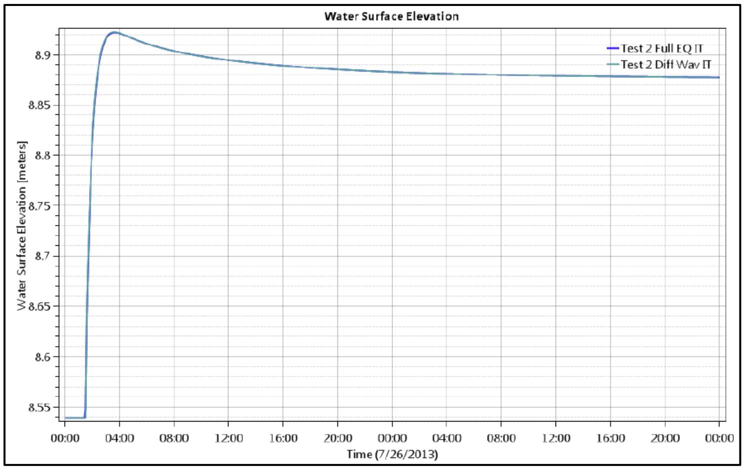

Figure 3-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

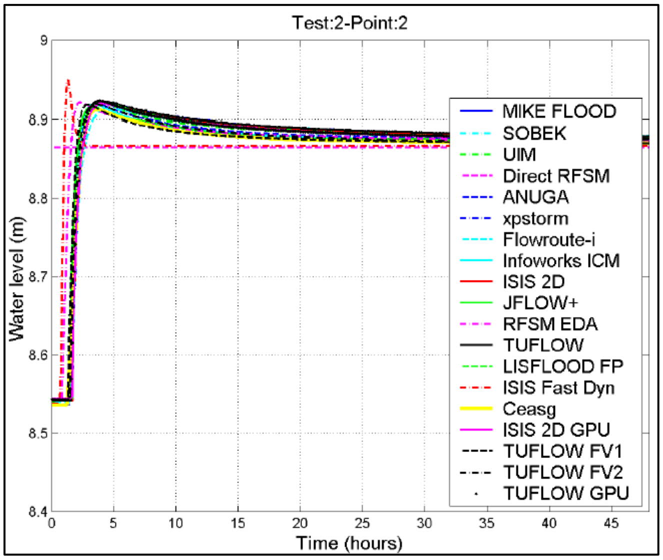

Figure 3-11 Test Point 2 – Water Level versus Time from Report SC120002 (2013)

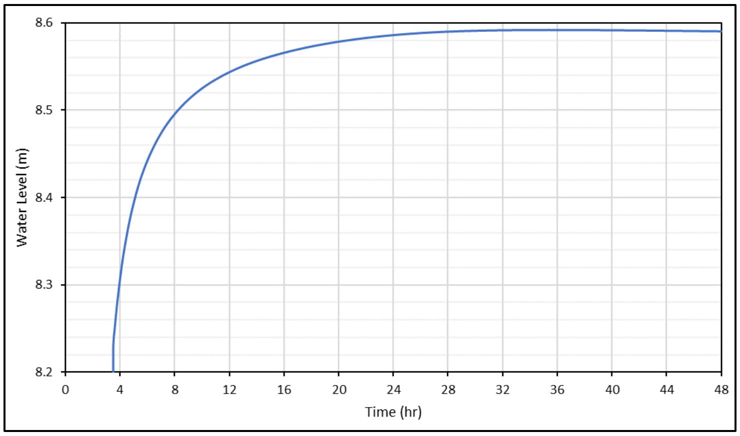

Figure 3-12 Test Point 1 – Water Level versus Time from SRH-2D

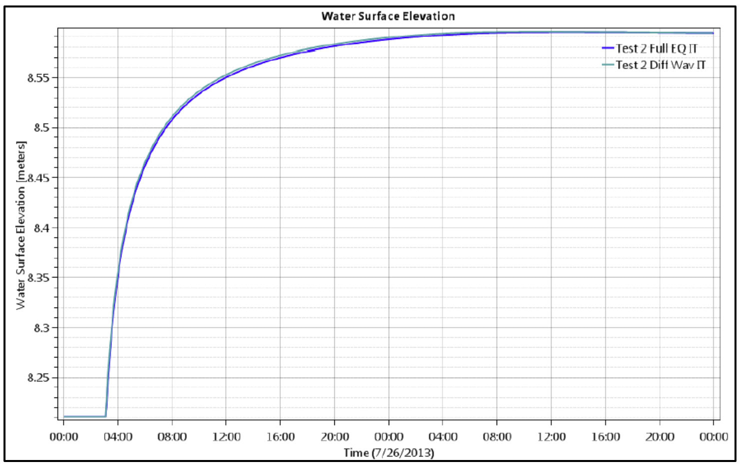

Figure 3-13 Test Point 1 – Water Level versus Time from RD-51 (2018)

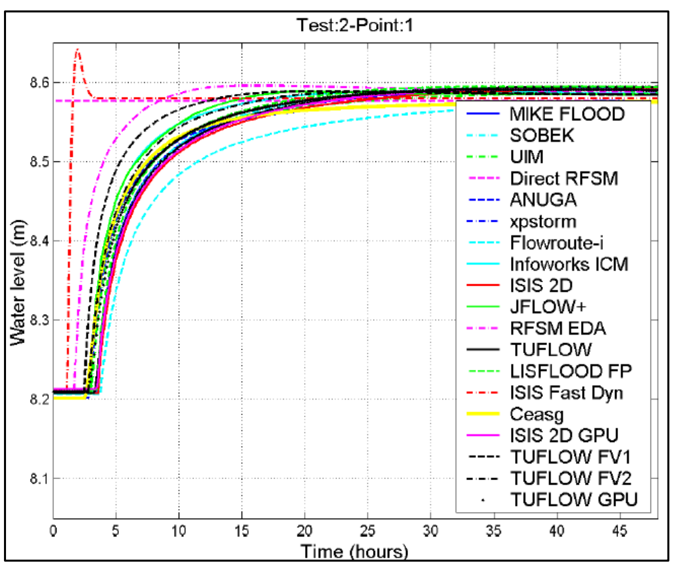

Figure 3-14 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

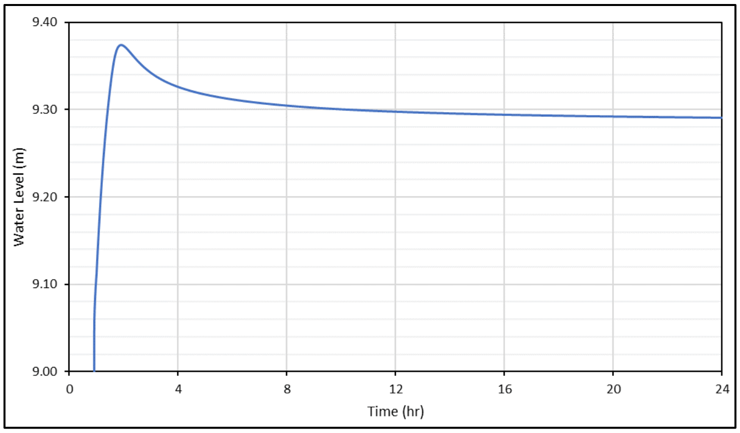

Figure 3-15 Test Point 8 – Water Level versus Time from SRH-2D

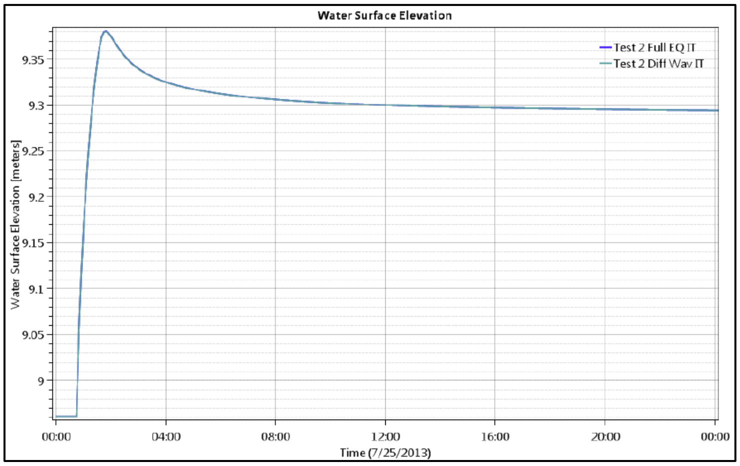

Figure 3-16 Test Point 8 – Water Level versus Time from RD-51 (2018)

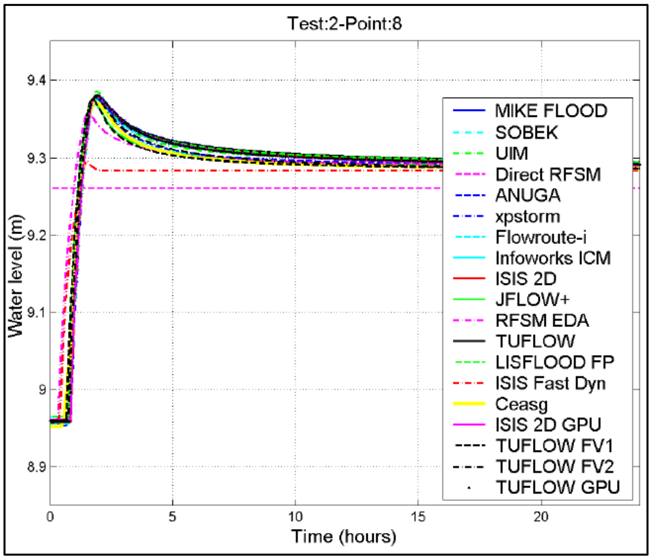

Figure 3-17 Test Point 8 – Water Level versus Time from Report SC120002 (2013)

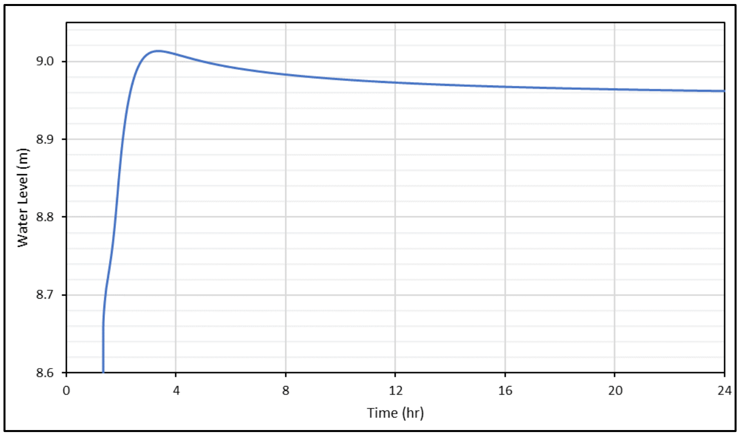

Figure 3-18 Test Point 7 – Water Level versus Time from SRH-2D

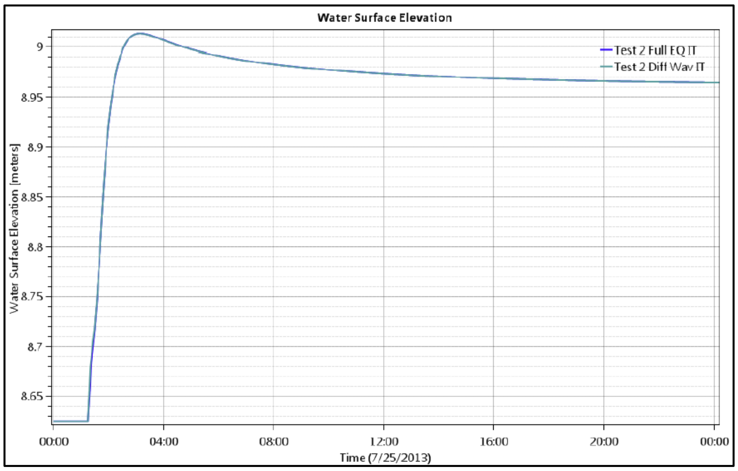

Figure 3-19 Test Point 7 – Water Level versus Time from RD-51 (2018)

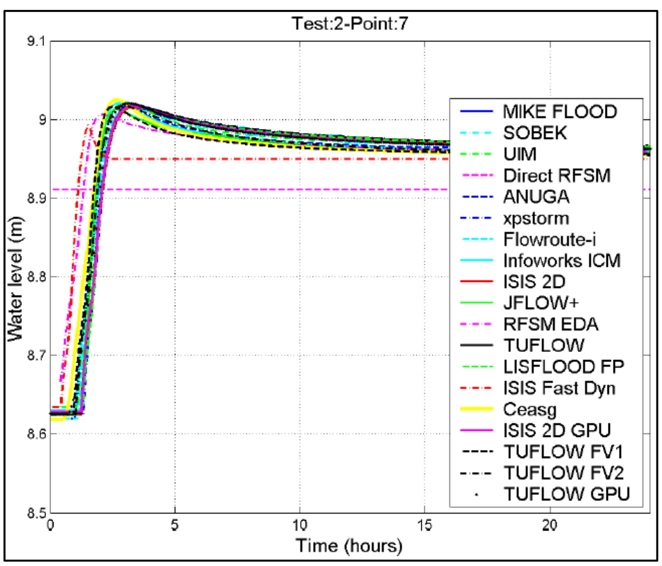

Figure 3-20 Test Point 7 – Water Level versus Time from Report SC120002 (2013)

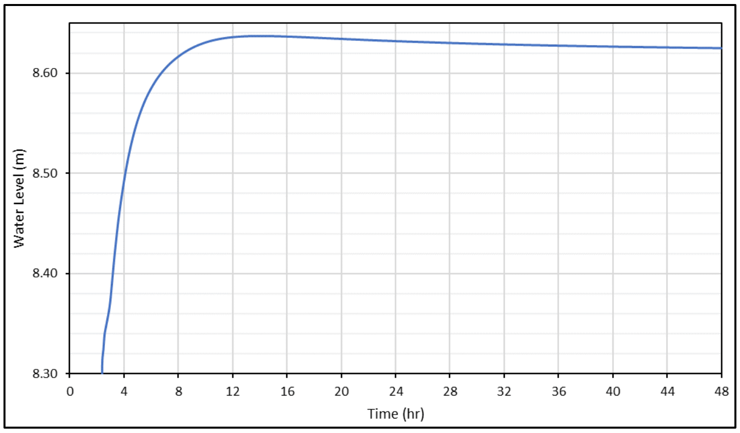

Figure 3-21 Test Point 6 – Water Level versus Time from SRH-2D

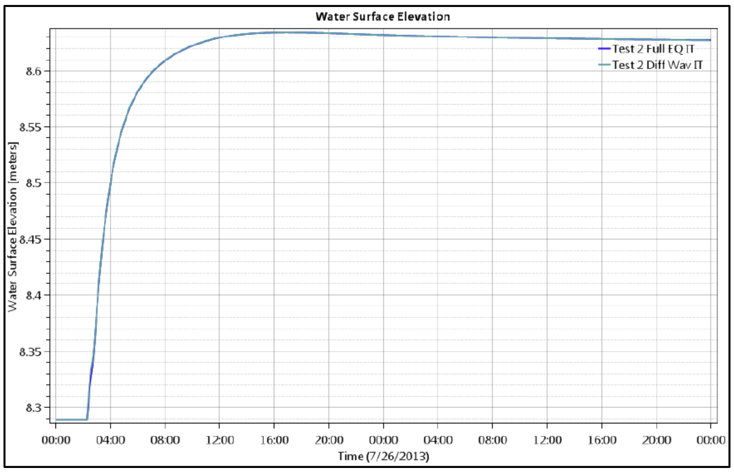

Figure 3-22 Test Point 6 – Water Level versus Time from RD-51 (2018)

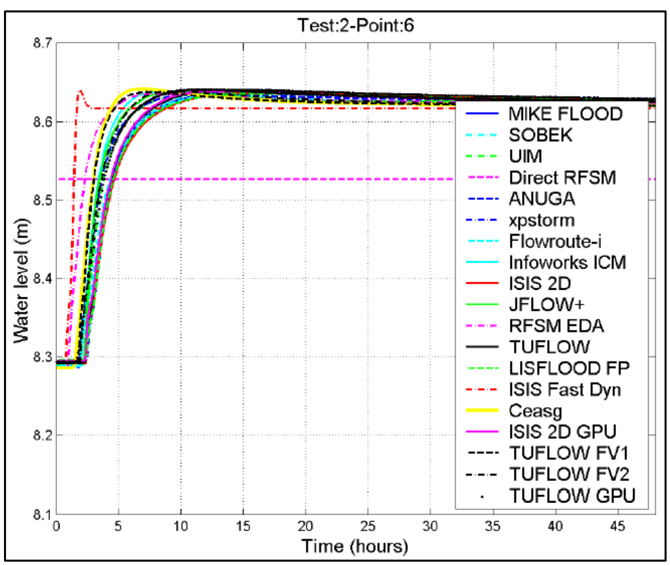

Figure 3-23 Test Point 6 – Water Level versus Time from Report SC120002 (2013)

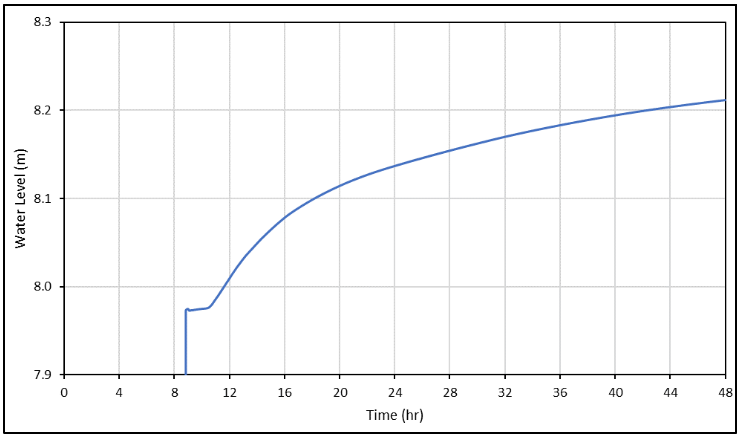

Figure 3-24 Test Point 5 – Water Level versus Time from SRH-2D

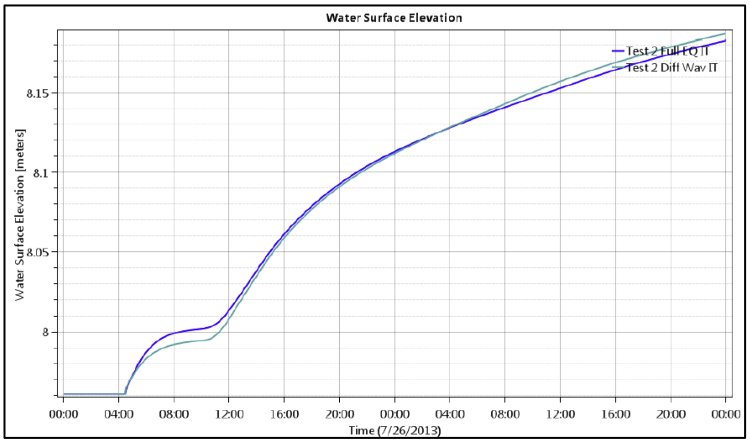

Figure 3-25 Test Point 5 – Water Level versus Time from RD-51 (2018)

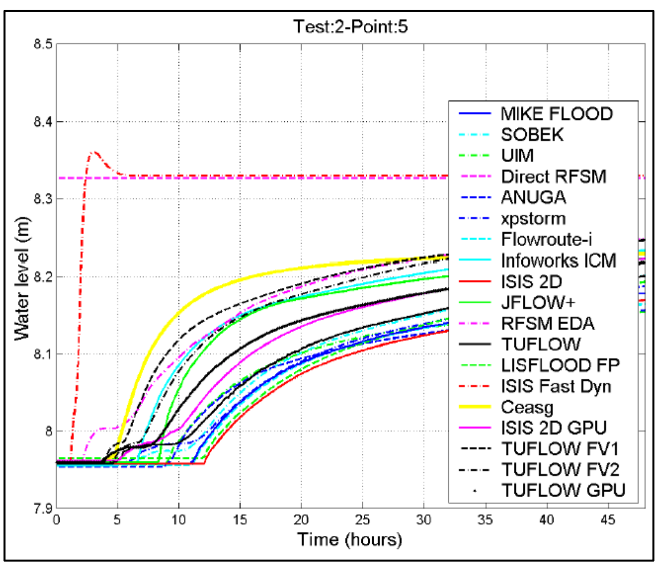

Figure 3-26 Test Point 5 – Water Level versus Time from Report SC120002 (2013)

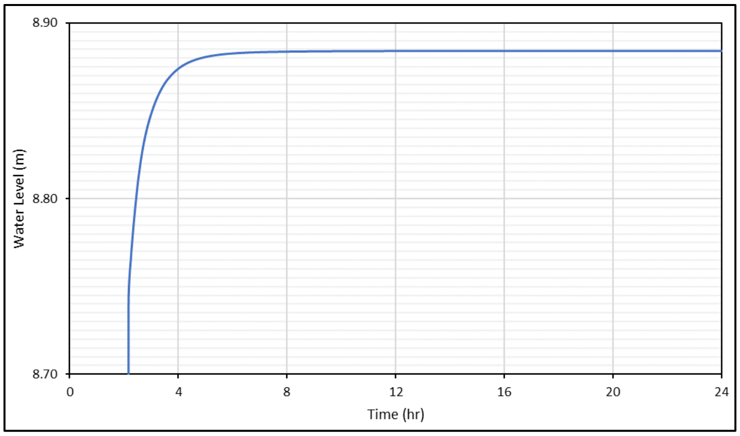

Figure 3-27 Test Point 12 – Water Level versus Time from SRH-2D

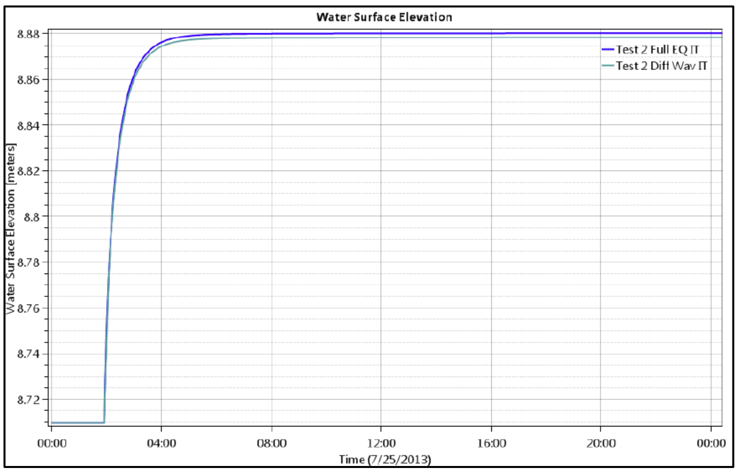

Figure 3-28 Test Point 12 – Water Level versus Time from RD-51 (2018)

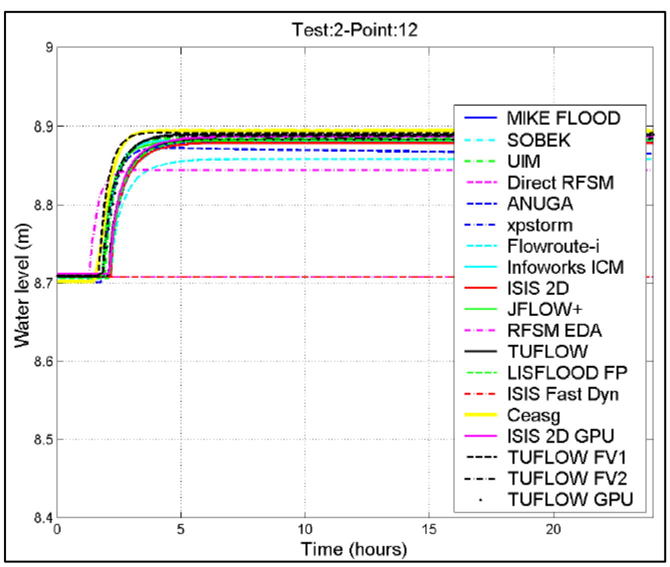

Figure 3-29 Test Point 12 – Water Level versus Time from Report SC120002 (2013)

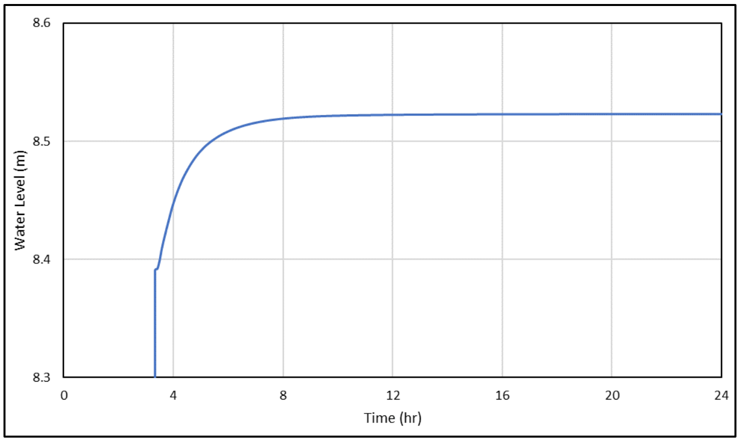

Figure 3-30 Test Point 11 – Water Level versus Time from SRH-2D

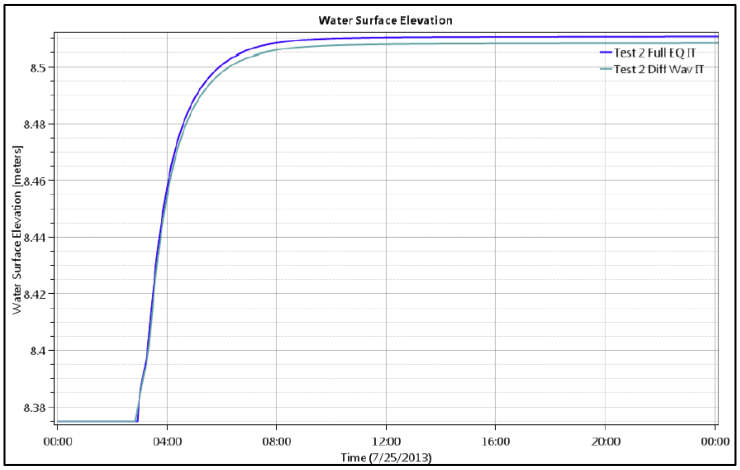

Figure 3-31 Test Point 11 – Water Level versus Time from RD-51 (2018)

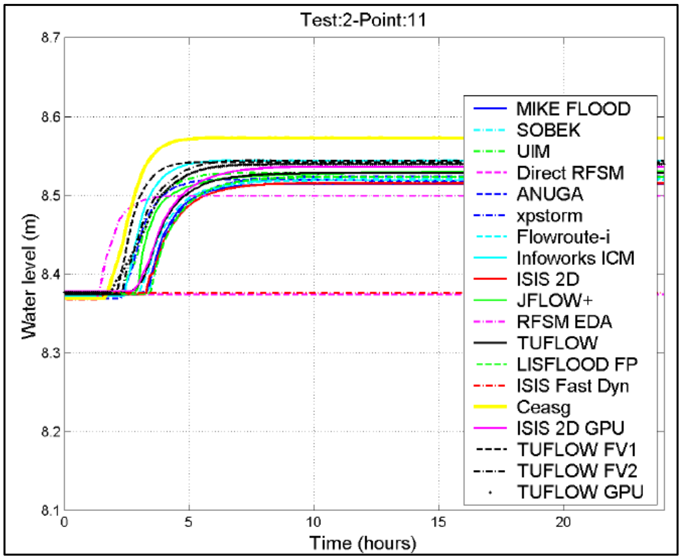

Figure 3-32 Test Point 11 – Water Level versus Time from Report SC120002 (2013)

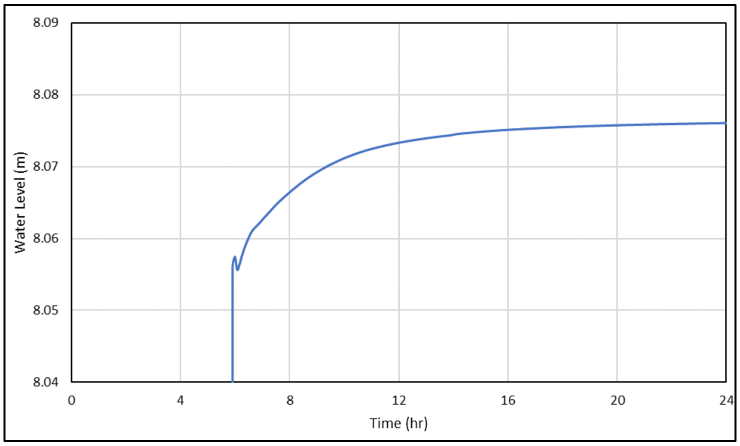

Figure 3-33 Test Point 10 – Water Level versus Time from SRH-2D

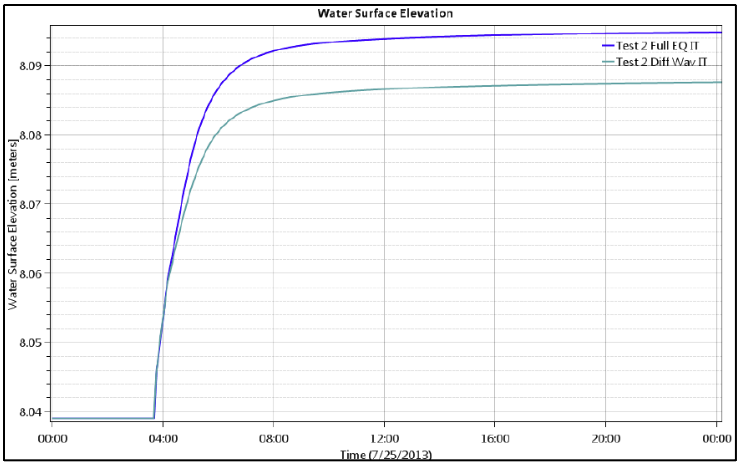

Figure 3-34 Test Point 10 – Water Level versus Time from RD-51 (2018)

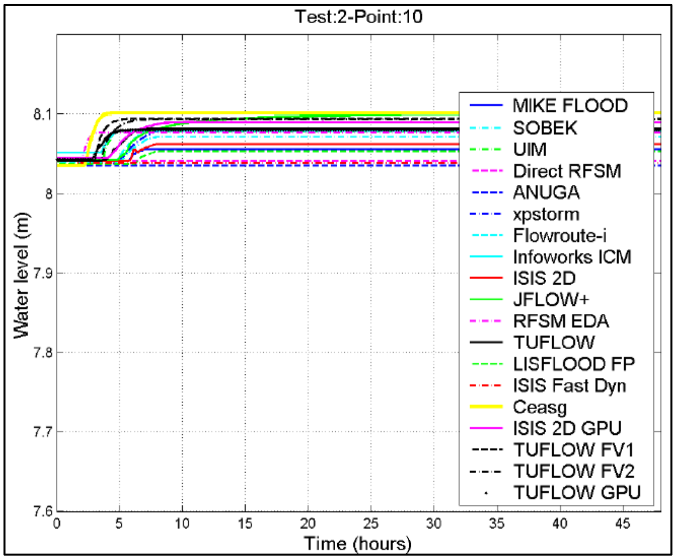

Figure 3-35 Test Point 10 – Water Level versus Time from Report SC120002 (2013)

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4 Benchmark Test 3: Momentum Conservation Over a Small Obstruction

4.1 Objective

The objective of Benchmark Test 3 is to assess the model's ability to conserve momentum over an obstruction in the topography. This capability is important when simulating sewer or pluvial flooding in urbanized floodplains. The barrier to flow in the channel is designed to differentiate the performance of models that do and do not include inertia terms. When including 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 4-1. The dimensions of the domain are 300 meters (984.3 feet) longitudinally (X) by 100 meters (328.1 feet) transversally (Y). A varying inflow discharge (see Figure 4-2) is applied as an upstream boundary condition at the left-hand side of the domain, causing a flood wave to travel down the 1:200 slope. While the total inflow volume is sufficient in filling the left-hand side depression at location X equals 150 meters (492.1 feet), some of this volume is expected to overtop the obstruction because of momentum conservation and settle in the depression on the right-hand side at location X equals 250 meters (820.2 feet). The model is run for 15 minutes to allow the water to settle.

4.3 Boundary and Initial Conditions

- Inflow (Figure 4-2) along the red line in Figure 4-1 (location and tables provided as part of dataset).
- All other boundaries closed.
- Initial condition: Dry bed.

4.4 Parameter Values

- Manning's n equals 0.01 (uniform).
- Model grid resolution equals 5 meters (16.4 feet), or 1,200 nodes in modeled area.
- Time of end: Model is to be run until time T equals 15 minutes.

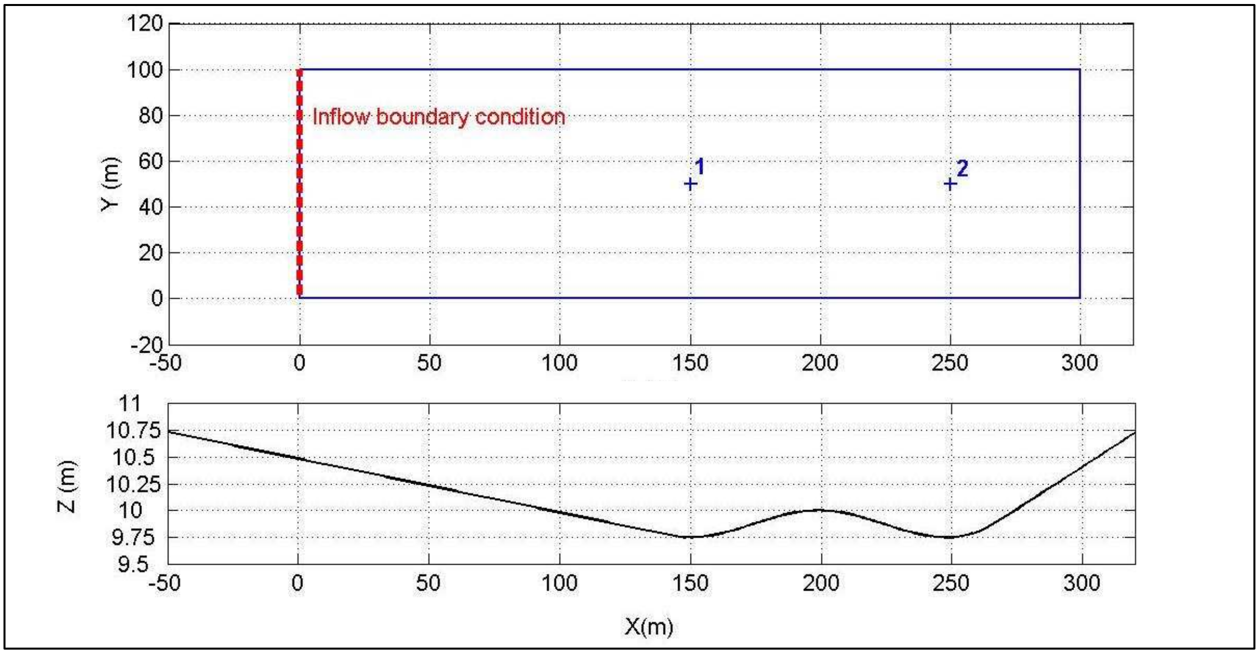

Figure 4-1 Plan (top) and profile (bottom) view of DEM used in Benchmark Test 3.

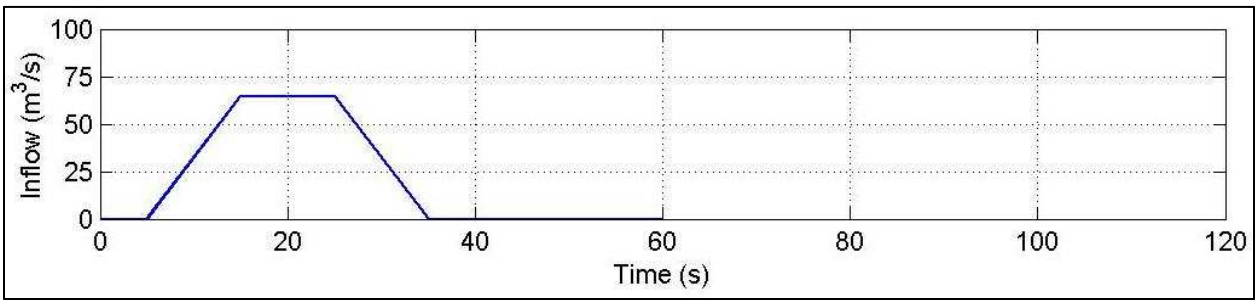

Figure 4-2 Inflow hydrograph used as upstream boundary condition.

4.5 Results

The results for Benchmark Test 3 were output at point 1 and point 2 (Figure 4-1). Water level and velocity versus time, at a 2 second output frequency and 1 second timestep, are displayed for the SRH-2D results starting with Figure 4-3. Table 4-1 provides information related to the modeling computer, grid resolution, number elements, computational timestep and total computational time.

Table 4-2 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included.

The results for this benchmark test, documented in Report SC120002 (2013), varied widely (see every third figure starting at Figure 4-5). Note that Report SC120002 does not contain a plot for velocity versus time at point 2. The results from HEC-RAS 2D (full momentum only) are presented below as well (see every third figure starting with Figure 4-4). The results from SRH-2D are similar to those identified in Report SC120002 (2013) and in RD-51 (2018).

In conclusion, and consistent with the other models that solve the shallow water equations from the original UK Benchmarking study and HEC-RAS2D, SRH-2D predicted and was successful in demonstrating the water contains sufficient momentum to flow over the obstruction between point 1 and point 2 (Figure 4-1).

Table 4-1 Benchmark Test 3 Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	5 meters (16.4 feet); 1,200 elements
Computational time increment used	1s
Total computational time	5.8s

Table 4-2 Benchmark Test 3 Model Parameters Adapted from Table 4.4 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time
ANUGA	1.1beta_7501	No	1207 elements	Adaptive, < 1s	6s
Ceasg	1.12	Yes - GPU	5m	0.5	2s
Flowroute-i™	3.2.0	Yes - 4CPUs	5m	Adaptive	<1s
HEC-RAS 2D	5.0.4	Yes	5m	1s	2s
InfoWorks ICM	2.5.2	Yes - GPU	1205 Triangles	2s	1s
ISIS 2D	3.6 (TVD)	No	5m	0.1s	3.6s
ISIS 2D GPU	1.17	Yes	5m	Adaptive	<1s
JFLOW+	2	Yes - GPU	5m	Average 1.5s	0.4s
LISFLOOD-FP	Not tested				
MIKE FLOOD	2012	Yes, 8 CPUs	5m	2s	0.7s
SOBEK	2.13	No	5m	0.1s	20s
SRH-2D	3.3	No	5 m	1s	5.8s
TUFLOW	2012-05-AA Single Precision	No	5m	2s	1.8s
TUFLOW GPU	2012-05-AA	Yes - 448 GPU Cores	5m	Adaptive (0.2-1.5s)	2s
TUFLOW FV	2012.000b First Order (and Second Order	Yes 12 CPU Cores	5m	Adaptive (~0.2s)	1.3s (1.5s)
XPSTORM	2011 2010-10-AB-iDP-w32	No	5m	2s	4.64s

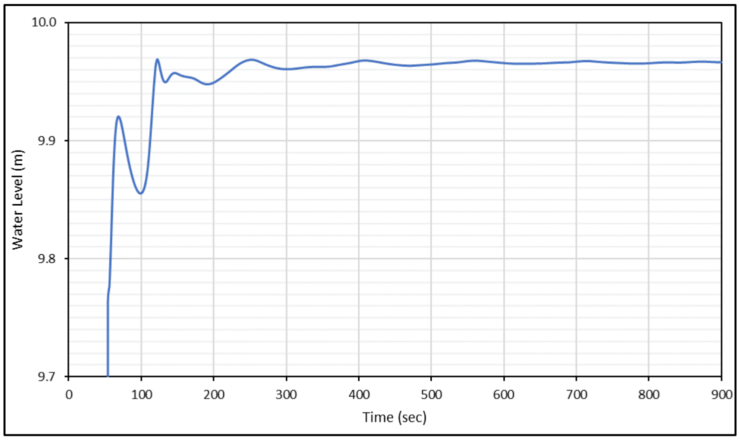

Figure 4-3 Test Point 1 – Water Level versus Time from SRH-2D

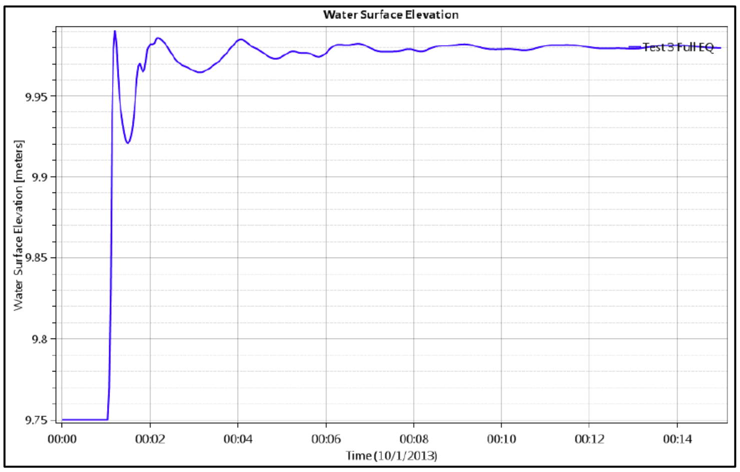

Figure 4-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

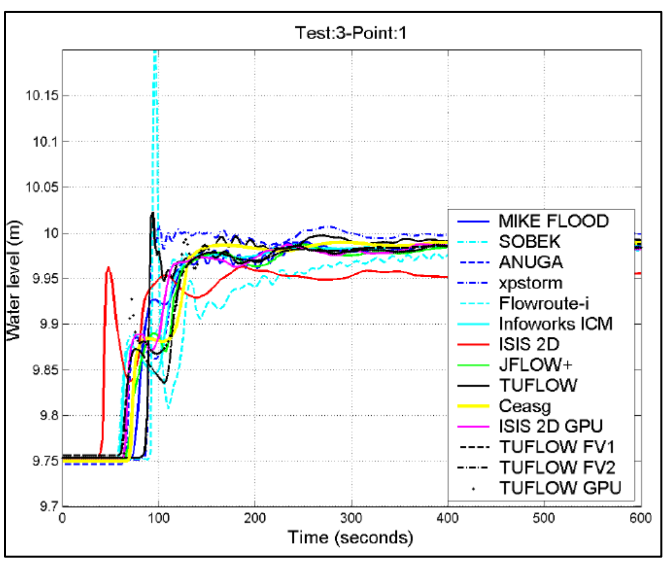

Figure 4-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

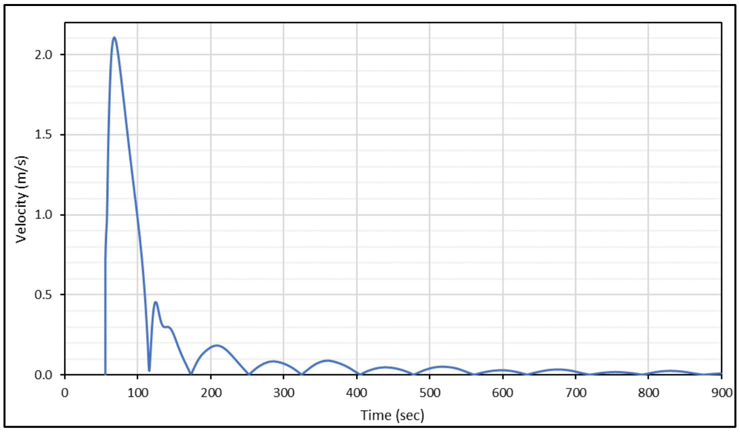

Figure 4-6 Test Point 1 – Velocity versus Time from SRH-2D

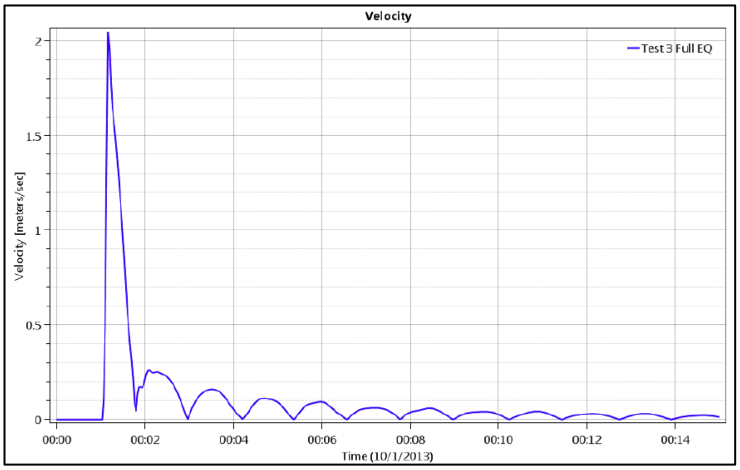

Figure 4-7 Test Point 1 – Velocity versus Time from RD-51 (2018)

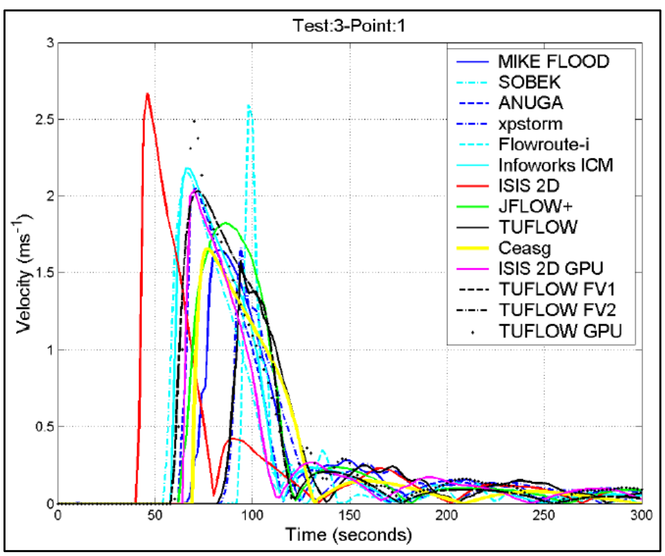

Figure 4-8 Test Point 1 – Velocity versus Time from Report SC120002 (2013)

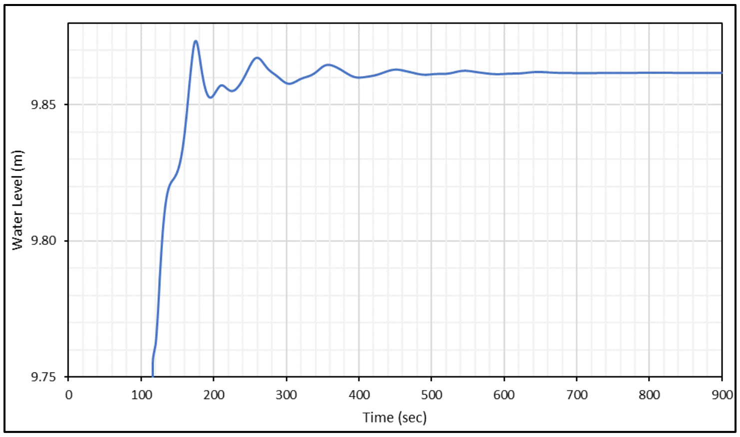

Figure 4-9 Test Point 2 – Water Level versus Time from SRH-2D

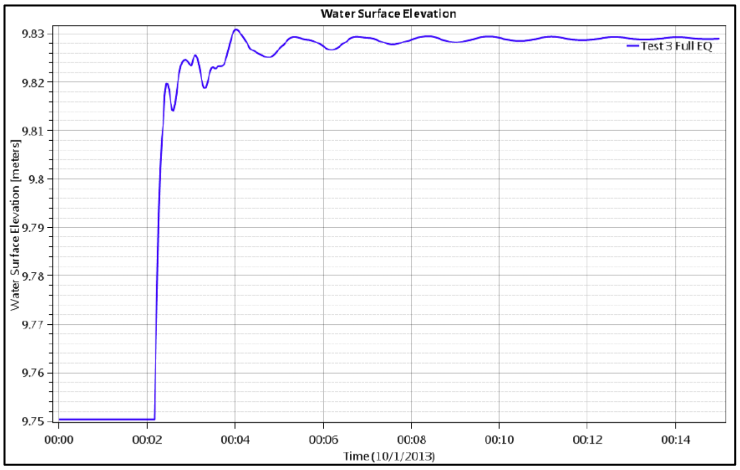

Figure 4-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

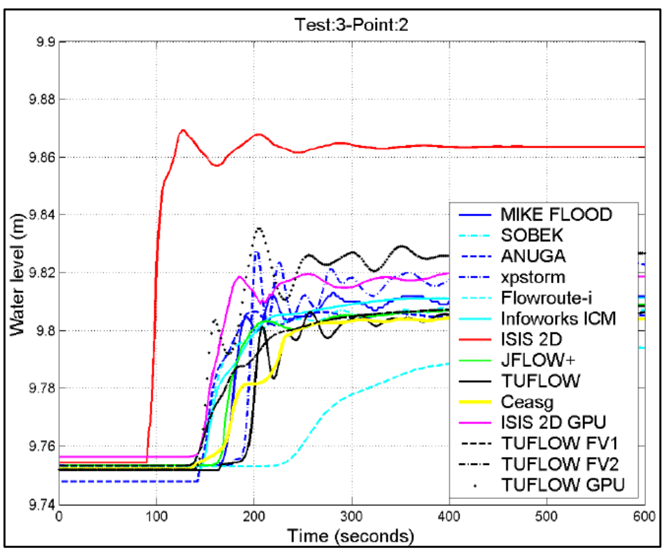

Figure 4-11 Test Point 2 – Water Level versus Time from Report SC120002 (2013)

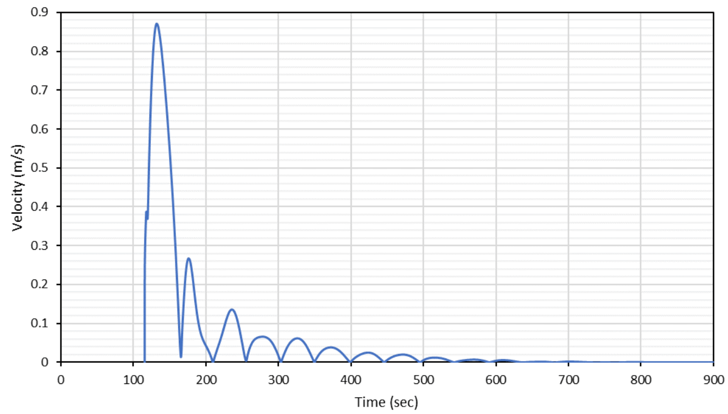

Figure 4-12 Test Point 2 – Velocity versus Time from SRH-2D

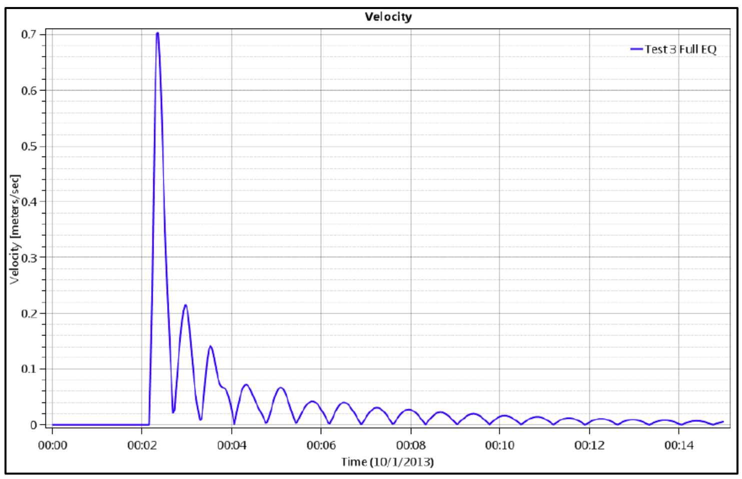

Figure 4-13 Test Point 2 – Velocity versus Time from RD-51 (2018)

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5 Benchmark Test 4: Speed of Flood Propagation Over an Extended Floodplain

5.1 Objective

The objective of the test is to assess the 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

This test is designed to simulate the rate of flood wave propagation over a 1,000-meter by 2,000-meter (3,280.8 feet by 6,561.7 feet) floodplain following an embankment failure (Figure 5-1). The floodplain surface is horizontal, at elevation zero meters. One inflow boundary condition is used, simulating the failure of an embankment by breaching or overtopping, with a peak flow of 20 cubic meters per second (706.3 cubic feet per second) and time base of approximately 5 hours (Figure 5-2). The boundary condition is applied along a 20-meter (65.6 feet) line in the middle of the western side of the floodplain.

5.3 Boundary and Initial Conditions

- Inflow (Figure 5-2) along the indicated line in Figure 5-1 (location and tables provided as part of dataset).
- All other boundaries closed.
- Initial condition: Dry bed.

5.4 Parameter Values

- Manning's n equals 0.05 (uniform).
- Model grid resolution equals 5 meters (16.4 feet), or 80,000 nodes in modeled area.
- Time of end: Model is to be run until time T equals 5 hours.

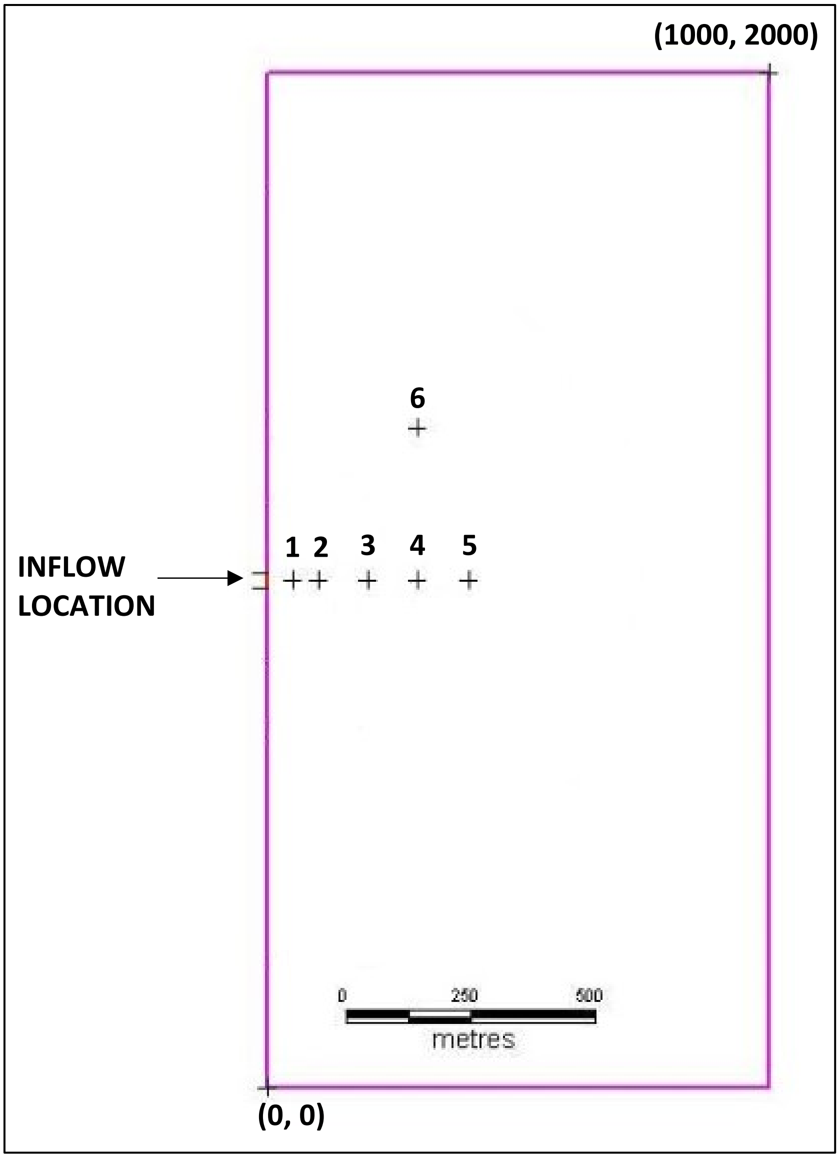

Figure 5-1 Modeled domain, showing the location of the 20 meter inflow hydrograph and output point locations.

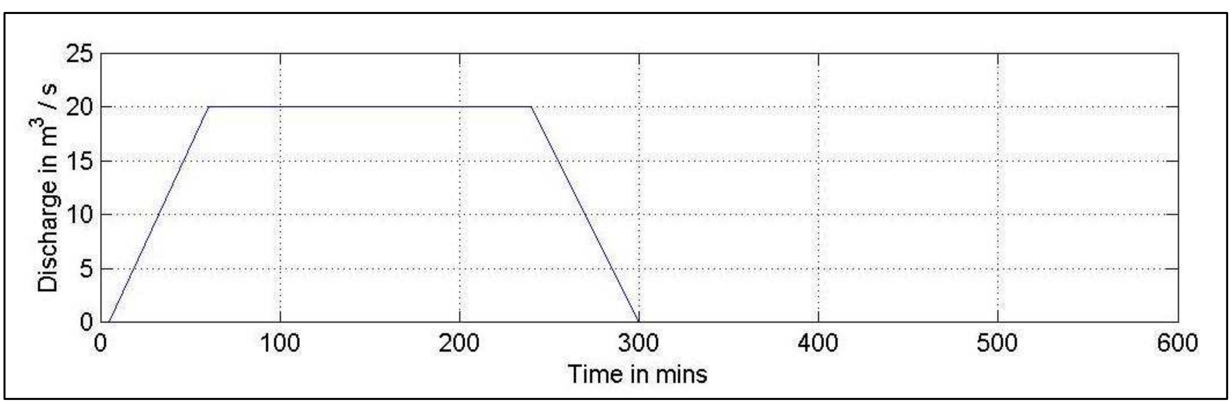

Figure 5-2 Inflow hydrograph used as upstream boundary condition.

5.5 Results

The results for Benchmark Test 4 were output at points 1 through 6 (Figure 5-1). Water level and velocity versus time, at a 20 second output frequency, are displayed for the SRH-2D results starting with Figure 5-3. Table 5-1 provides information related to the modeling computer, grid resolution, number elements, computational timestep and total computational time. Table 5-2 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included. A sensitivity analysis on the computational timestep was performed on timesteps varying from 2 seconds up to 20 seconds. It was determined that timesteps from 2 to 20 seconds provided converged solutions, therefore SRH-2D results contained in Figure 5-3 through Figure 5-40 illustrate SRH-2D results at a 20 second timestep. Instructions for Benchmark Test 4 indicated that the results should be output at a 20 second frequency. Therefore, the computational timestep could not be increased beyond this limiting time interval.

The SRH-2D results were comparable in terms of timing and magnitude to the other 2D models from the original Benchmarking Study (see figures starting at Figure 5-5). The results are also similar to the output from the HEC-RAS 2D model (see figures starting at Figure 5-4).

Arrival times at each point for SRH-2D are consistent with the results produced for HEC-RAS 2D in RD-51 as well as the other models evaluated in Report SC120002. The velocity values at point 1 vary greatly between the different models, included in Report SC120002, and between the full momentum and diffusive wave results in HEC-RAS 2D. Point 1 is nearest to the inflow boundary condition which is likely the cause for the slight variation evident between models. The velocity magnitudes at test points further away from the inflow boundary condition are much more consistent with each other. See Figure 5-35 to Figure 5-40, which contain plots of depth and velocity values along a line perpendicular to the inflow boundary condition extending out to point 5 (Figure 5-1). While there is more variation between the models, near the boundary condition (distance of 0 feet in the figures), the results are much more similar further away from the boundary condition location.

In conclusion, SRH-2D performed well compared to the other 2D models from the original Benchmarking Study, as well as HEC-RAS 2D (Figure 5-3 to Figure 5-40). It also provides a good demonstration that predictions of velocities in the immediate vicinity of a boundary condition (inflow in this test) shows less consistency and are found to be sensitive to the approach used to implement the boundary condition.

Table 5-1 Benchmark Test 4 Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	5 meters (16.4 feet); 80,000 elements
Computational time increment used	20s
Total computational time	253.3s

Table 5-2 Benchmark Test 4 Model Parameters Adapted from Table 4.5 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time
ANUGA	1.1beta_7501	No	80149 Elements	Adaptive	2650s
Ceasg	1.12	Yes - GPU	5m	0.5s	72s
Flowroute-i™	3.2.0	Yes - 4 CPUs	5m	Adaptive	21s
HEC-RAS 2D Full EQ (Diff Wav)	5.0.4	Yes	5m	30s	56s (41s)
InfoWorks ICM	2.5.2	Yes - GPU	79,857 Triangles	20s	44s
ISIS 2D	3.6 (TVD)	Partial	5m	5s	82s
ISIS 2D GPU	1.17	Yes	5m	Adaptive	25s
JFLOW+	2	Yes - GPU	5m	Adaptive Average 0.9s	17.6s
LISFLOOD-FP	Not tested	Yes	5m	Adaptive	21s
MIKE FLOOD	2012	Yes - 8 CPUs	5m	10s	32.1s
RFSM - EDA	1.20	No	8611	Adaptive, Typically 12s	13s
SOBEK	2.13	No	5m	2s	1014s
SRH-2D	3.3	No	5 m	20s	253.3s
TUFLOW	2012-05-AA Single Precision	No	5m	Adaptive (1-30s)	47s
TUFLOW GPU	2012-05-AA Single Precision	Yes - 448 GPU Cores	5m	Adaptive (0.8-1.7s)	25s
TUFLOW FV	2012.000b First order (and second order)	Yes - 12 CPU Cores	5m	Adaptive (~0.7s) (~0.4s)	142s (481s)
UIM	209.12	OMP	5m	0.1s	17,000s
XPSTORM	2011 2010-10-AB-iDP-w32	No	5m	5s	84s

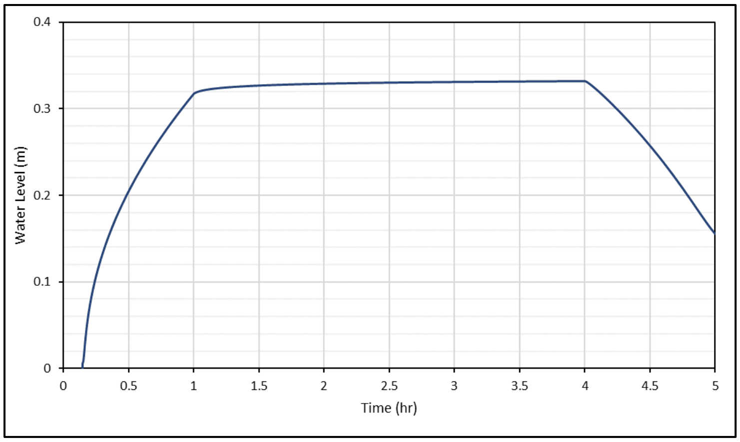

Figure 5-3 Test Point 1 – Water Level versus Time from SRH-2D

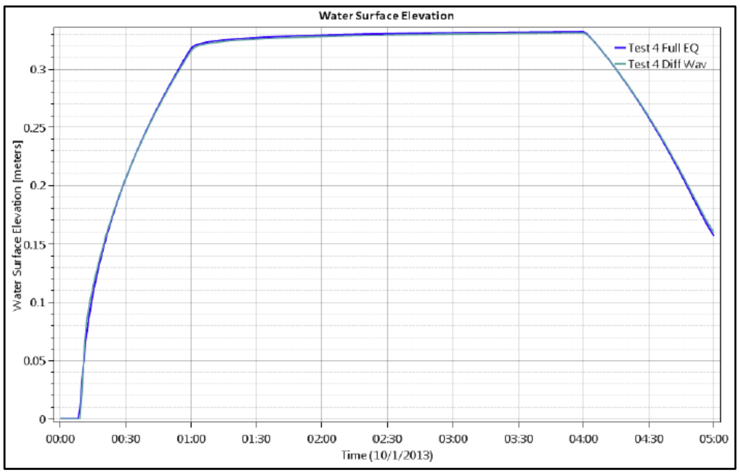

Figure 5-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

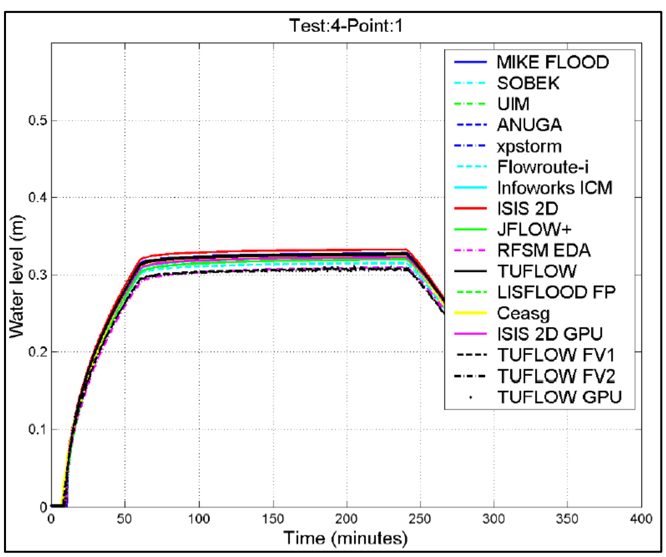

Figure 5-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

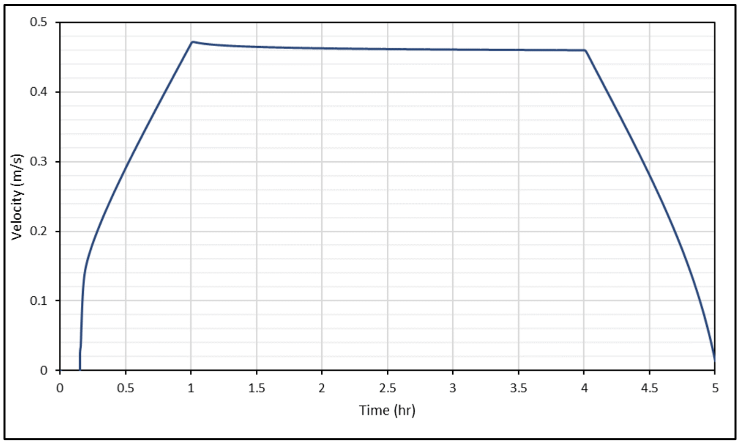

Figure 5-6 Test Point 1 – Velocity versus Time from SRH-2D

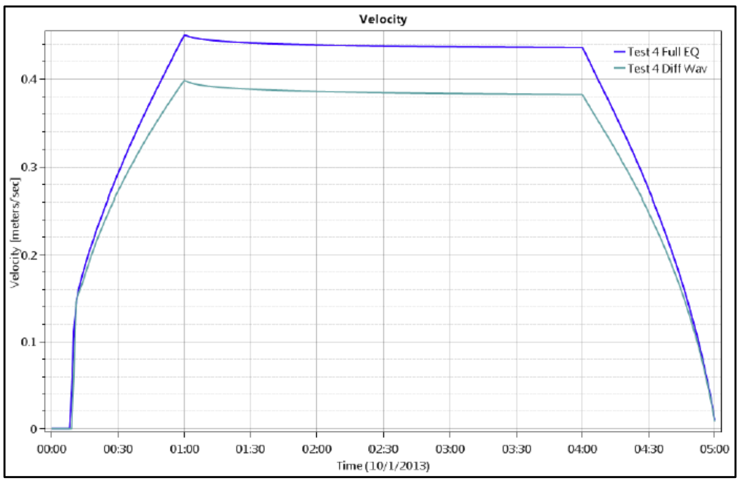

Figure 5-7 Test Point 1 – Velocity versus Time from RD-51 (2018)

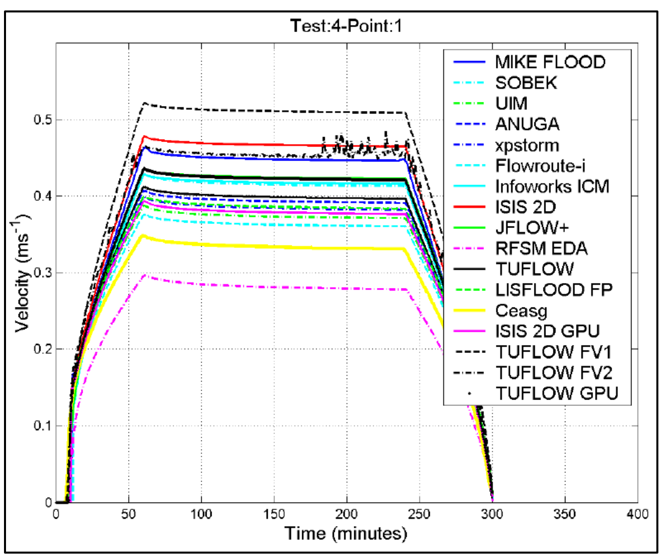

Figure 5-8 Test Point 1 – Velocity versus Time from Report SC120002 (2013)

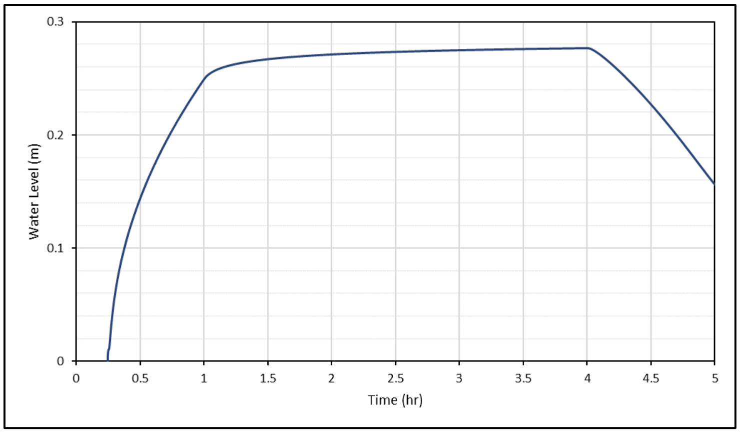

Figure 5-9 Test Point 2 – Water Level versus Time from SRH-2D

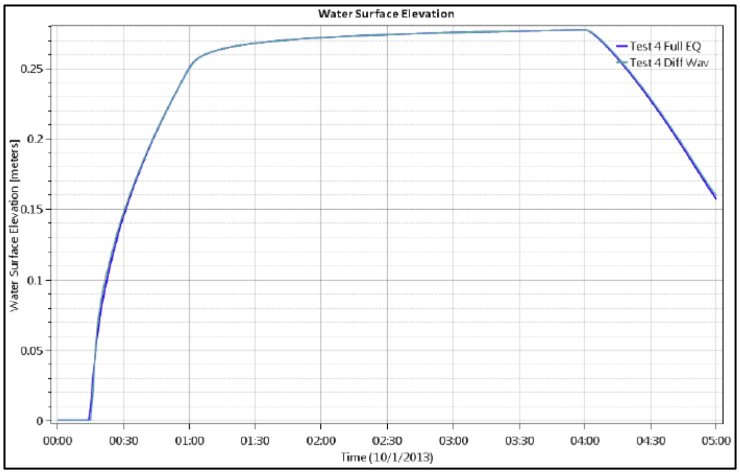

Figure 5-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

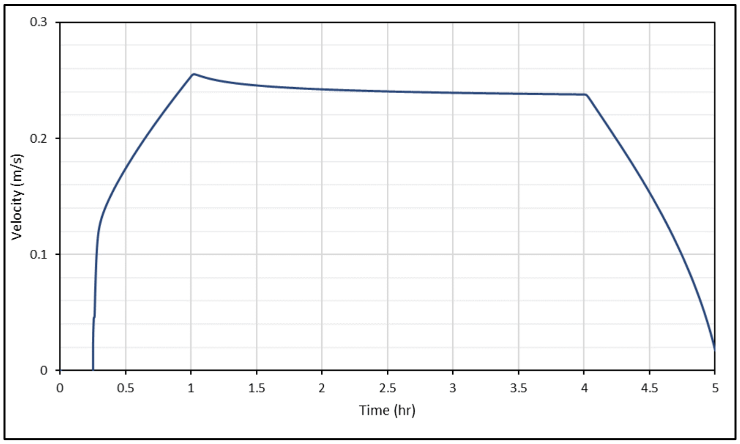

Figure 5-11 Test Point 2 – Velocity versus Time from SRH-2D

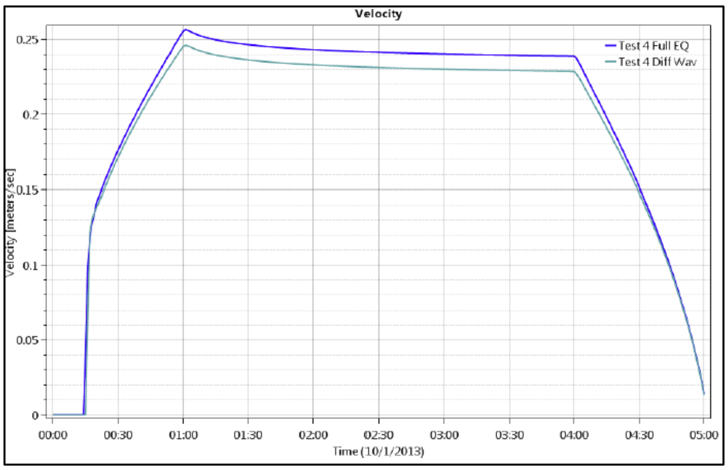

Figure 5-12 Test Point 2 – Velocity versus Time from RD-51 (2018)

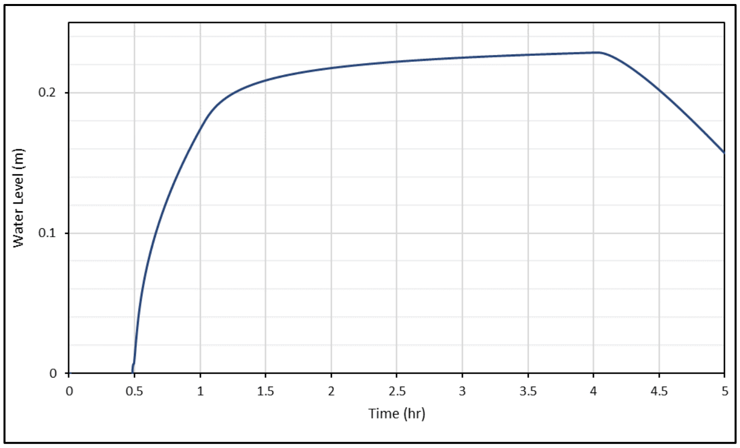

Figure 5-13 Test Point 3 – Water Level versus Time from SRH-2D

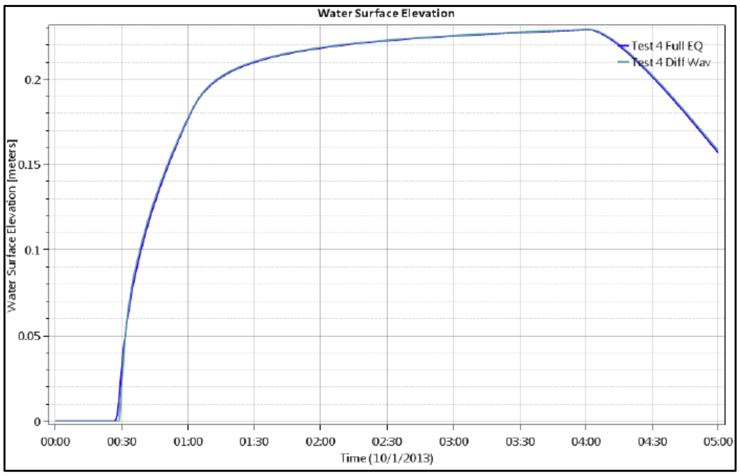

Figure 5-14 Test Point 3 – Water Level versus Time from RD-51 (2018)

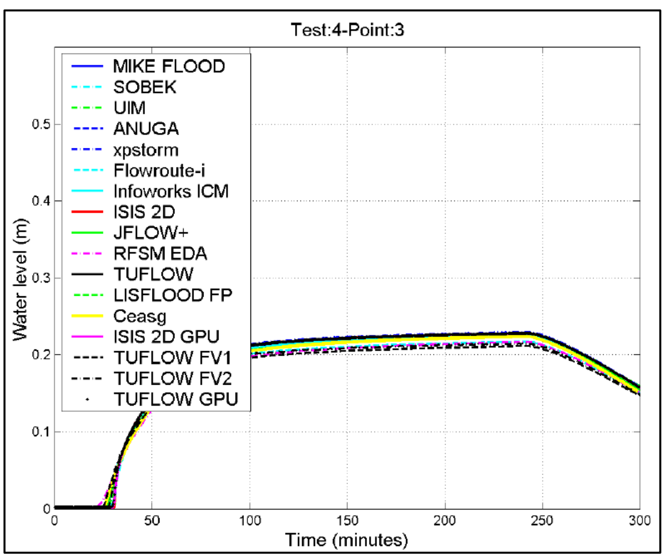

Figure 5-15 Test Point 3 – Water Level versus Time from Report SC120002 (2013)

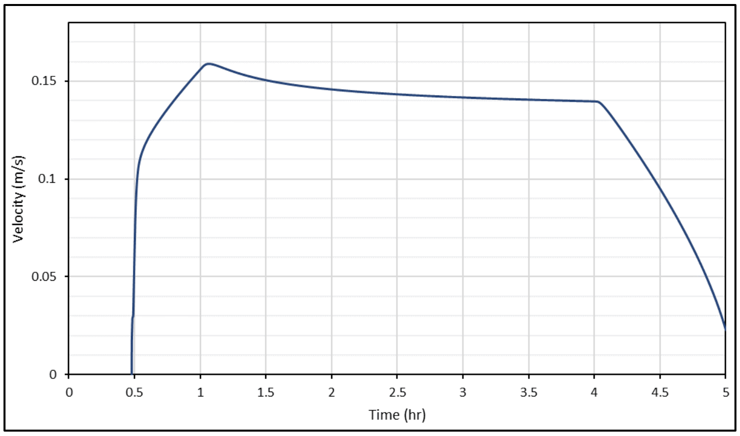

Figure 5-16 Test Point 3 – Velocity versus Time from SRH-2D

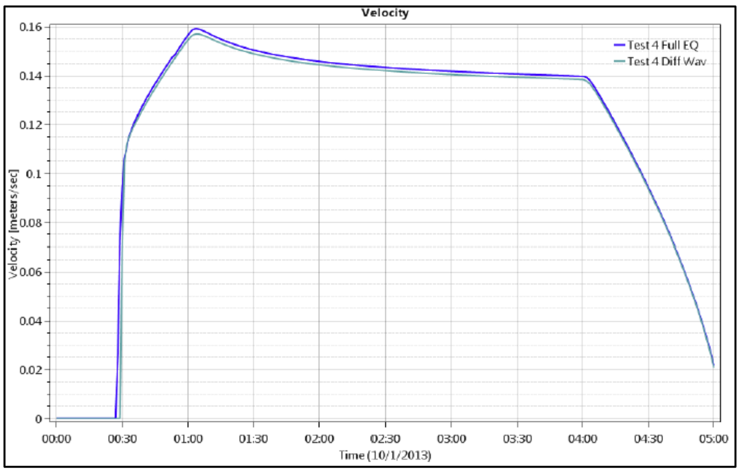

Figure 5-17 Test Point 3 – Velocity versus Time from RD-51 (2018)

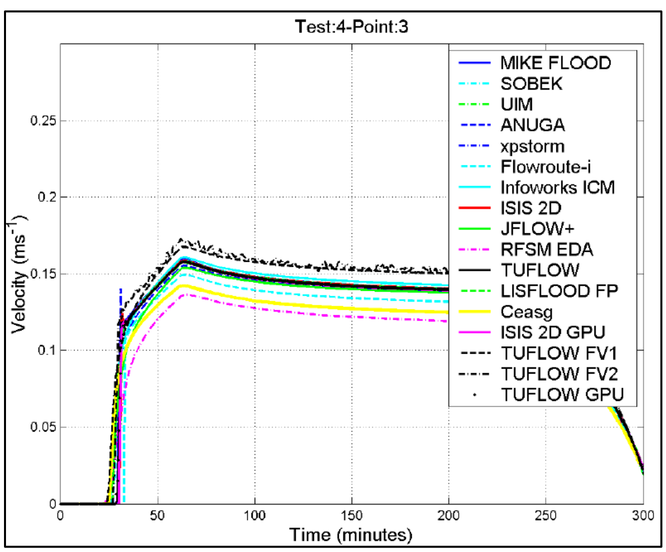

Figure 5-18 Test Point 3 – Velocity versus Time from Report SC120002 (2013)

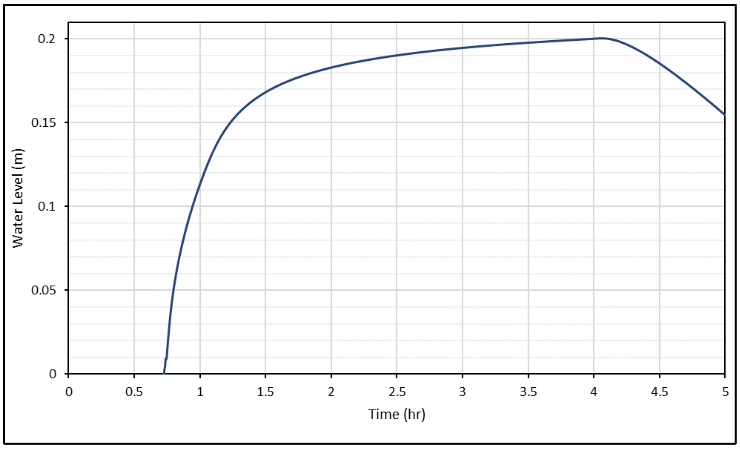

Figure 5-19 Test Point 4 – Water Level versus Time from SRH-2D

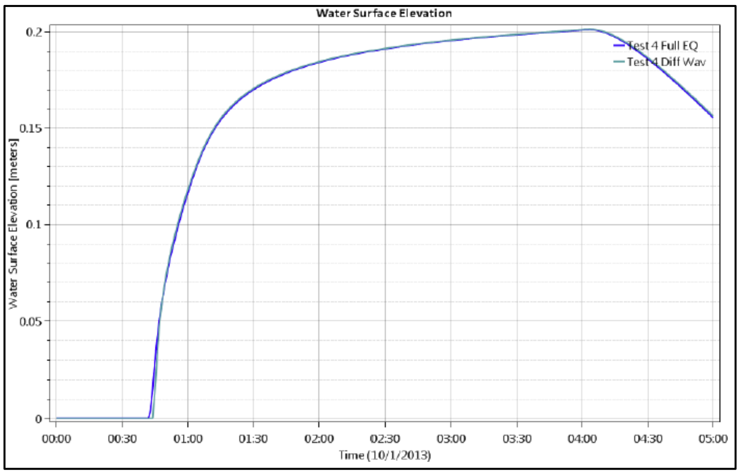

Figure 5-20 Test Point 4 – Water Level versus Time from RD-51 (2018)

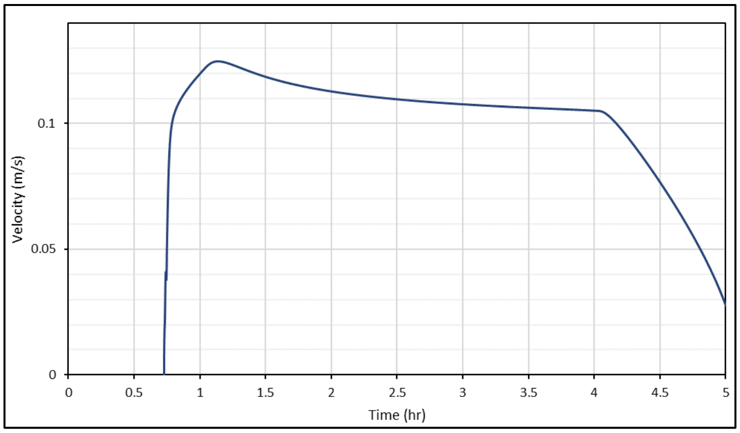

Figure 5-21 Test Point 4 – Velocity versus Time from SRH-2D

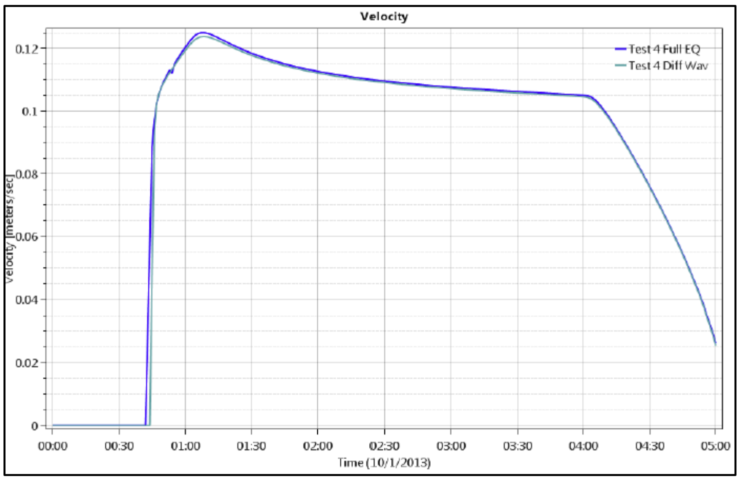

Figure 5-22 Test Point 4 – Velocity versus Time from RD-51 (2018)

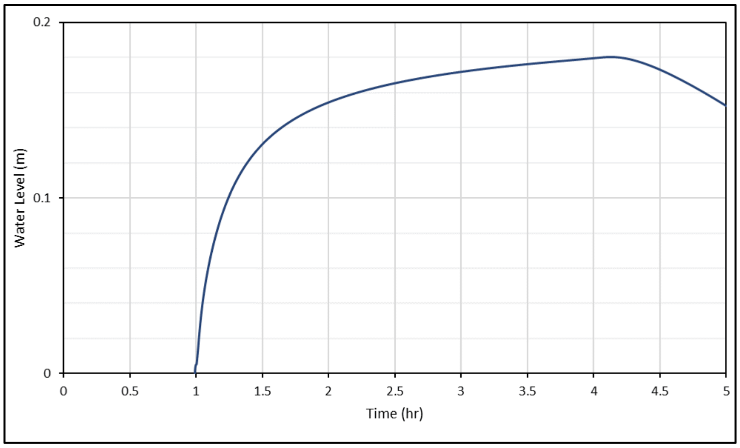

Figure 5-23 Test Point 5 – Water Level versus Time from SRH-2D

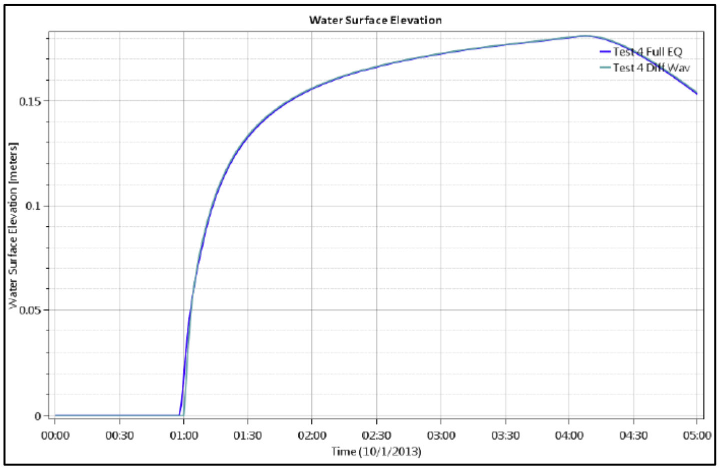

Figure 5-24 Test Point 5 – Water Level versus Time from RD-51 (2018)

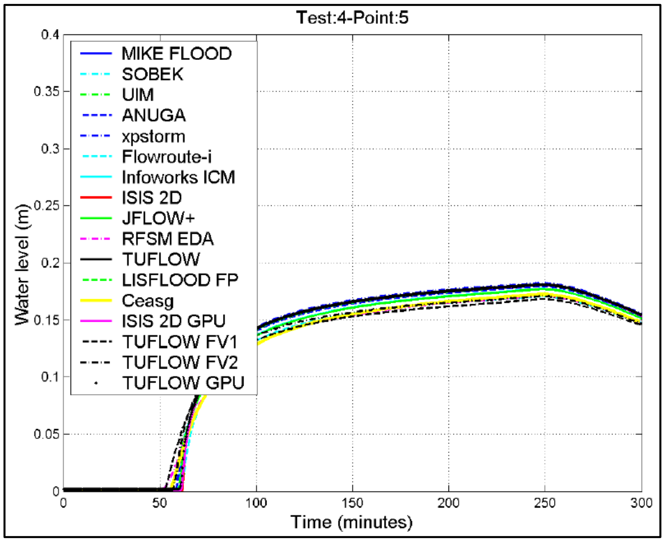

Figure 5-25 Test Point 5 – Water Level versus Time from Report SC120002 (2013)

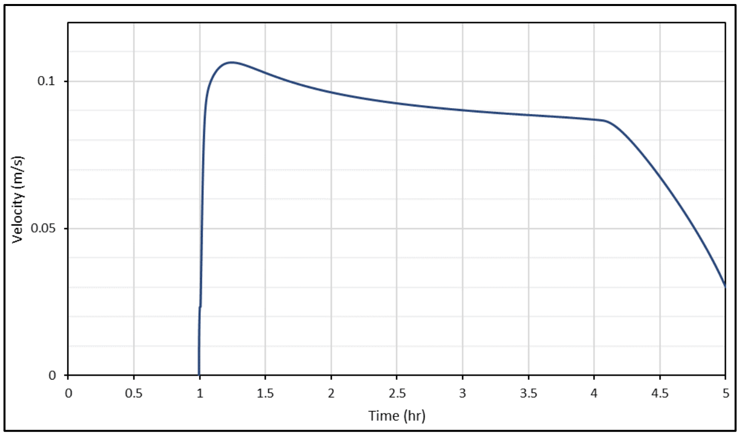

Figure 5-26 Test Point 5 – Velocity versus Time from SRH-2D

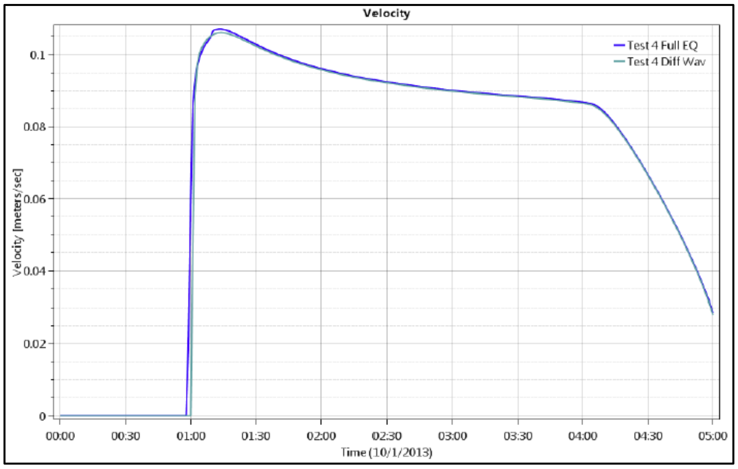

Figure 5-27 Test Point 5 – Velocity versus Time from RD-51 (2018)

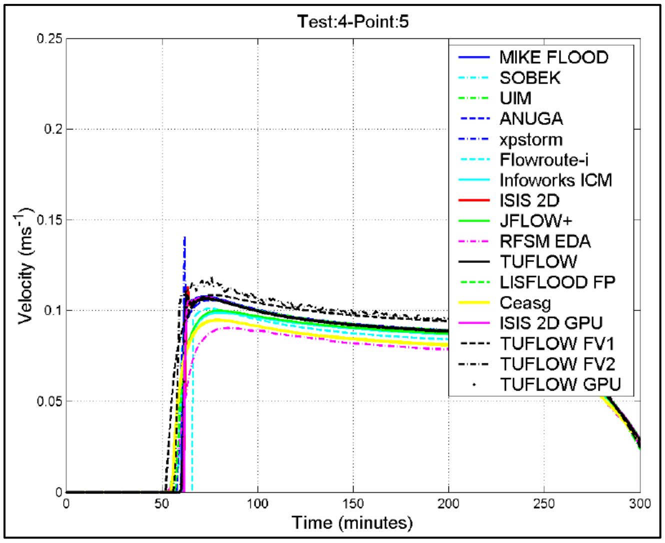

Figure 5-28 Test Point 5 – Velocity versus Time from Report SC120002 (2013)

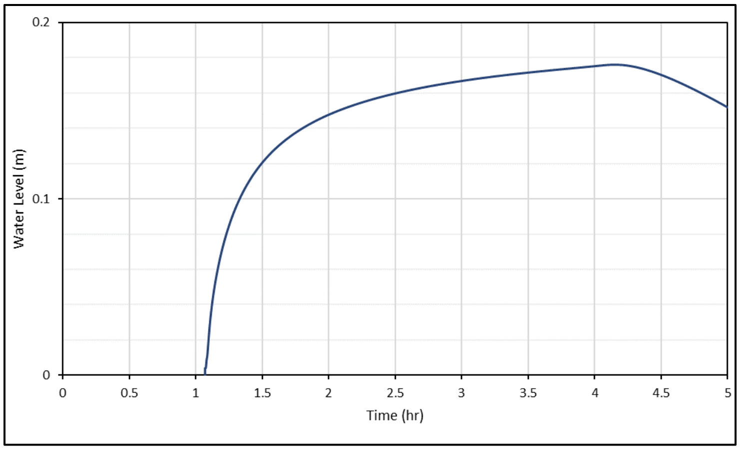

Figure 5-29 Test Point 6 – Water Level versus Time from SRH-2D

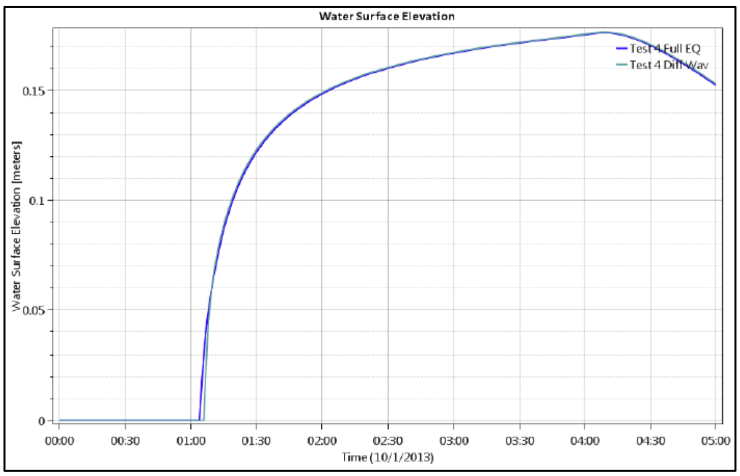

Figure 5-30 Test Point 6 – Water Level versus Time from RD-51 (2018)

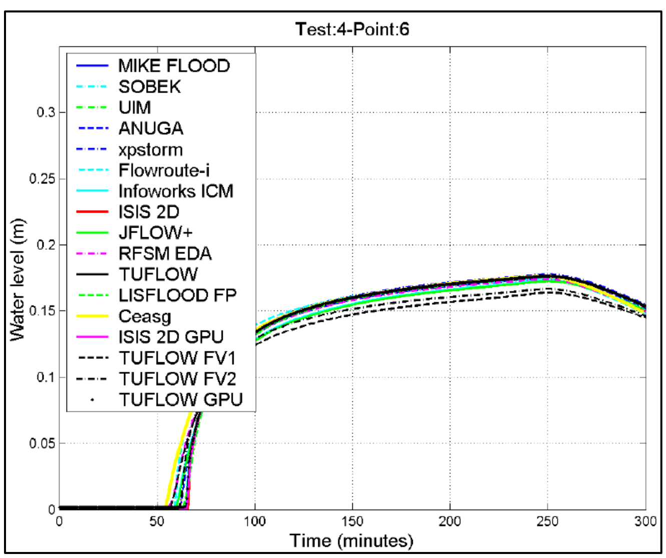

Figure 5-31 Test Point 6 – Water Level versus Time from Report SC120002 (2013)

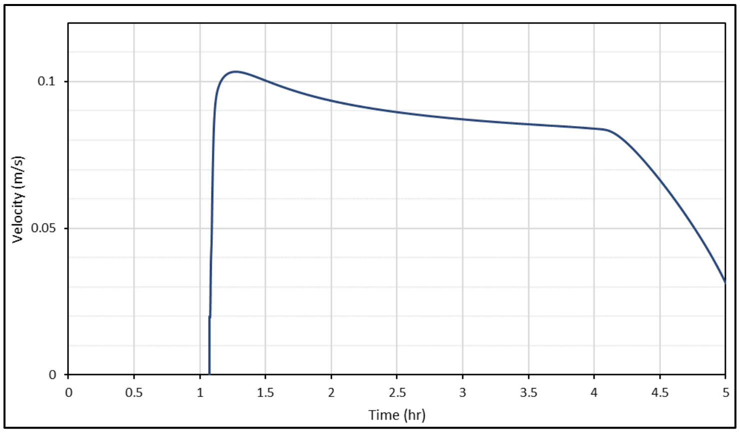

Figure 5-32 Test Point 6 – Velocity versus Time from SRH-2D

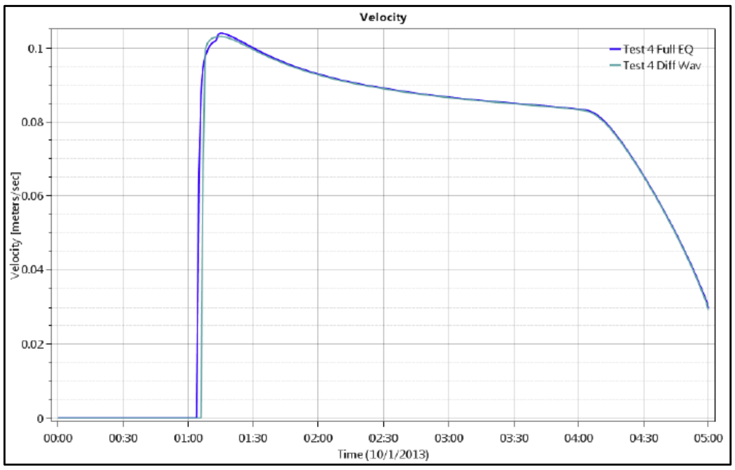

Figure 5-33 Test Point 6 – Velocity versus Time from RD-51 (2018)

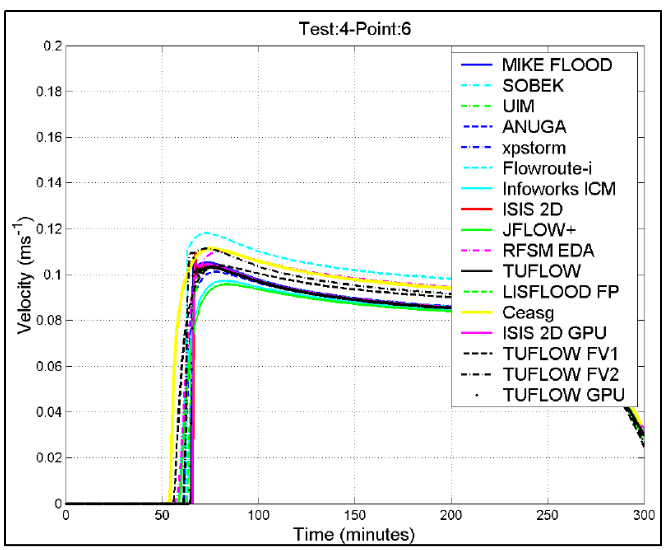

Figure 5-34 Test Point 6 – Velocity versus Time from Report SC120002 (2013)

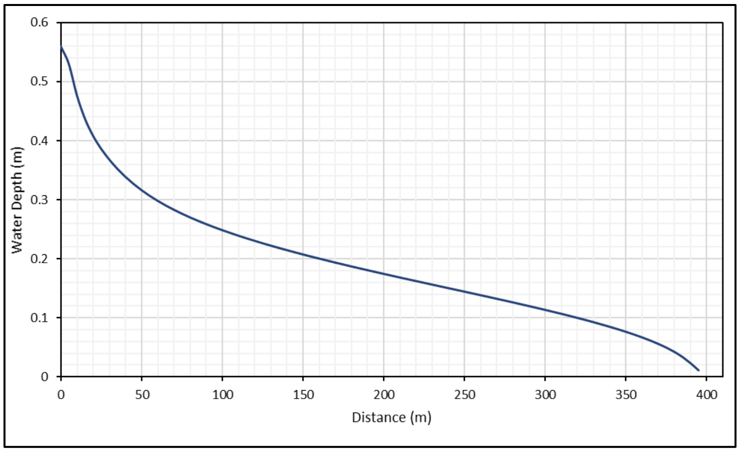

Figure 5-35 Cross Section from Inflow to Point 5 – Water Level versus Distance at 1 Hour from SRH-2D

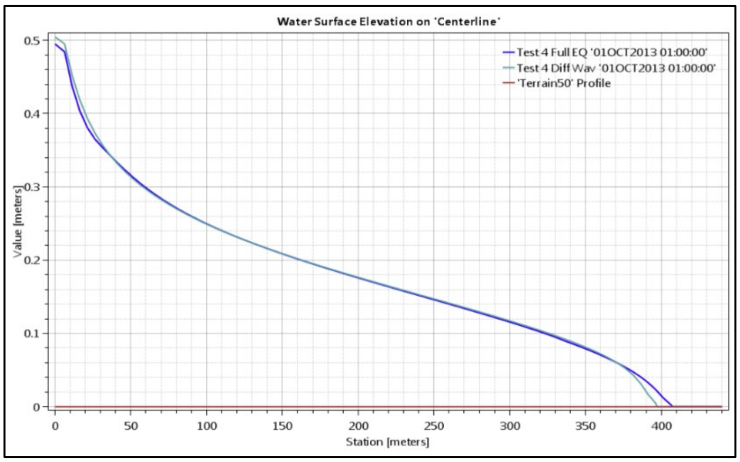

Figure 5-36 Cross Section from Inflow to Point 5 – Water Level versus Distance at 1 Hour from RD-51 (2018)

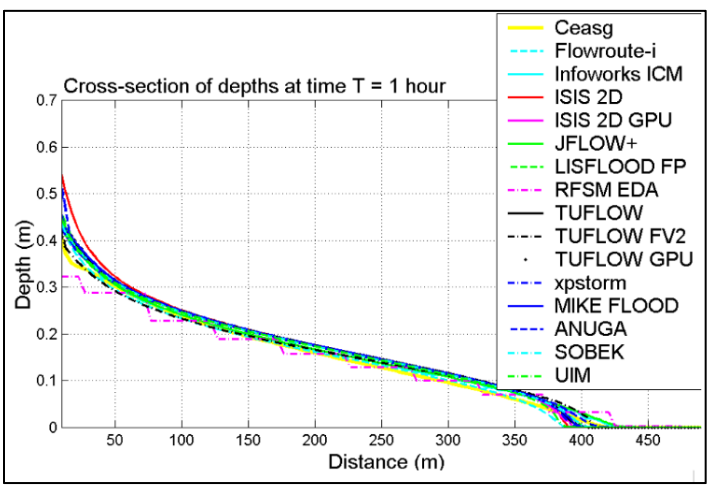

Figure 5-37 Cross Section from Inflow to Point 5 – Water Level versus Distance at 1 Hour from Report SC120002 (2013)

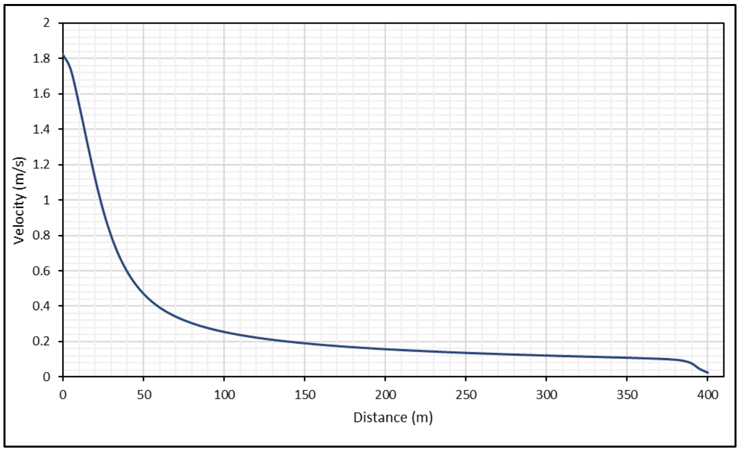

Figure 5-38 Cross Section from Inflow to Point 5 – Velocity versus Distance at 1 Hour from SRH-2D

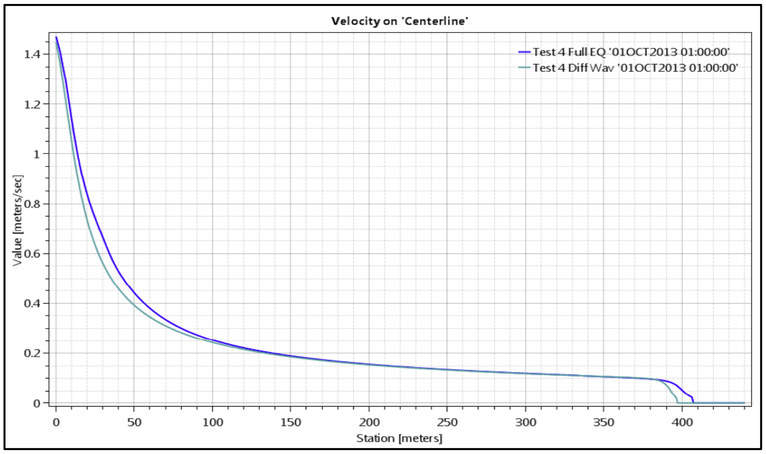

Figure 5-39 Cross Section from Inflow to Point 5 – Velocity versus Distance at 1 Hour from RD-51 (2018)

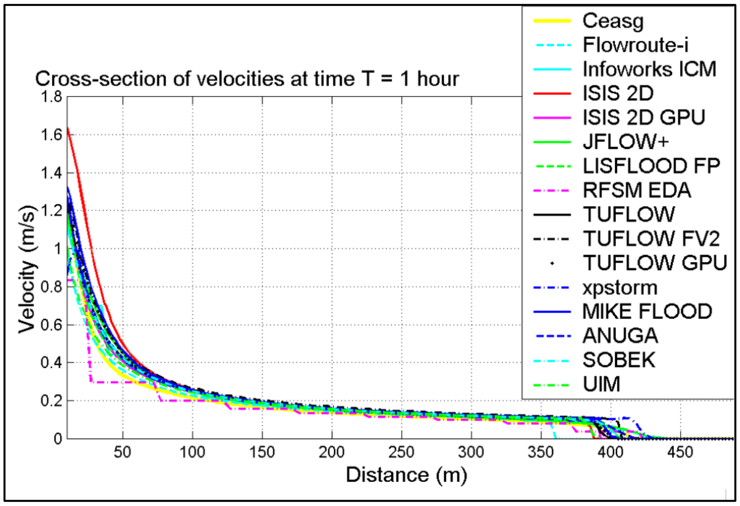

Figure 5-40 Cross Section from Inflow to Point 5 – Velocity versus Distance at 1 Hour from Report SC120002 (2013)

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6 Benchmark Test 5: Valley Flooding

6.1 Objective

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

6.2 Description

This test is designed to simulate flood wave propagation down a river valley following the failure of a dam. The valley DEM (Figure 6-1) is approximately 0.8 kilometers by 17 kilometers (0.5 miles by 10.6 miles), 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 6-2), applied as a boundary condition along a line approximately 260 meters (853 feet) long, at the upstream end is designed to account for a typical failure of a small embankment dam and to ensure that both supercritical and subcritical flows will occur in different parts of the flow field. The model is run for 30 hours to allow the flood to settle in the lower parts of the valley.

6.3 Boundary and Initial Conditions

- Inflow (Figure 6-2) along the red line in Figure 6-1 (location and tables provided as part of dataset).
- All other boundaries closed.
- Initial condition: Dry bed.

6.4 Parameter Values

- Manning's n equals 0.04 (uniform).
- Model grid resolution equals 50 meters (164 feet), or approximately 7,600 nodes in modeled area.
- Time of end: Model is to be run until time T equals 30 hours.

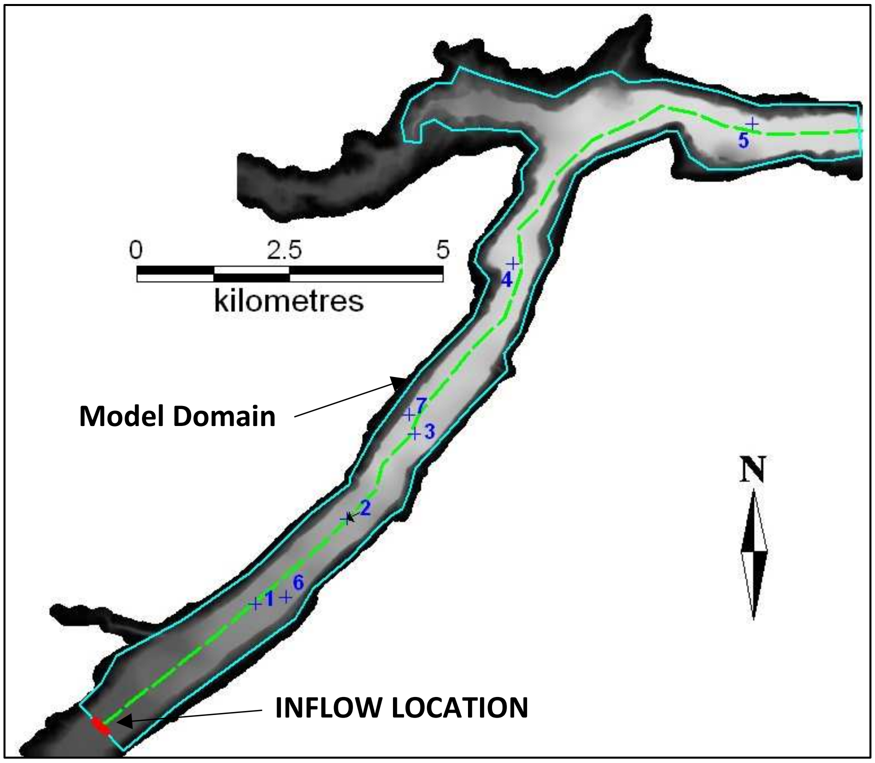

Figure 6-1 Plan view of DEM used in Benchmark Test 5 including output point locations. The red line indicates the location of the boundary condition and the cyan polygon represents the extents of the model's domain.

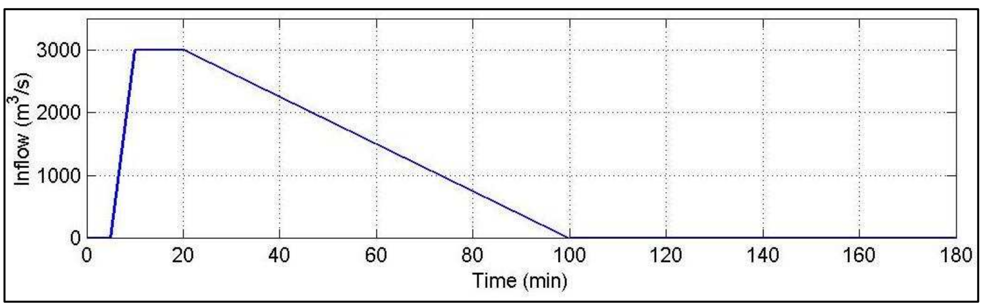

Figure 6-2 Inflow hydrograph used as upstream boundary condition.

6.5 Results

The results for Benchmark Test 5 were output at points 1 through 7 (Figure 6-1). Water level and velocity versus time, at a 60 second output frequency, are displayed for the SRH-2D results starting with Figure 6-3. A sensitivity analysis was performed by varying from the computational timestep from 20 seconds up to 60 seconds. Instructions for Benchmark Test 5 indicated that the results should be output at a 60 second frequency. Therefore, the computational timestep could not be increased beyond this limiting time interval. Based on the timestep sensitivity analysis, a 30-second timestep was determined to provide a converged solution, therefore SRH-2D results contained in Figure 6-3 through Figure 6-38 illustrate SRH-2D results at a 30 second timestep. Note that in the UK report water level is not available for points 2, 4 and 6 and velocity is not available in points 2, 5 and 6. Table 6-1 provides information related to the modeling computer, grid resolution, number elements, computational timestep, and total computational time. Table 6-2 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included.

The SRH-2D results were comparable in terms of timing and magnitude to the other 2D models from the original Benchmarking Study (see figures starting at Figure 6-5). The results are also similar to the output from the HEC-RAS 2D model (see figures starting at Figure 6-4).

Arrival time and water surface elevation at test point 5 from SRH-2D, located near the downstream limit of the model domain where water backs up during the simulation (Figure 6-1), are consistent with the other 2D models. The water depth and velocity values from SRH-2D fall within the ranges observed from the other 2D models, as described in Report SC120002.

In conclusion, SRH-2D performed well compared to the other 2D models from the original Benchmarking Study, as well as HEC-RAS 2D (Figure 6-3 to Figure 6-38).

Table 6-1 Benchmark Test 5 Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	50 meters (164 feet); 7,600 elements
Computational time increment used	30 sec
Total computational time	108 sec

Table 6-2 Benchmark Test 5 Model Parameters Adapted from Table 4.6 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time
ANUGA	1.1beta_7501	No	7828 elements	Adaptive	4160s
Ceasg	1.12	Yes - GPU	10m	0.25s	569s
Flowroute-i™	3.2.0	Yes - 4 CPUs	50m	Adaptive	9s
HEC-RAS 2D Full EQ (Diff Wav)	5.0.4	Yes	50m	30s	48s (30s)
InfoWorks ICM	2.5.2	Yes - GPU	7758 Triangles	60s	9s
ISIS 2D	3.6 (ADI)	Partial	50m	5s	58.5s
ISIS 2D GPU	1.17	Yes	50m	Adaptive	57s
ISIS Fast	3.6	No	50m	N/A	3.6s
JFLOW+	2	Yes - GPU	5m	Average 3.55s	22s
LISFLOOD-FP	5.5.2	Yes	50m	Adaptive	28.2s
MIKE FLOOD	2012	Yes - 8 CPUs	50m	15s	28.3s
RFSM (Direct)	3.5.4	No	58 Elements	N/A	<1s
RFSM - EDA	1.2	No	530 Elements	Adaptive Typical 10-15s	13.8s
SOBEK	2.13	No	50m	10s	168s
SRH-2D	3.3	No	50 m	30s	108s
TUFLOW	2012-05-AA Single Precision	No	50m	Adaptive (5-18s)	26s
TUFLOW GPU	2012-05-AA	Yes - 448 GPU Cores	50m	Adaptive (2.3-3.3s)	9s
TUFLOW FV	2012.00b First order (and second order)	Yes - 12 CPU Cores	7424 Elements	Adaptive (~1s)	67s (150s)
UIM	2009.12	OMP	50m	0.5s	2670s
XPSTORM	2011 2010-10-AB-iDP-w32	No	50m	10s	52.3s

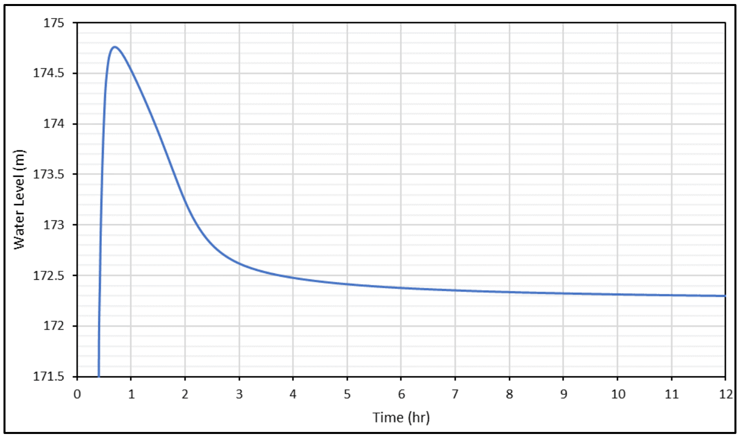

Figure 6-3 Test Point 1 – Water Level versus Time from SRH-2D

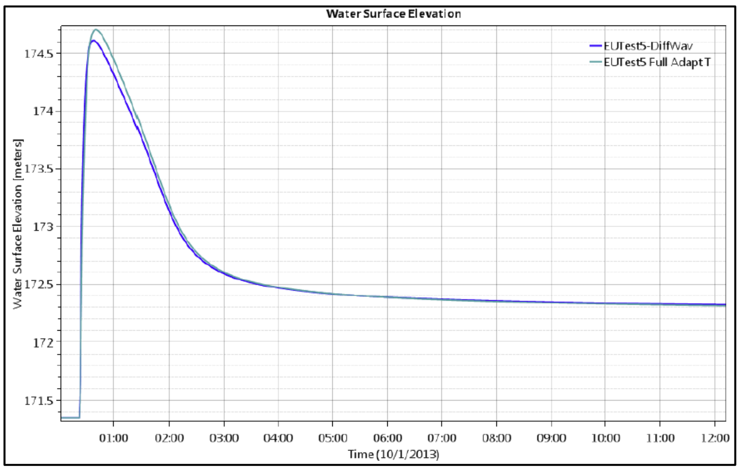

Figure 6-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

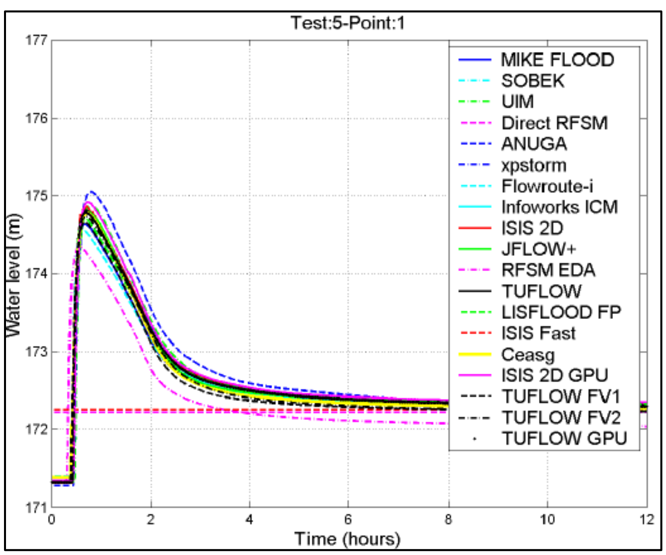

Figure 6-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

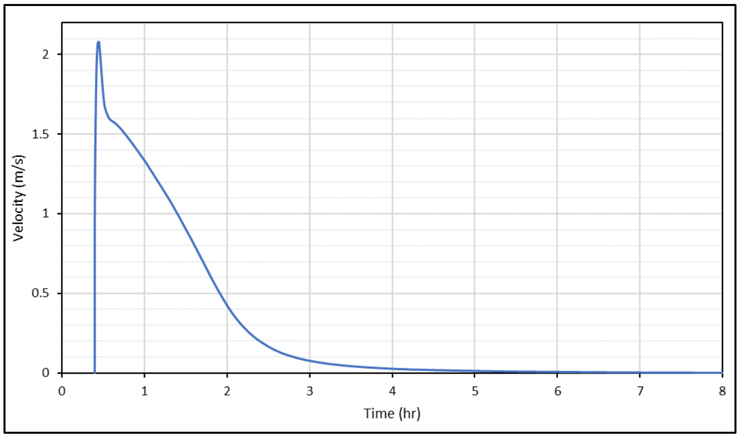

Figure 6-6 Test Point 1 – Velocity versus Time from SRH-2D

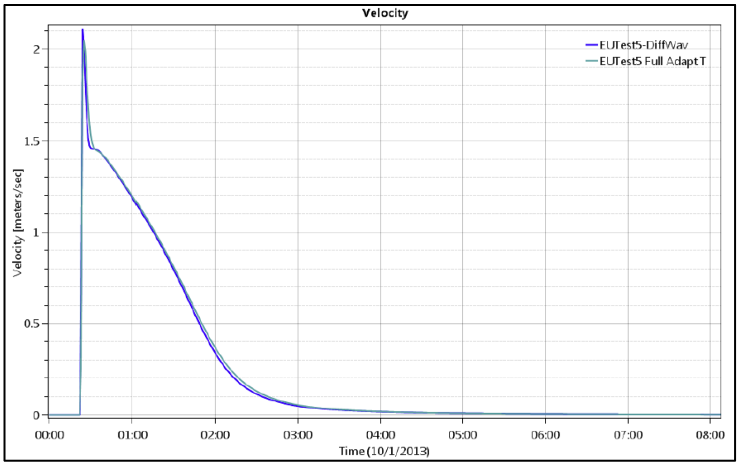

Figure 6-7 Test Point 1 – Velocity versus Time from RD-51 (2018)

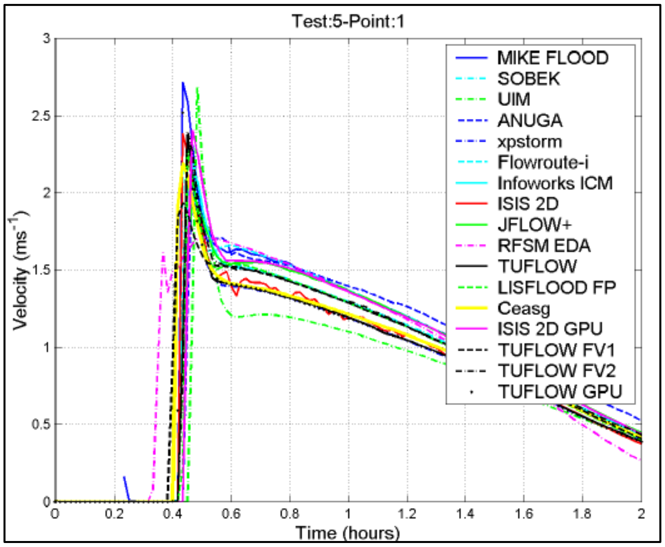

Figure 6-8 Test Point 1 – Velocity versus Time from Report SC120002 (2013)

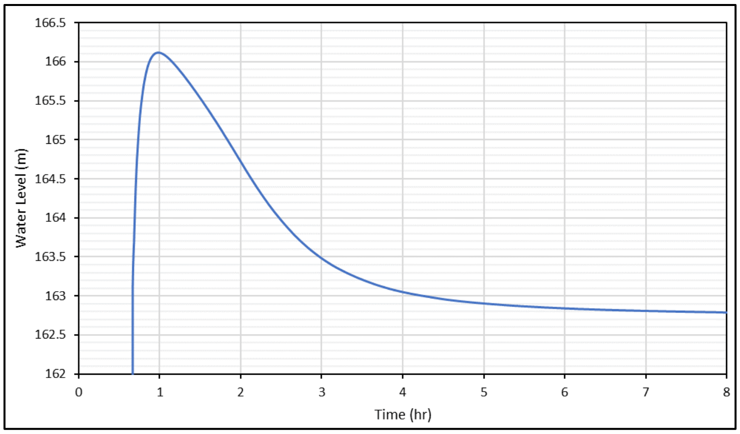

Figure 6-9 Test Point 2 – Water Level versus Time from SRH-2D

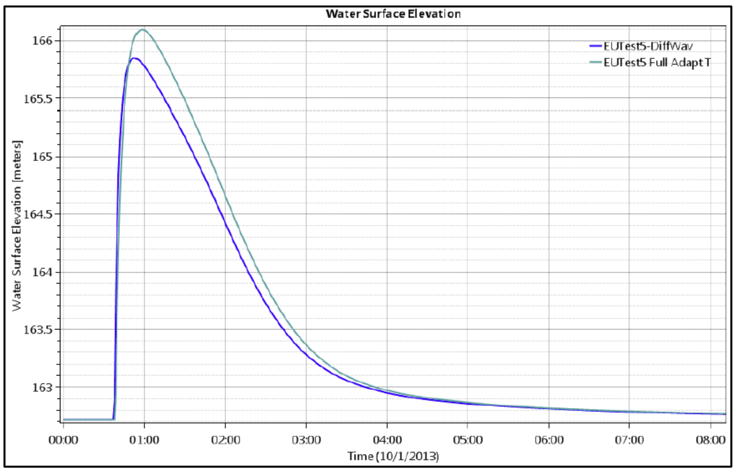

Figure 6-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

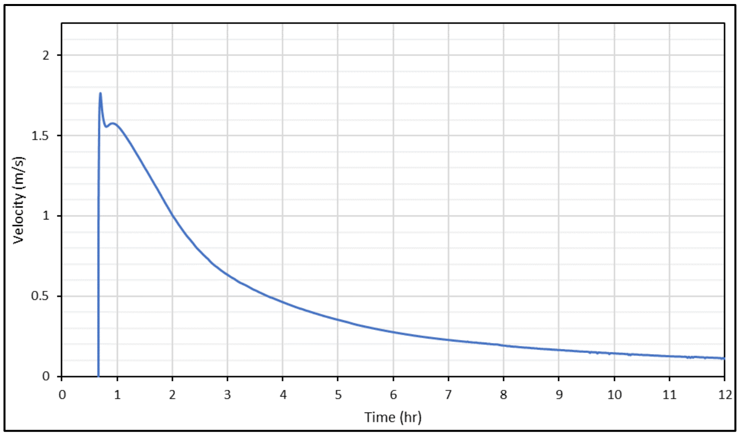

Figure 6-11 Test Point 2 – Velocity versus Time from SRH-2D

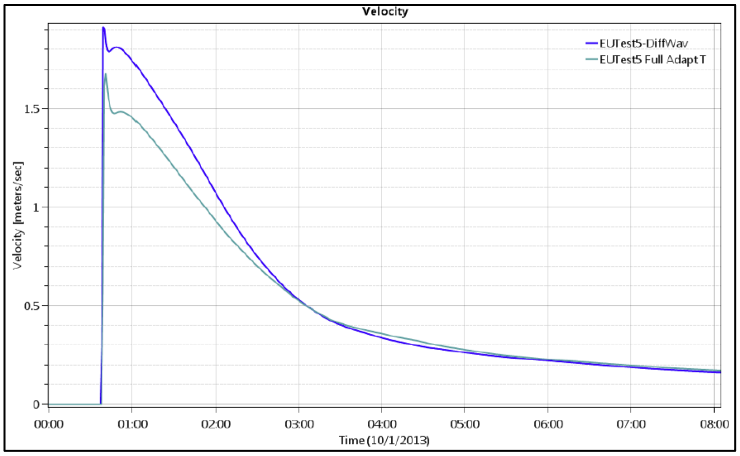

Figure 6-12 Test Point 2 – Velocity versus Time from RD-51 (2018)

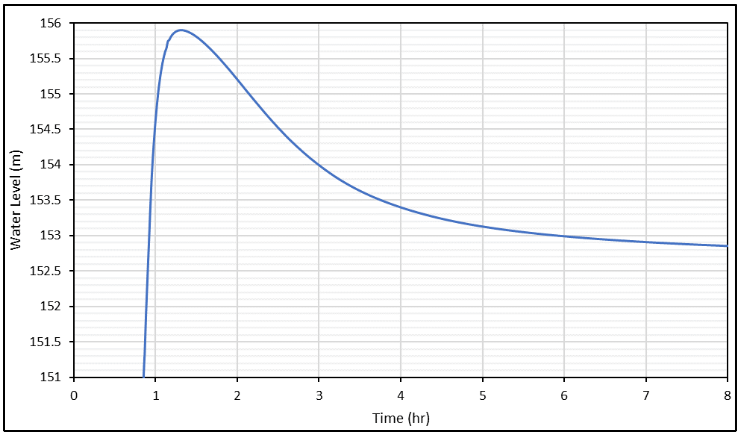

Figure 6-13 Test Point 3 – Water Level versus Time from SRH-2D

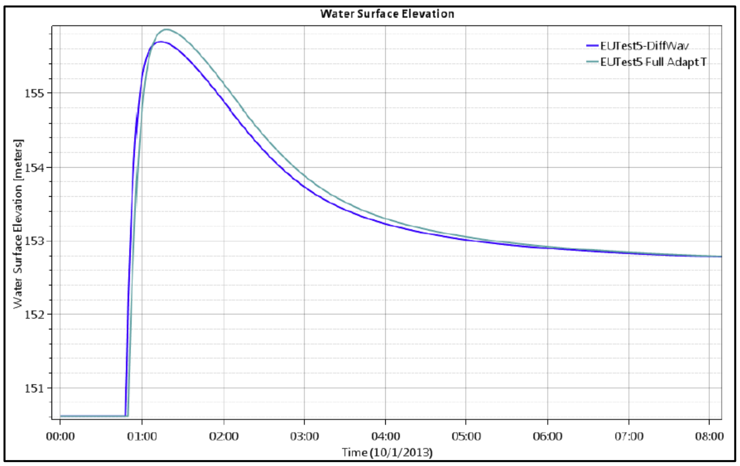

Figure 6-14 Test Point 3 – Water Level versus Time from RD-51 (2018)

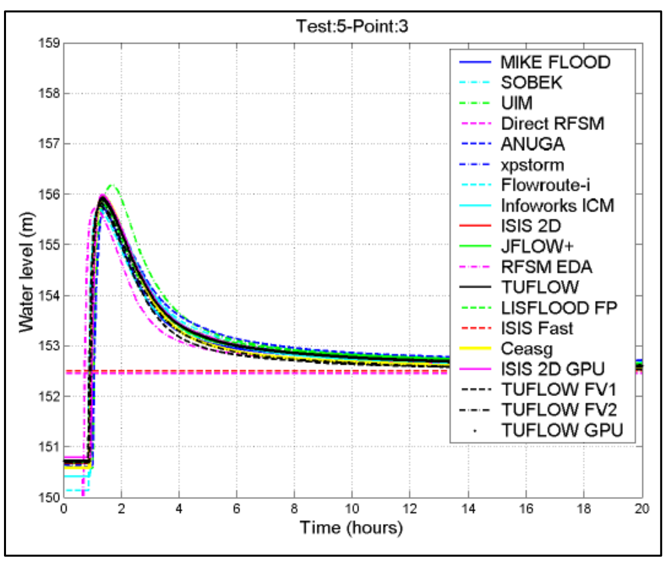

Figure 6-15 Test Point 3 – Water Level versus Time from Report SC120002 (2013)

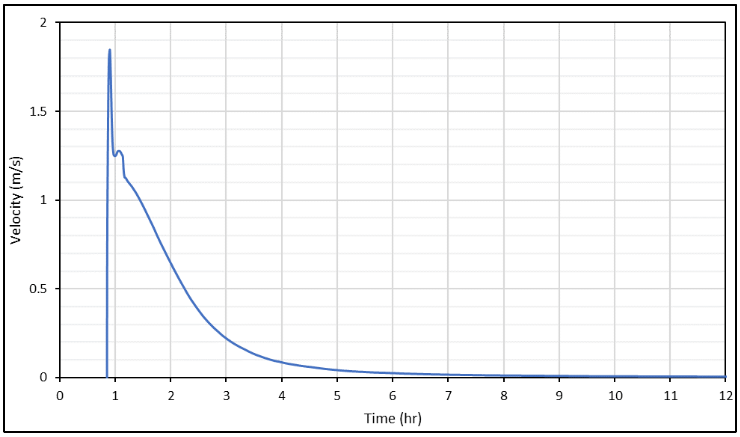

Figure 6-16 Test Point 3 – Velocity versus Time from SRH-2D

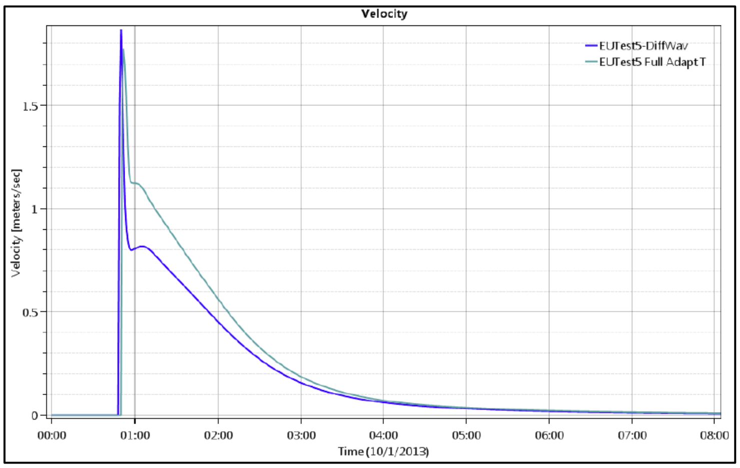

Figure 6-17 Test Point 3 – Velocity versus Time from RD-51 (2018)

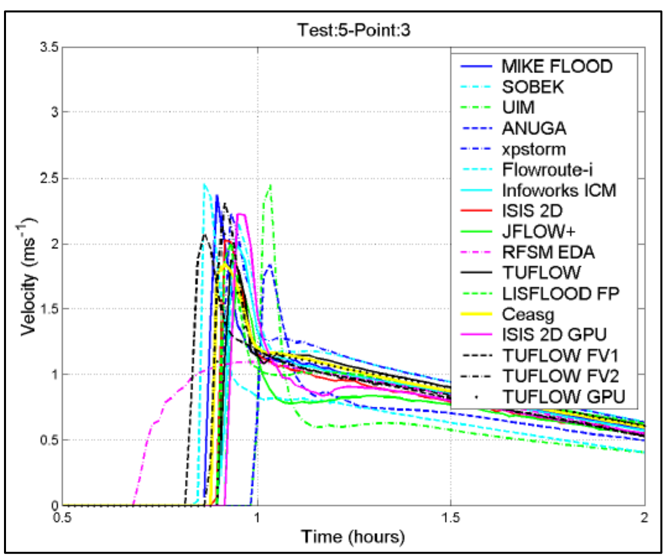

Figure 6-18 Test Point 3 – Velocity versus Time from Report SC120002 (2013)

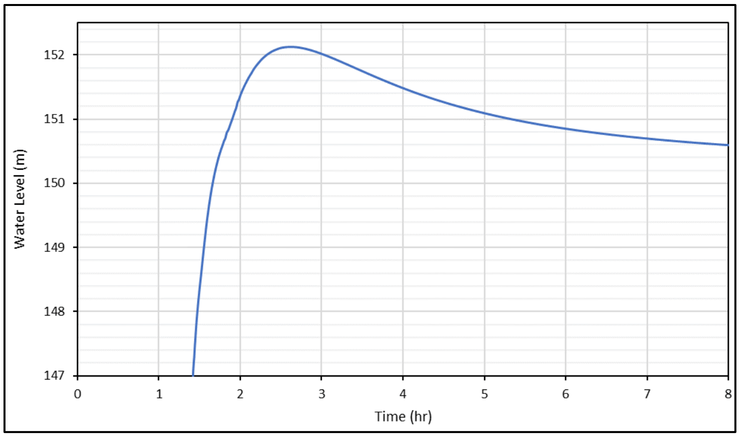

Figure 6-19 Test Point 4 – Water Level versus Time from SRH-2D

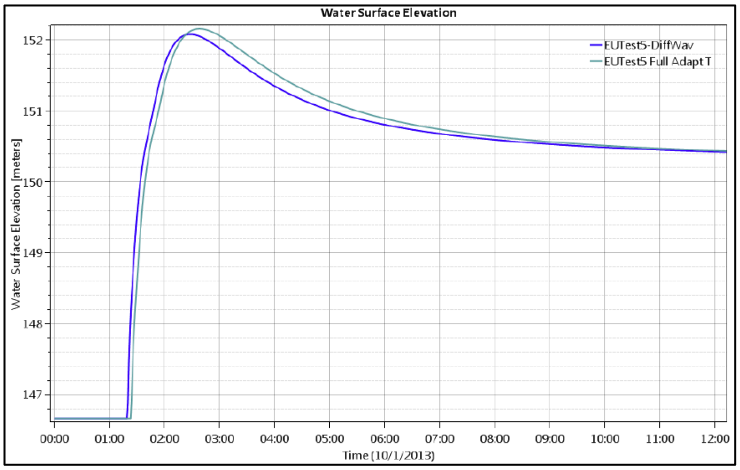

Figure 6-20 Test Point 4 – Water Level versus Time from RD-51 (2018)

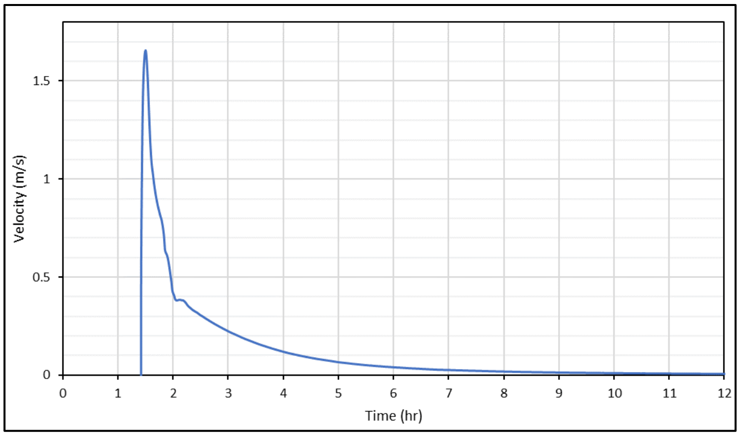

Figure 6-21 Test Point 4 – Velocity versus Time from SRH-2D

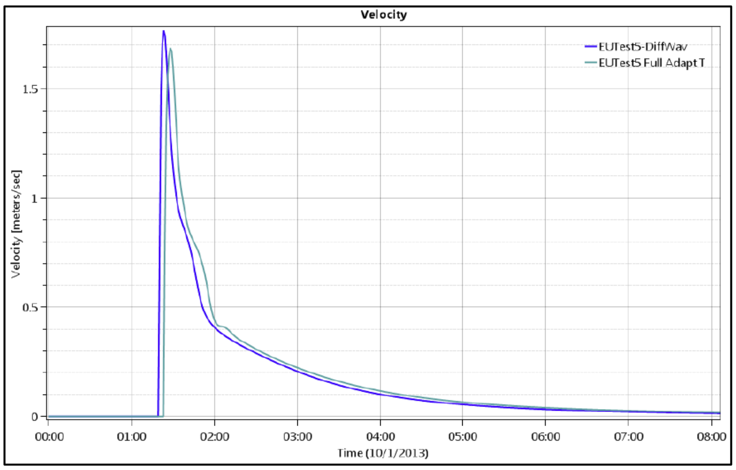

Figure 6-22 Test Point 4 – Velocity versus Time from RD-51 (2018)

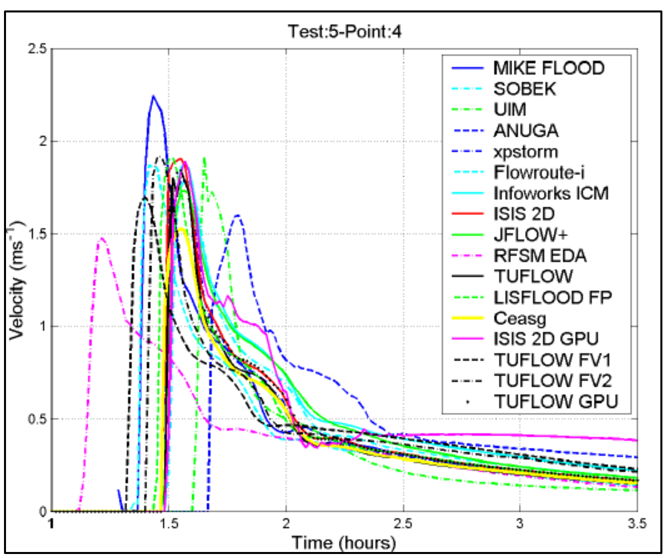

Figure 6-23 Test Point 4 – Velocity versus Time from Report SC120002 (2013)

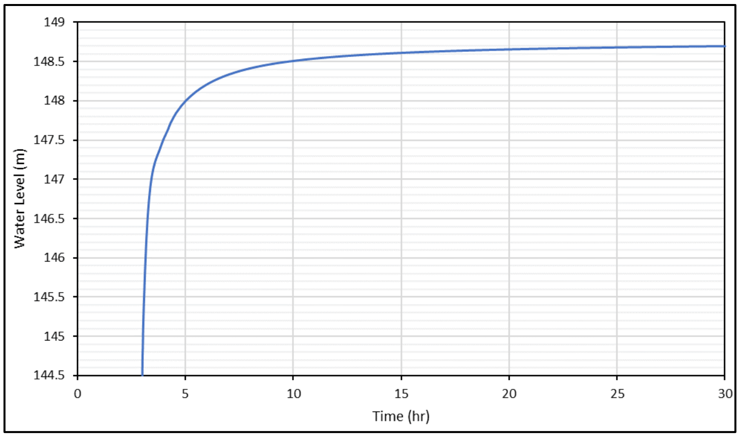

Figure 6-24 Test Point 5 – Water Level versus Time from SRH-2D

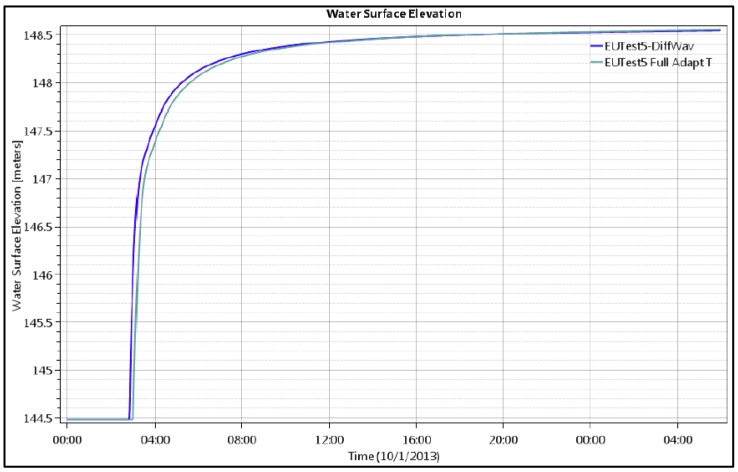

Figure 6-25 Test Point 5 – Water Level versus Time from RD-51 (2018)

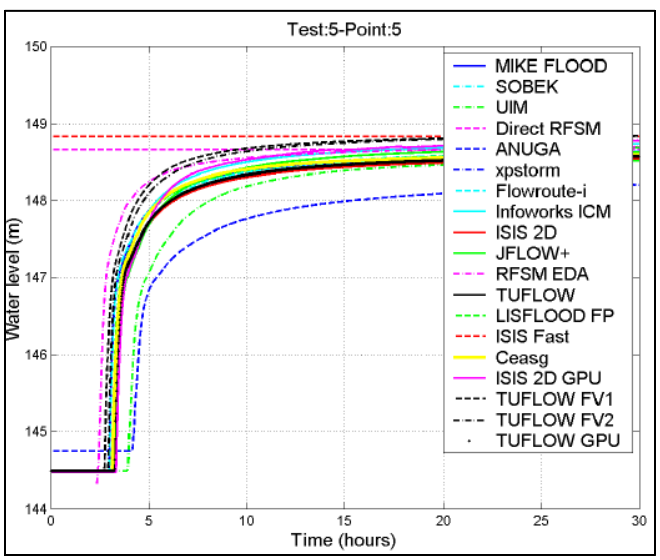

Figure 6-26 Test Point 5 – Water Level versus Time from Report SC120002 (2013)

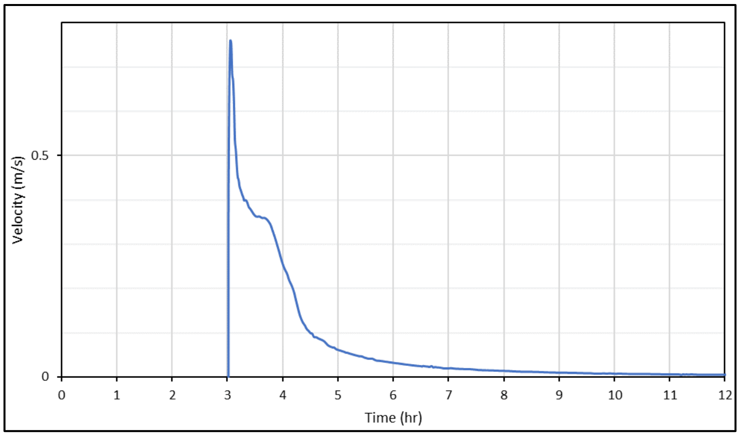

Figure 6-27 Test Point 5 – Velocity versus Time from SRH-2D

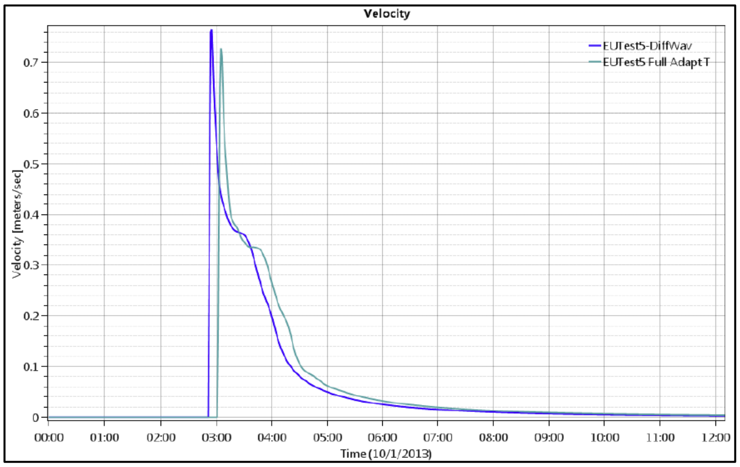

Figure 6-28 Test Point 5 – Velocity versus Time from RD-51 (2018)

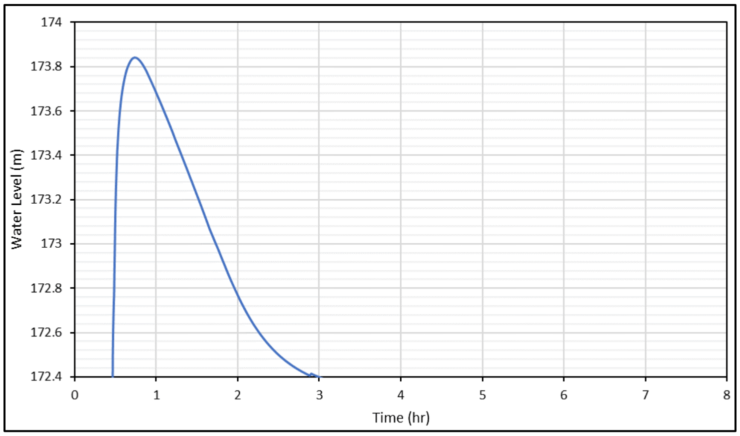

Figure 6-29 Test Point 6 – Water Level versus Time from SRH-2D

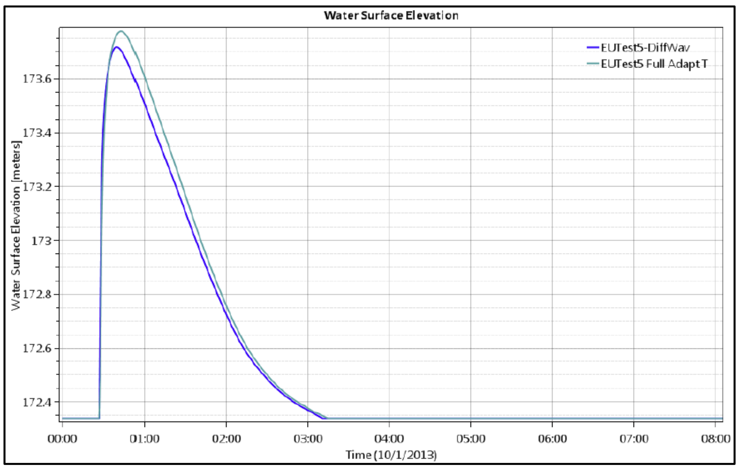

Figure 6-30 Test Point 6 – Water Level versus Time from RD-51 (2018)

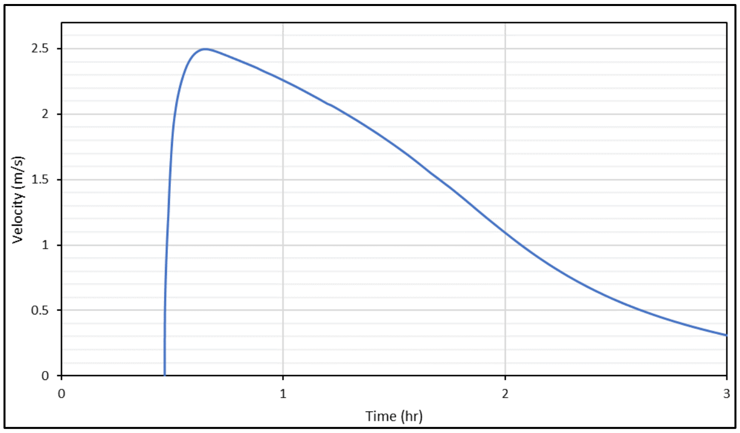

Figure 6-31 Test Point 6 – Velocity versus Time from SRH-2D

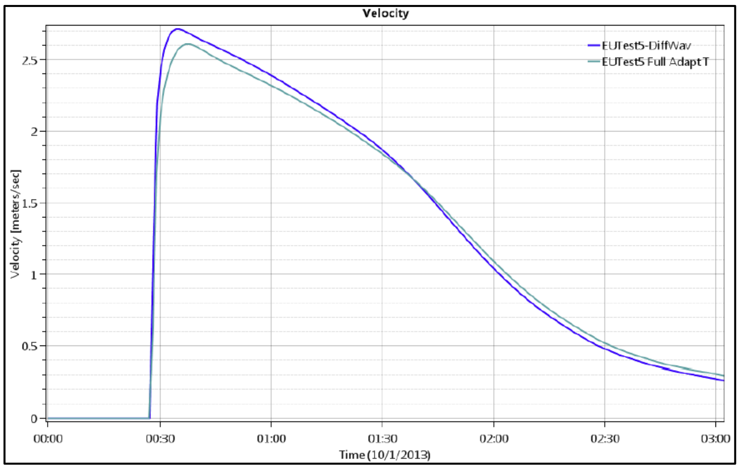

Figure 6-32 Test Point 6 – Velocity versus Time from RD-51 (2018)

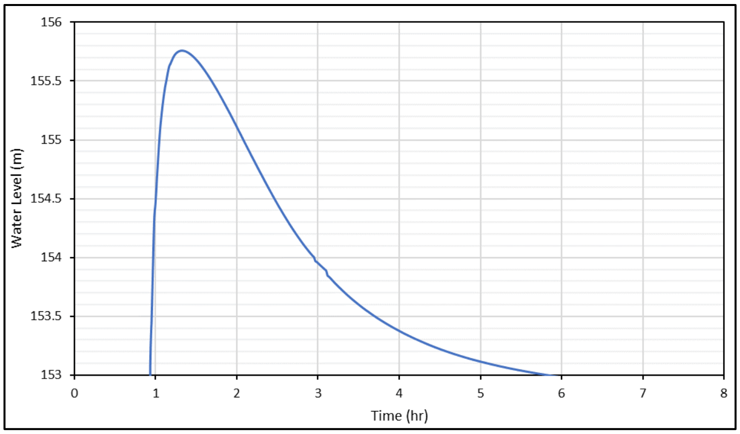

Figure 6-33 Test Point 7 – Water Level versus Time from SRH-2D

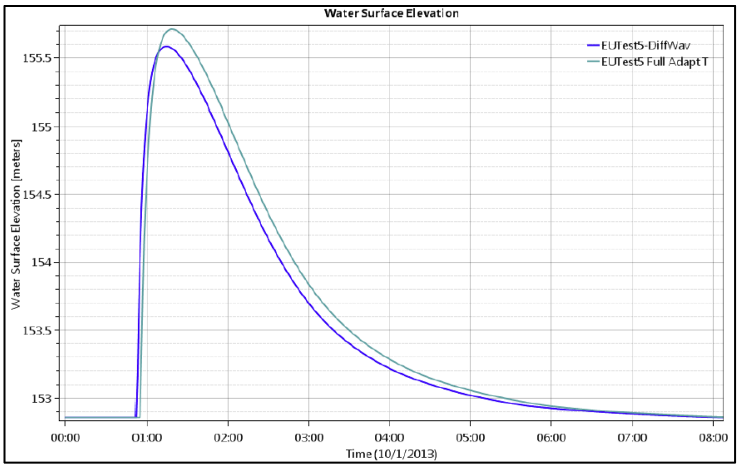

Figure 6-34 Test Point 7 – Water Level versus Time from RD-51 (2018)

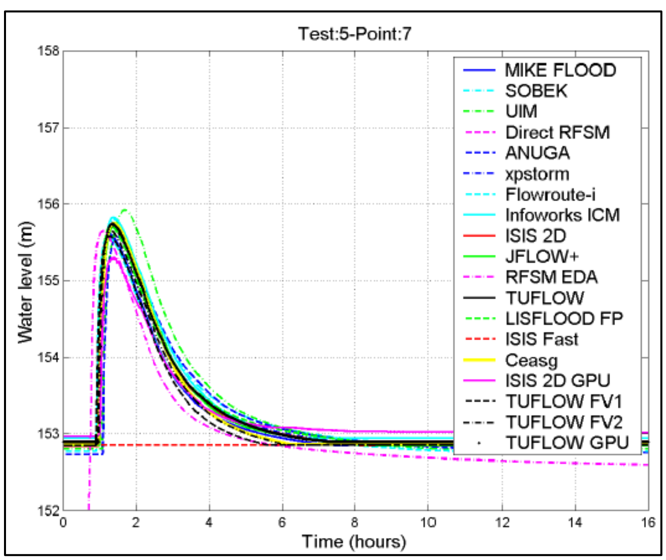

Figure 6-35 Test Point 7 – Water Level versus Time from Report SC120002 (2013)

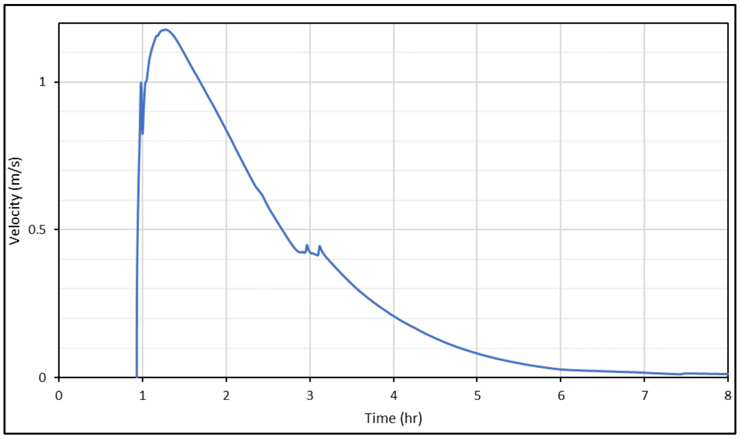

Figure 6-36 Test Point 7 – Velocity versus Time from SRH-2D

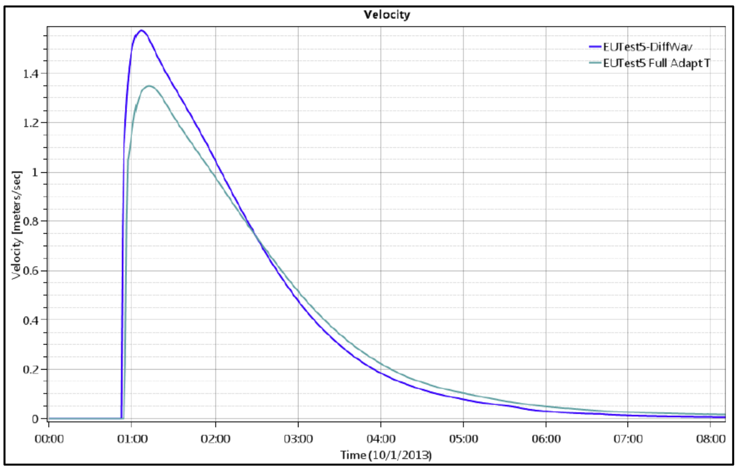

Figure 6-37 Test Point 7 – Velocity versus Time from RD-51 (2018)

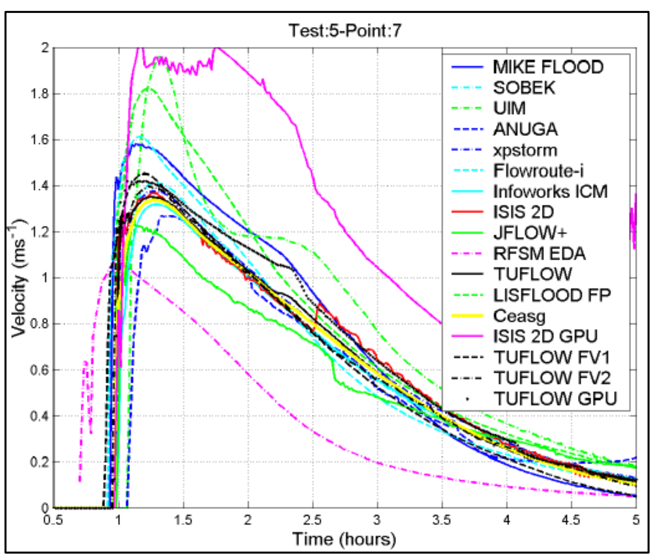

Figure 6-38 Test Point 7 – Velocity versus Time from Report SC120002 (2013)

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7 Benchmark Tests 6A & 6B: Dam Break

7.1 Objective

Benchmark Test 6A and 6B test the capability of a model to correctly simulate hydraulic jumps and wake zones behind buildings using high-resolution modeling. The test simulates a dam break scenario at two different physical scales.

7.2 Description

This dam-break test case has been adapted from an original benchmark test case available from the IMPACT project (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 7-1). An initial condition is applied, consisting of a uniform depth of 0.4 meters (1.3 feet) upstream from the dam, and 0.02 meters (0.07 feet) downstream from the dam. The flow is contained by vertical walls at all boundaries of the DEM.

Test 6B is identical to Test 6A except that all physical dimensions have been multiplied by 20 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 conditions in Test 6A:
    - Depth equals 0.4 meters (1.3 feet) upstream from the dam.
    - Depth equals 0.02 meters (0.07 feet) downstream from the dam.
- Initial conditions in Test 6B:
    - Depth equals 8 meters (26.2 feet) upstream from the dam.
    - Depth equals 0.4 (1.3 feet) meters downstream from the dam.

7.4 Parameter Values

- No preferred value of eddy viscosity is specified.
- In Test 6A:
    - Manning's n equals 0.01 (uniform).
    - Model grid resolution equals 0.1 meters (0.33 feet), or approximately 36,000 nodes in area bounded by vertical walls.
    - Time of end: Model is to be run until time T equals 2 minutes.
- In Test 6B:
    - Manning's n equals 0.05 (uniform).

- Model grid resolution equals 2 meters (6.6 feet), or approximately 36,000 nodes in area bounded by vertical walls.
- Time of end: Model is to be run until time T equals 30 minutes.

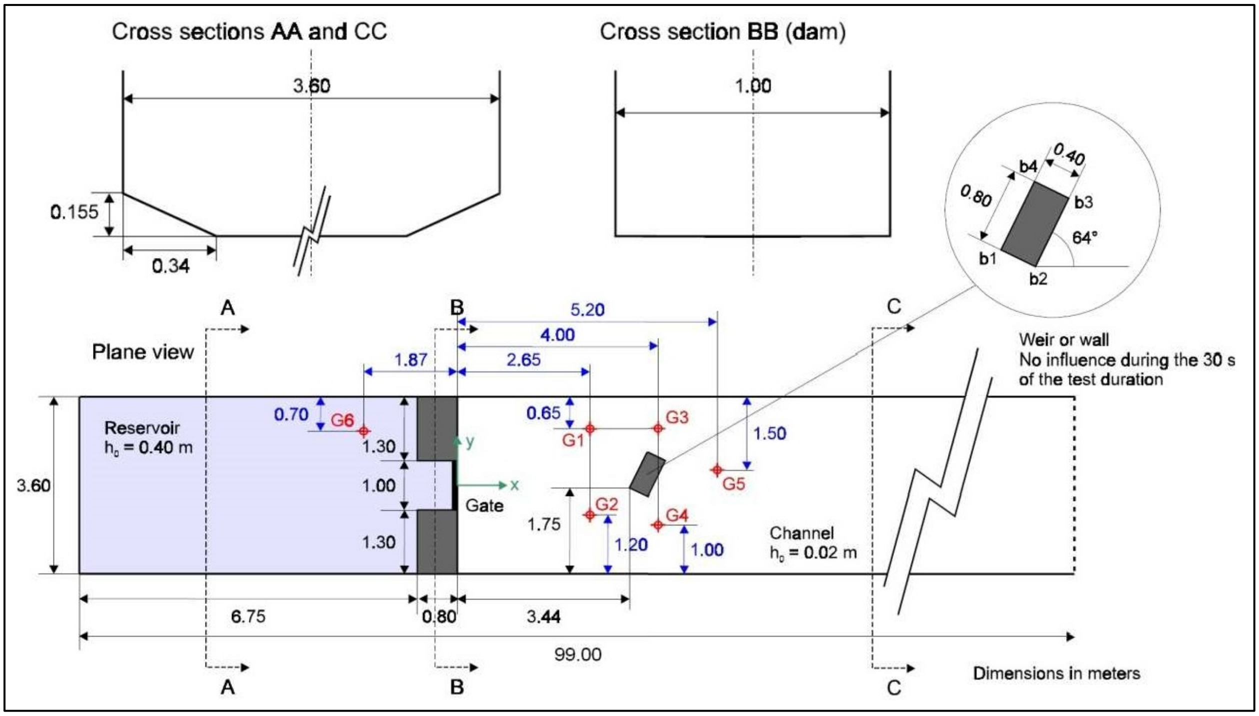

Figure 7-1 Setup for Benchmark Test 6A adapted from Soares-Frazao and Zech (2002).

7.5 Results

7.5.1 Test 6A Results

The results for Benchmark Test 6A were output at points G1 through G6 (Figure 7-1). Water level and velocity versus time, at a 0.1 second output frequency, are displayed for the SRH-2D results starting with Figure 7-2. A sensitivity analysis on the computational timestep was performed on timesteps varying from 0.025 seconds up to 0.1 seconds. It was determined that the 0.025 second timestep provided similar results to the 0.05 second timestep, with the exception of a couple test points. SRH-2D results contained in Figure 7-2 through Figure 7-26 illustrate SRH-2D results at a 0.05 second timestep. Table 7-1 provides information related to the modeling computer, grid resolution, number elements, computational timestep, total computational time, and Eddy Viscosity. Table 7-2 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included.

The results from the original Benchmarking Study are depicted starting at Figure 7-5. The results for Benchmark Test 6A for HEC-RAS 2D were not documented in RD-51 and are therefore not contained in this section. Results for Test 6A are less consistent at the test points than those of the previous benchmark tests. The small timestep and mesh resolution may be beyond the capabilities of the models and therefore impact the accuracy of the modeled results. The results located behind the dam at point G6 (Figure 7-18), from the models contained in the UK Benchmark report, are more consistent than the results at the other test points. Maximum water surface elevation and velocity values are depicted in plan view starting at Figure 7-20. Two cross sections shown in Figure 7-20 were used to plot maximum water surface elevation and velocity values, which are provided beginning at Figure 7-23.

In conclusion, as documented in Report SC120002 and SRH-2D, Test 6A results did not demonstrate conclusive ability to accurately predict hydraulic jumps and wake zones around buildings at the scale of the physical model data. 2D models are typically not developed at this scale in practice; test 6B results provide a more practical scale that modelers would typically utilize for modeling this type of scenario.

Table 7-1 Benchmark Test 6A Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	0.1 meters (0.33 feet); 36,000 elements in area bounded by vertical walls
Computational time increment used	0.05 seconds
Total computational time	187 seconds

Table 7-2 Benchmark Test 6A Model Parameters Adapted from Table 4.7 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time	Eddy Viscosity (m^2/s)
ANUGA	1.1beta_7501	No	37046 elements	Adaptive	690s	N/A
Ceasg	1.12	Yes -GPU	0.1m	0.02s	5.4s	N/A
InfoWorks ICM	2.5.2		36,066 nodes	1s	5s	N/A
ISIS 2D	3.6 (TVD)	No	0.1m	0.005s	386.1s	0
ISIS 2D GPU	1.17	Yes	0.1m	Adaptive	12s	0
JFLOW+	2	Yes -GPU	0.1m	Average	2.9s	None
MIKE FLOOD	2012	Yes - 8 CPUs	0.1m	0.025s	59s	0.010
SOBEK	*2.13*	No	0.1m	0.02s	390s	0
SRH-2D	3.3	No	0.1m	0.05s	196.6s	N/A
TUFLOW	2012-05-AA Single Precision	No	0.1m	Adaptive (0.01-0.5s)	32s	Spatially and time varying
TUFLOW GPU	2012-05-AA	Yes - 448 GPU Cores	0.1m	Adaptive (0.013-0.05s)	5s	As for TUFLOW
TUFLOW FV	2012.00b First order (and second order)	Yes - 12 CPU Cores	31,254 Elements	Adaptive (~0.005s)	45s (87s)	Spatially varying using S = 0.2
XPSTORM	2011 2010-10-AB-iDP-w32	No	0.1m	0.05s	42.9s	0.05 S + 0.05 C

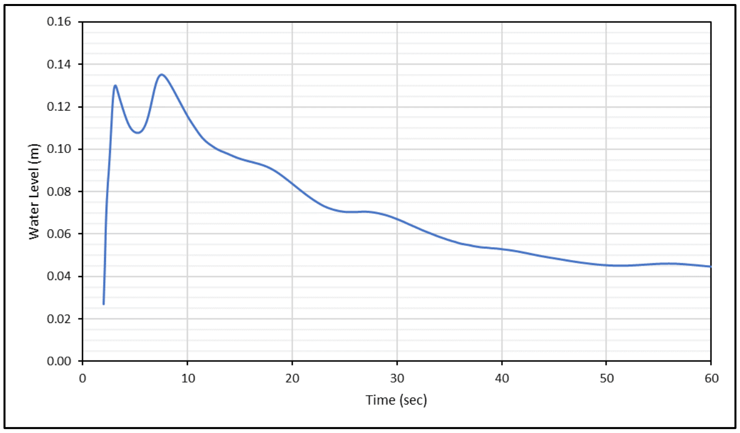

Figure 7-2 Test Point G1 – Water Level versus Time from SRH-2D

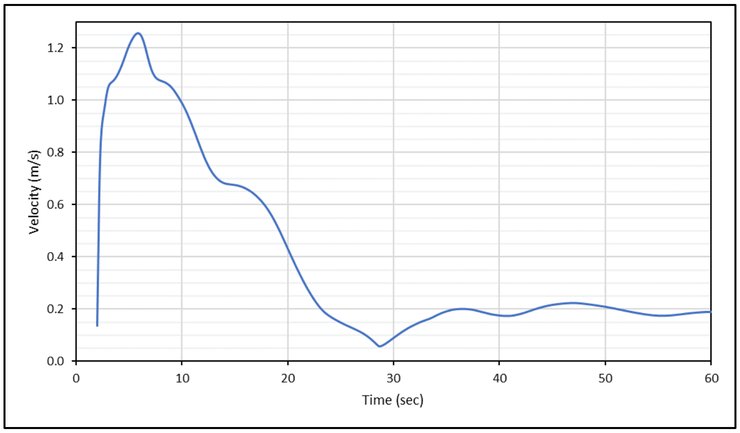

Figure 7-3 Test Point G1 – Velocity versus Time from SRH-2D

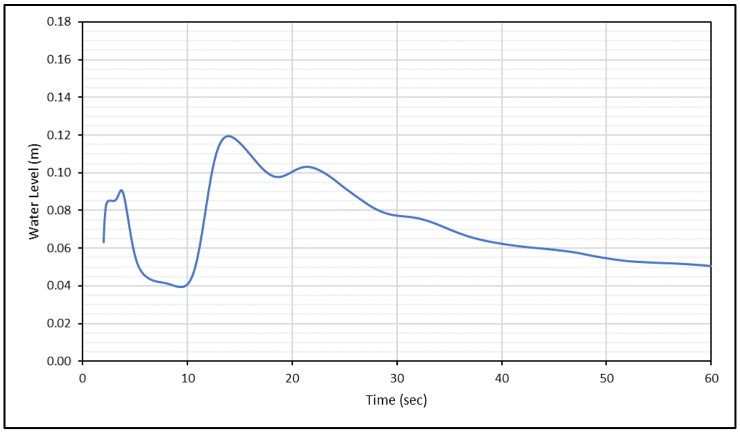

Figure 7-4 Test Point G2 – Water Level versus Time from SRH-2D

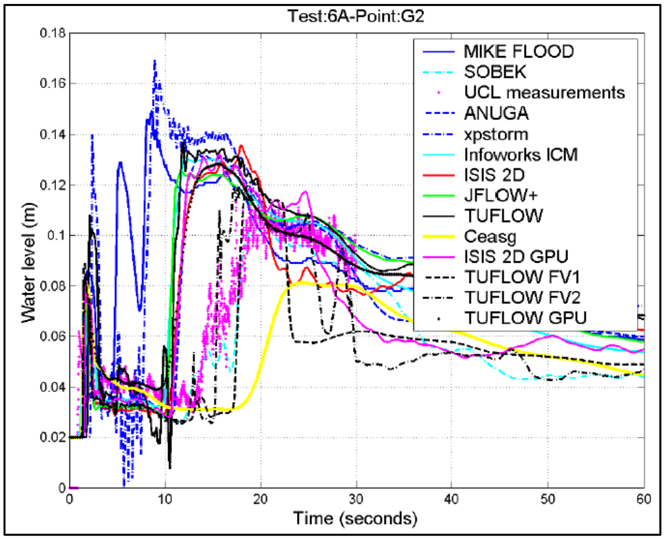

Figure 7-5 Test Point G2 – Water Level versus Time from Report SC120002 (2013)

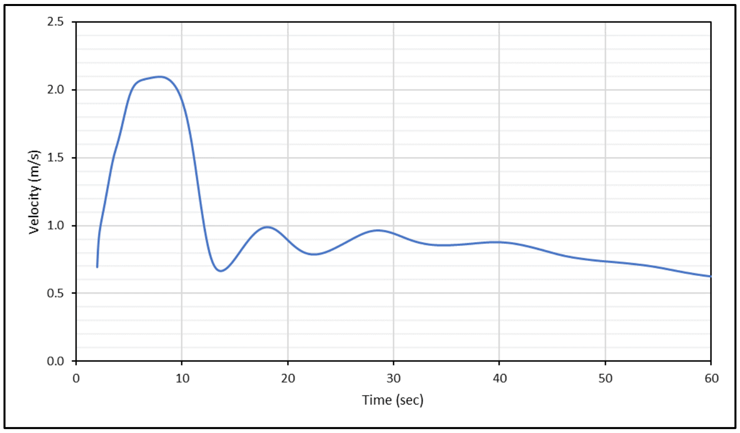

Figure 7-6 Test Point G2 – Velocity versus Time from SRH-2D

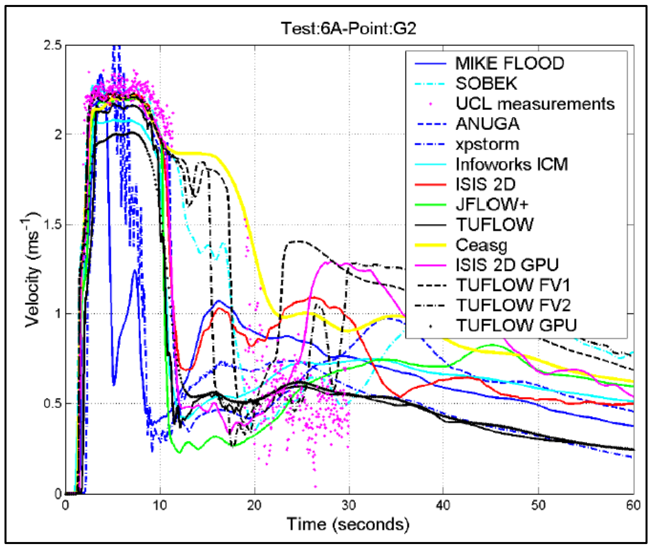

Figure 7-7 Test Point G2 – Velocity versus Time from Report SC120002 (2013)

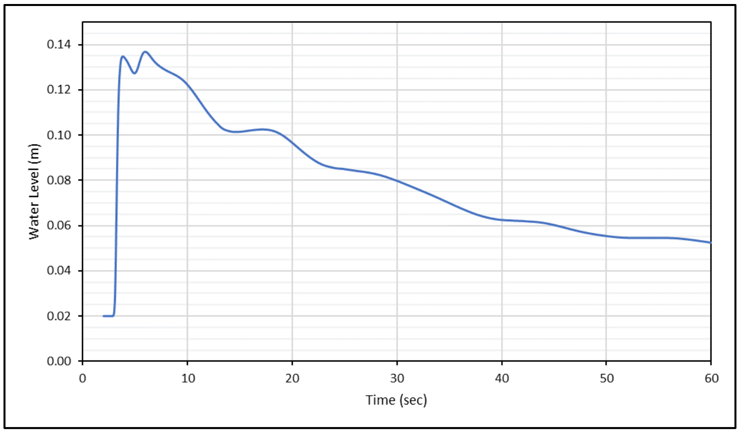

Figure 7-8 Test Point G3 – Water Level versus Time from SRH-2D

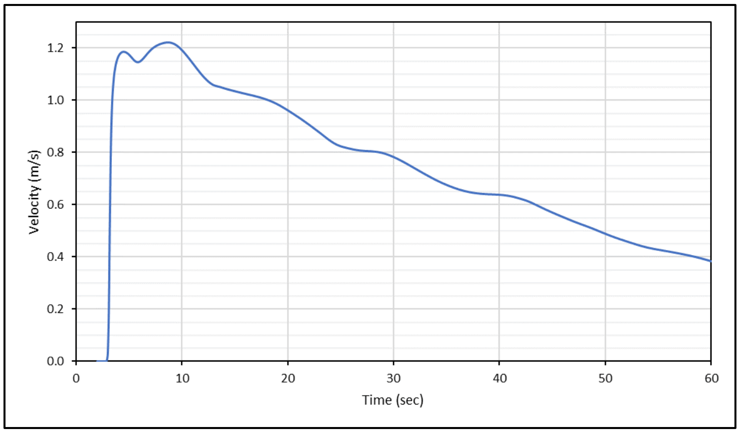

Figure 7-9 Test Point G3 – Velocity versus Time from SRH-2D

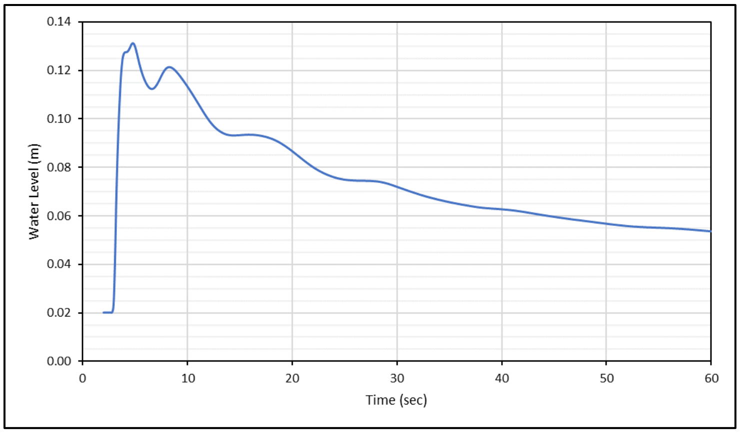

Figure 7-10 Test Point G4 – Water Level versus Time from SRH-2D

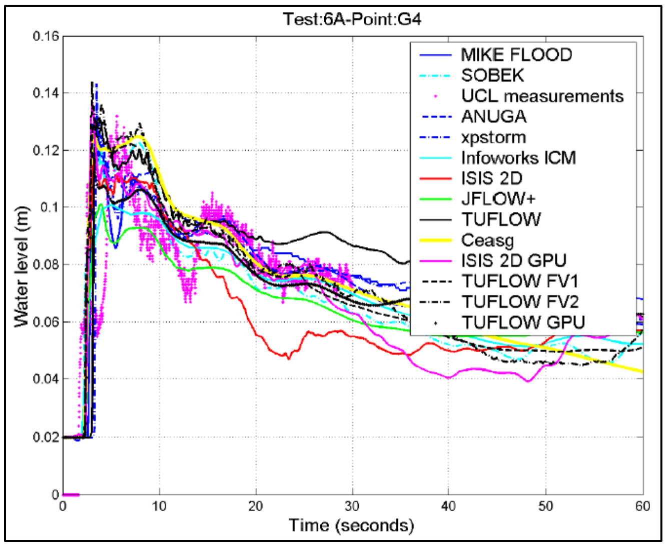

Figure 7-11 Test Point G4 – Water Level versus Time from Report SC120002 (2013)

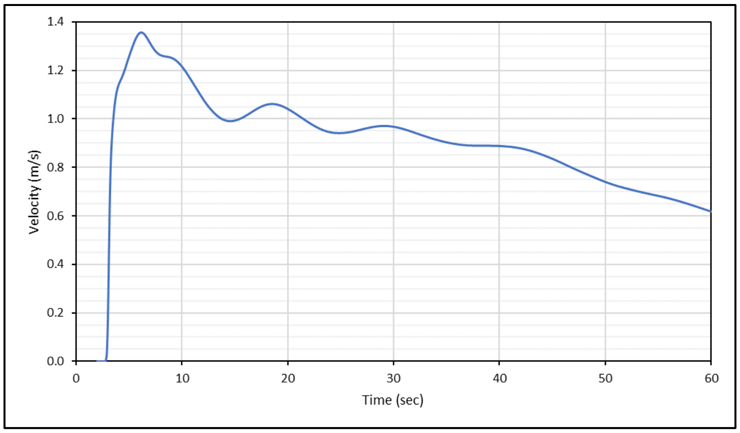

Figure 7-12 Test Point G4 – Velocity versus Time from SRH-2D

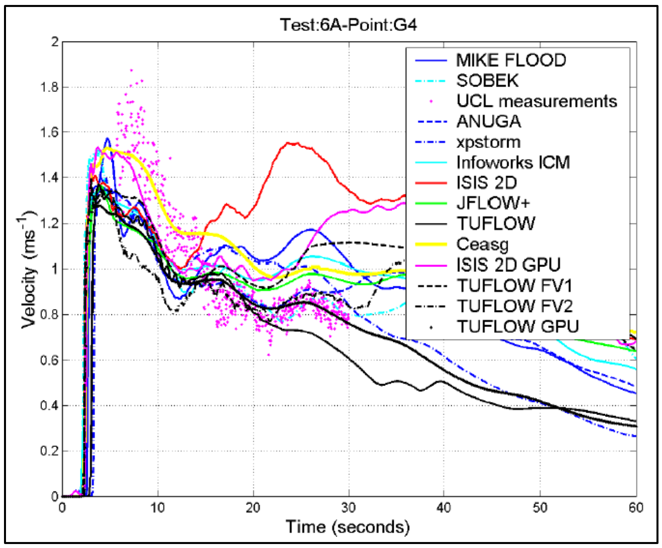

Figure 7-13 Test Point G4 – Velocity versus Time from Report SC120002 (2013)

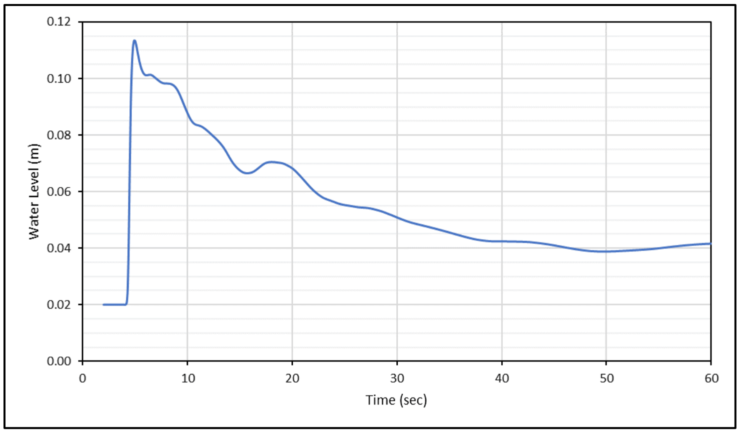

Figure 7-14 Test Point G5 – Water Level versus Time from SRH-2D

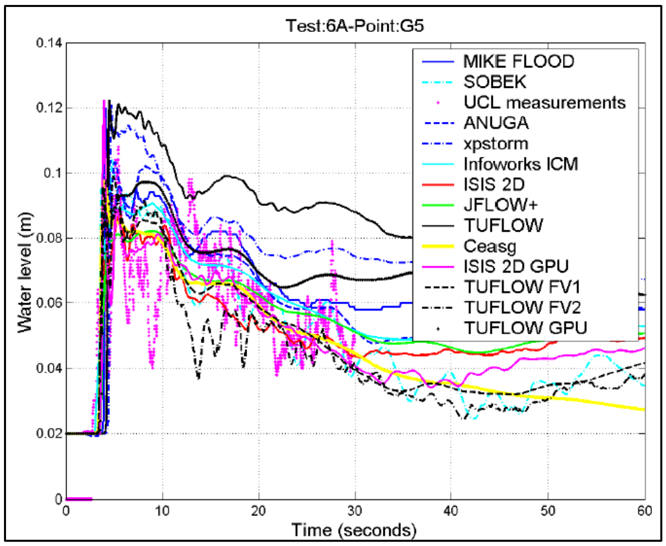

Figure 7-15 Test Point G5 – Water Level versus Time from Report SC120002 (2013)

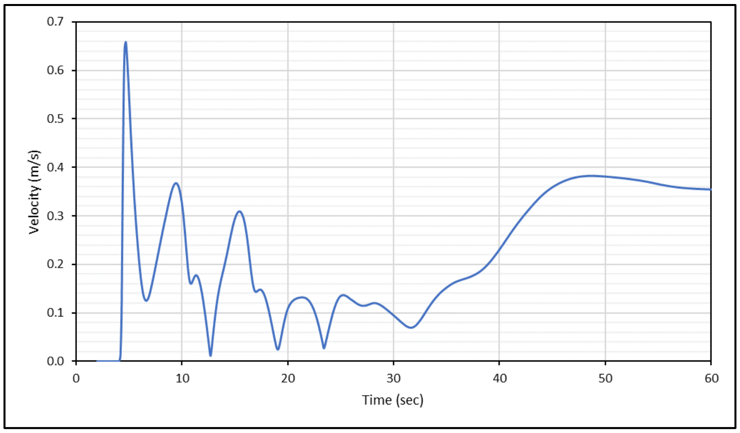

Figure 7-16 Test Point G5 – Velocity versus Time from SRH-2D

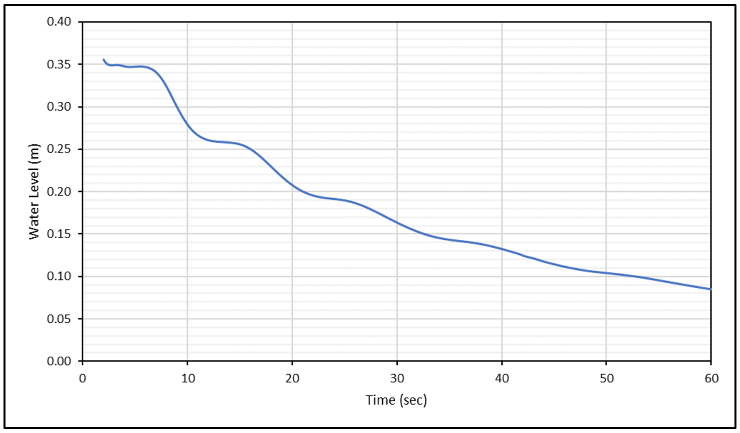

Figure 7-17 Test Point G6 – Water Level versus Time from SRH-2D

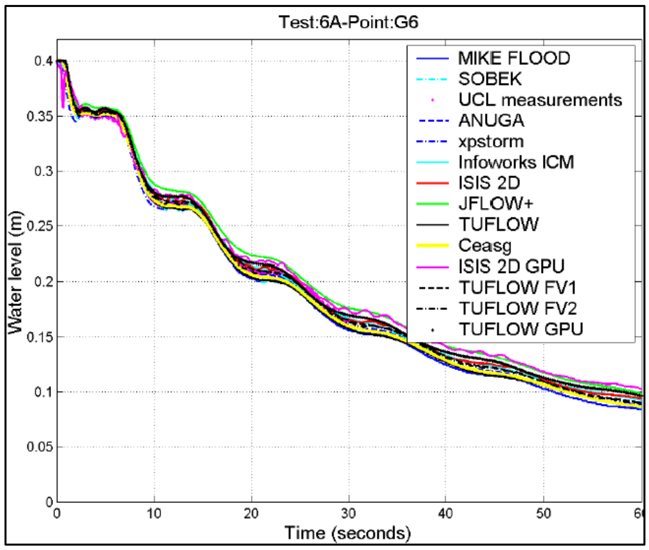

Figure 7-18 Test Point G6 – Water Level versus Time from Report SC120002 (2013)

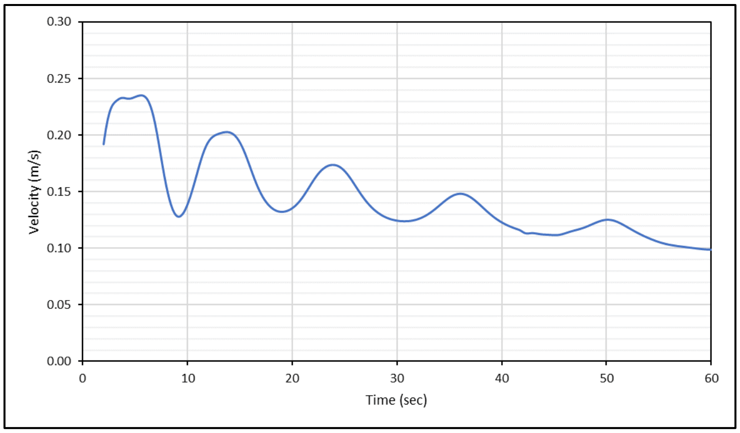

Figure 7-19 Test Point G6 – Velocity versus Time from SRH-2D

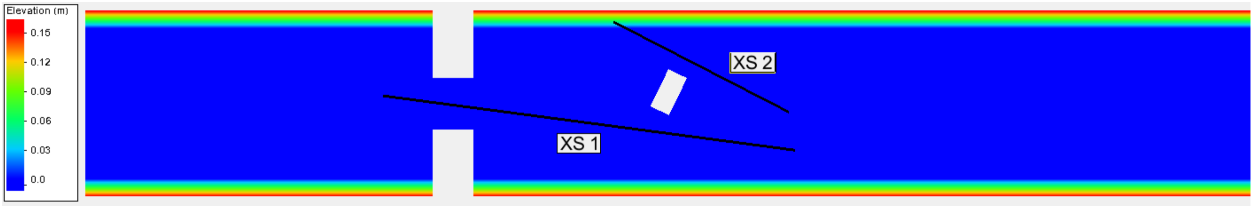

Figure 7-20 Test 6A Elevation Mesh Depicting XS 1 and XS 2 from SRH-2D

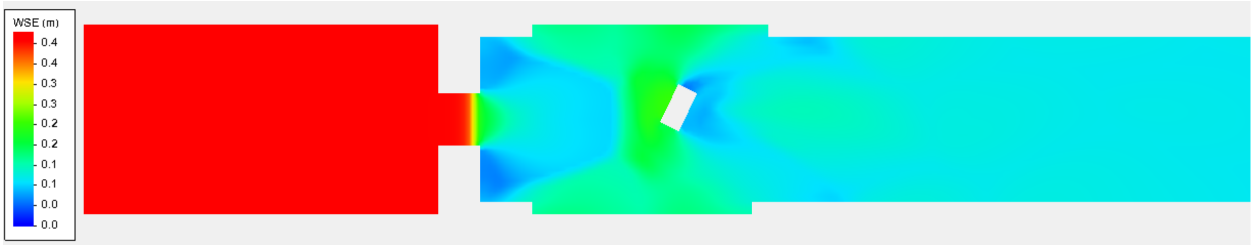

Figure 7-21 Test 6A Maximum Water Surface Elevation (meters) from SRH-2D

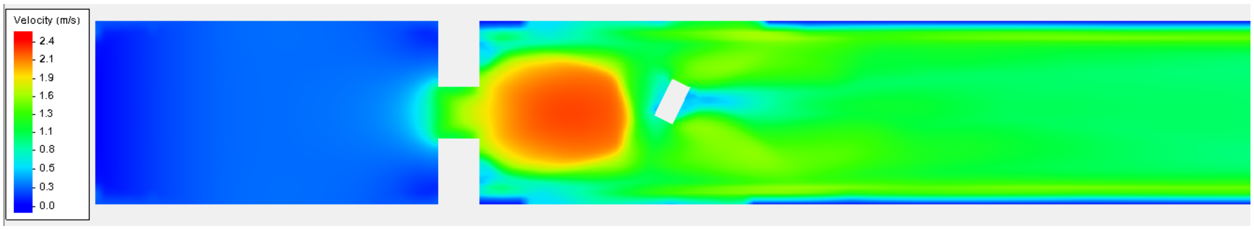

Figure 7-22 Test 6A Maximum Velocity Magnitude (meters per second) from SRH-2D

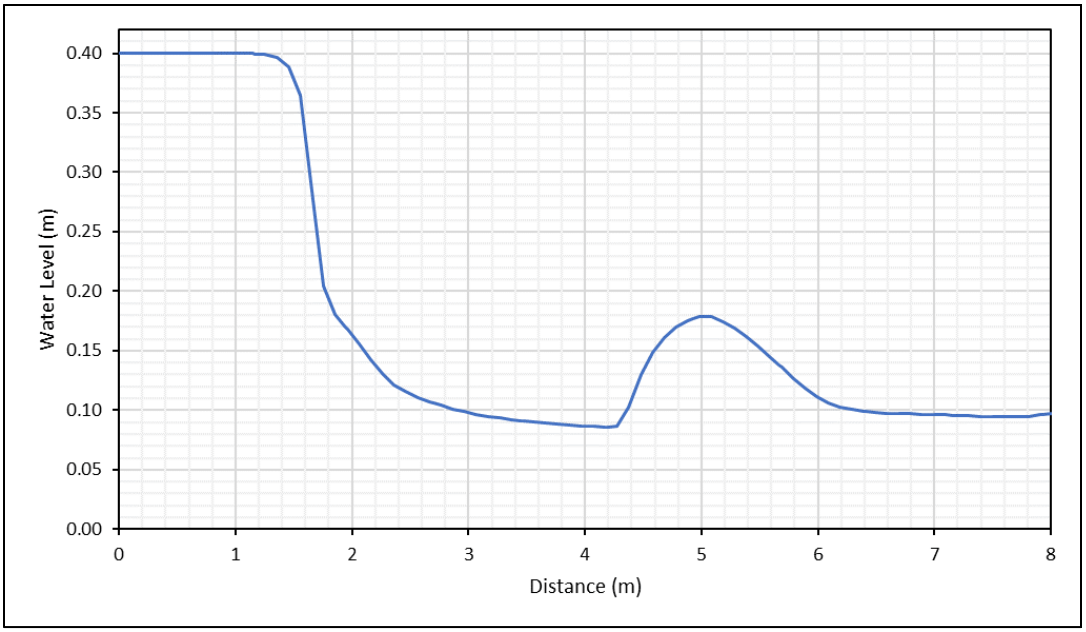

Figure 7-23 Test 6A Maximum Water Surface Elevation Along XS 1 from SRH-2D

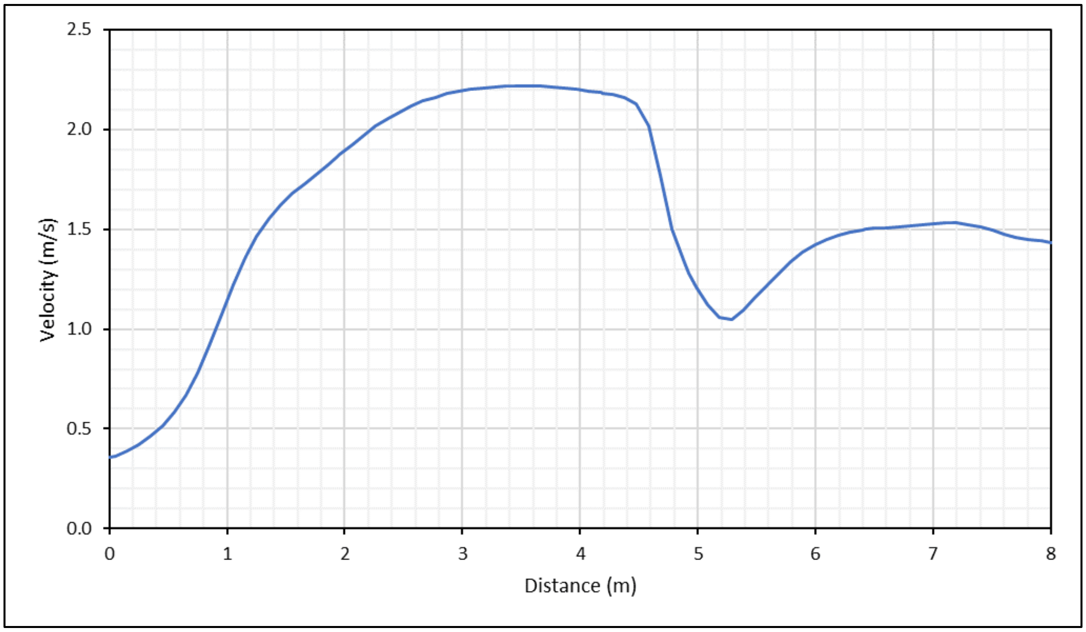

Figure 7-24 Test 6A Maximum Velocity Magnitude Along XS 1 from SRH-2D

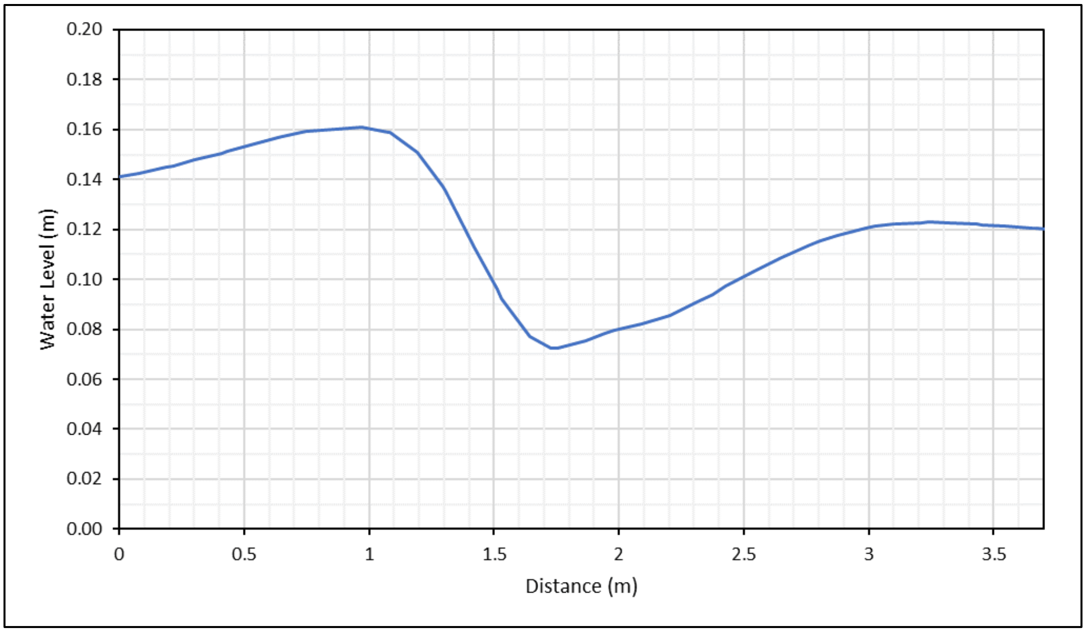

Figure 7-25 Test 6A Maximum Water Surface Elevation Along XS 2 from SRH-2D

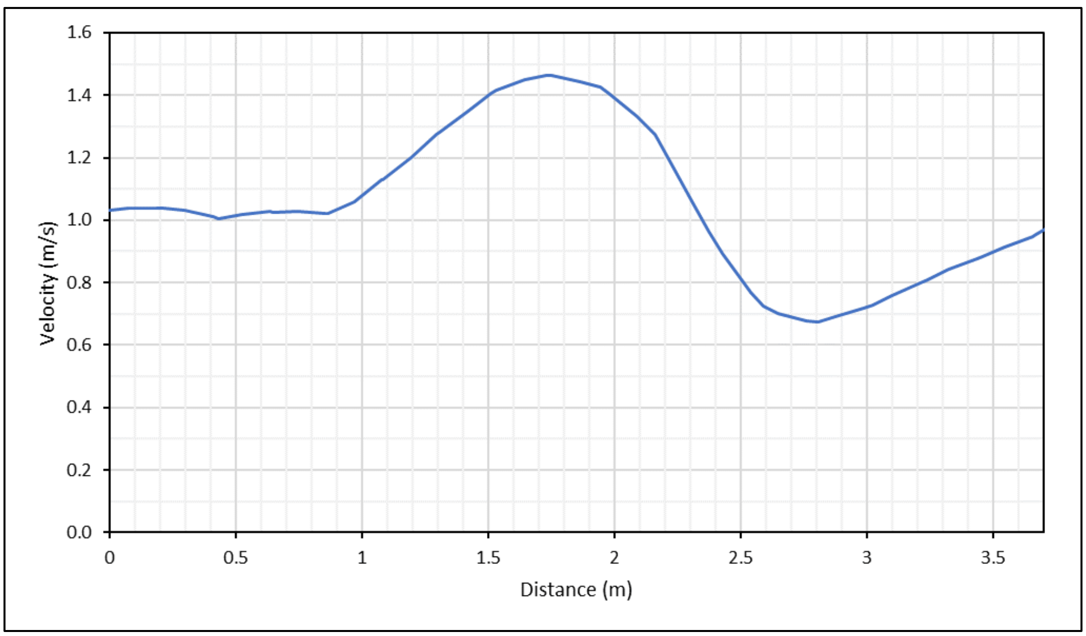

Figure 7-26 Test 6A Maximum Velocity Magnitude Along XS 2 from SRH-2D

7.5.2 Test 6B Results

The results for Benchmark Test 6B were output at points G1 through G6 (scaled by a factor of 20 compared to Figure 7-1). Water level and velocity versus time, at a 1 second output frequency, are displayed for the SRH-2D results starting with Figure 7-27. A sensitivity analysis on the computational timestep was performed on timesteps varying from 0.1 seconds up to 1 second. It was determined that the 0.25 second timestep provided similar results to the 0.1 second timestep, with the exception of a couple of locations within test points. Table 7-3 provides information related to the modeling computer, grid resolution, number elements, computational timestep, total computational time, and Eddy Viscosity. Table 7-4 provides information for the model parameters from the UK benchmark tests with the SRH-2D and HEC-RAS 2D parameters included. Both tables include the 0.25 and 0.1 second timestep with corresponding total computation times.

The results from the original Benchmarking Study are depicted starting at Figure 7-33. The results for Benchmark Test 6B for HEC-RAS 2D are depicted beginning with Figure 7-28. Overall, SRH-2D performed well compared to the models from the original UK benchmark tests.

Maximum water surface elevation and velocity values throughout the domain from SRH-2D are depicted in plan view starting at Figure 7-58. The HEC-RAS 2D results for these maximum values are also included starting at Figure 7-60. When comparing the maximum velocity results of SRH-2D (Figure 7-59) to HEC-RAS-2D (Figure 7-61), it can be seen that HEC-RAS 2D maximum velocities near the downstream location of the dam extend further in the transverse direction.

Two cross sections shown in Figure 7-57 were used to plot maximum water surface elevation and velocity values, which are provided beginning at Figure 7-62. Figures from HEC-RAS 2D and the UK Benchmark study models are also included for comparison starting at Figure 7-63 and Figure 7-64, respectively. In general, SRH-2D maximum water surface elevations and velocities along cross section 1 in Figure 7-62 through Figure 7-67 compare well with HEC-RAS 2D and the majority of the models reported in the UK Benchmark report.

SRH-2D maximum water surface elevations and velocities, along cross section 2 in Figure 7-68 through Figure 7-73 tend to have higher water surface elevations and lower velocities compared to HEC-RAS 2D. Velocities vary both in magnitude and timing of peaks along cross section 2 with the models reported in the UK Benchmark report (Figure 7-73), however SRH-2D results fall within where most model results in the UK report converge.

In conclusion, SRH-2D performed well compared to the other 2D models from the original Benchmarking Study, as well as HEC-RAS 2D (Figure 7-2 to Figure 7-73) to accurately predict hydraulic jumps and wake zones around buildings at a field scale, which is a more practical than test 6A.

Table 7-3 Benchmark Test 6B Summary Information

Version Number and Numerical Scheme	SRH-2D Version 3.3 Two-dimensional finite volume solution of the St. Venant/shallow-water equations.
Specification of hardware used to undertake the simulation	Dell Precision 3431, 32 GB RAM Intel Core i7-9700 with 3.0 GHz base frequency to 4.8 GHz turbo frequency
Minimum recommended hardware specifications	Refer to hardware details in Table 1-1
Grid resolution; number of element nodes	2 meters (6.6 feet); 36,000 elements in area bounded by vertical walls
Computational time increment used	0.25 (0.1) seconds
Total computational time	475 (1021) seconds

Table 7-4 Benchmark Test 6B Model Parameters Adapted from Table 4.8 in Report SC120002 (2013)

Name	Version	Multi-Processing	Resolution	Computational Time Increment	Run Time	Eddy Viscosity (m^2/s)
ANUGA	1.1beta_7501	No	36219 elements	Adaptive	1390s	N/A
Ceasg	1.12	No - GPU	2m	0.1s	14s	N/A
HEC-RAS 2D	5.0.4	Yes	2m	1s	78s	Unspecified
InfoWorks ICM	2.5.2	Yes - GPU	36,910 Triangles	1s	34s	N/A
ISIS 2D	3.6 (TVD)	No	2m	0.05s	559.1s	0
ISIS 2D GPU	1.17	Yes	2m	Adaptive	19s	0
JFLOW+	2	Yes - GPU	2m	Average 0.25s	6s	0
MIKE FLOOD	2012	Yes-8 CPUs	2m	0.4s	54.9s	0.36
SOBEK	2.13	No	2m	0.1s	1010s	0.000
SRH-2D	3.3	No	2m	0.25s (0.1s)	475s (1021s)	N/A
TUFLOW	2012-05-AA Single Precision	No	2m	Adaptive (0.1-3.3s)	38s	Spatially and time varying
TUFLOW GPU	2012-05-AA	Yes - 448 GPU Cores	2m	Adaptive (0.06-0.25s)	12s	Same as TUFLOW
TUFLOW FV	2012.00b First order (and second order)	Yes - 12 CPU cores	31,254 Elements	Adaptive (~0.035s)	109s (195s)	Spatially varying using S=0.2
XPSTORM	2011 2010-10-AB-iDP-w32	No	2m	0.2s	61.7s	0.5 S + 0.1 C

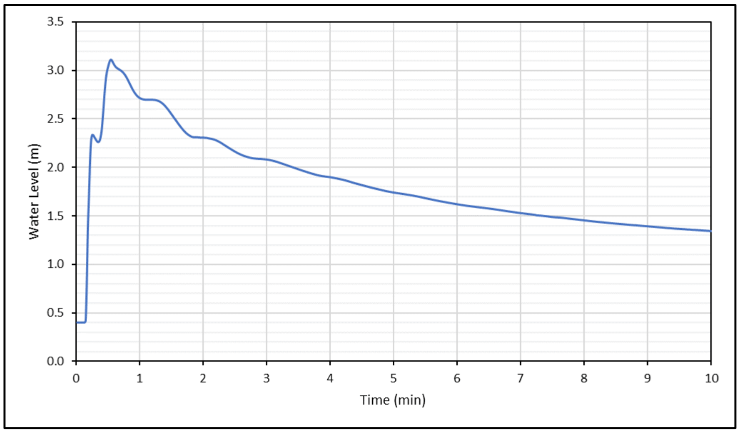

Figure 7-27 Test Point G1 – Water Level versus Time from SRH-2D

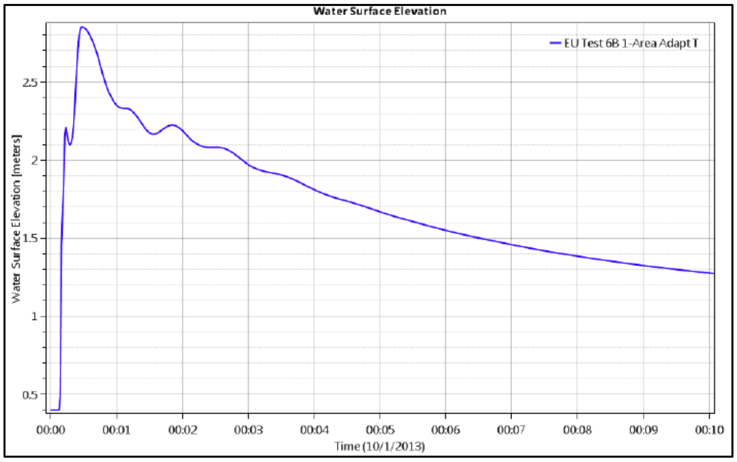

Figure 7-28 Test Point G1 – Water Level versus Time from RD-51 (2018)

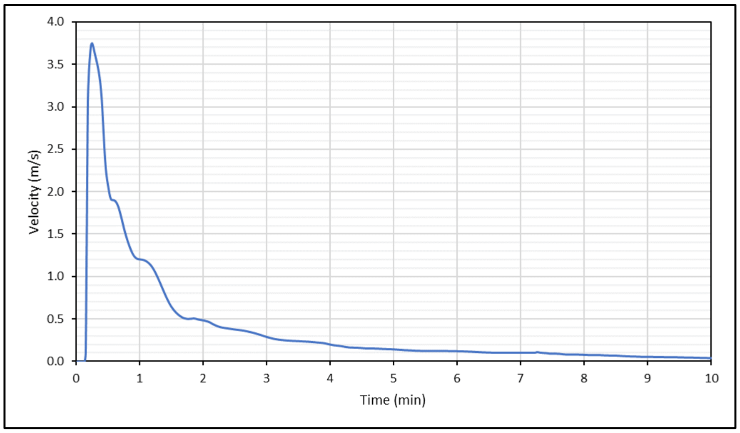

Figure 7-29 Test Point G1 – Velocity versus Time from SRH-2D

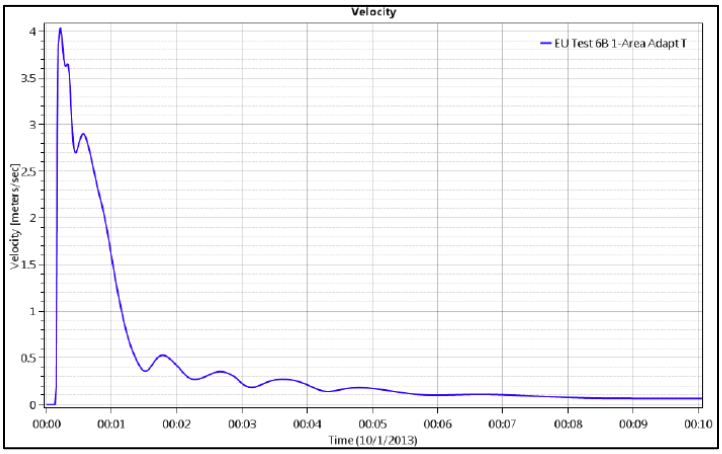

Figure 7-30 Test Point G1 – Velocity versus Time from RD-51 (2018)

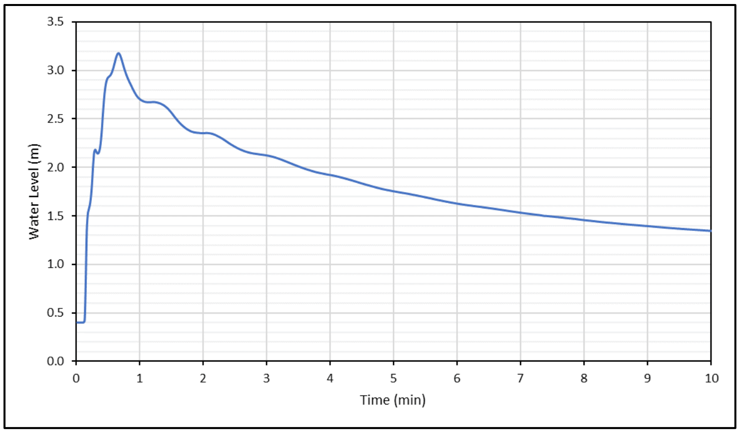

Figure 7-31 Test Point G2 – Water Level versus Time from SRH-2D

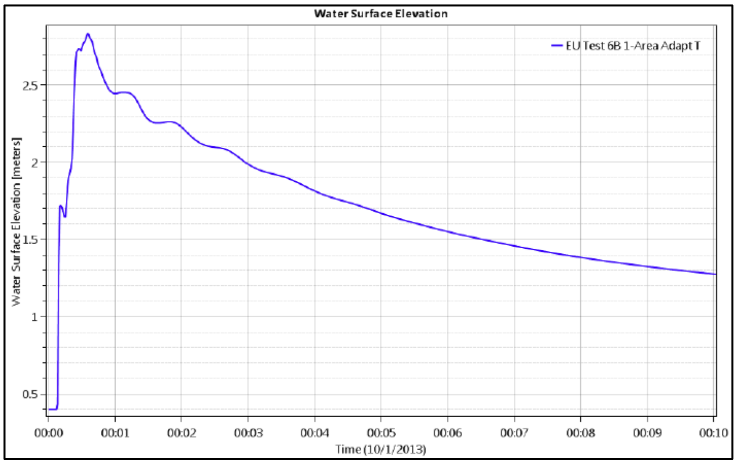

Figure 7-32 Test Point G2 – Water Level versus Time from RD-51 (2018)

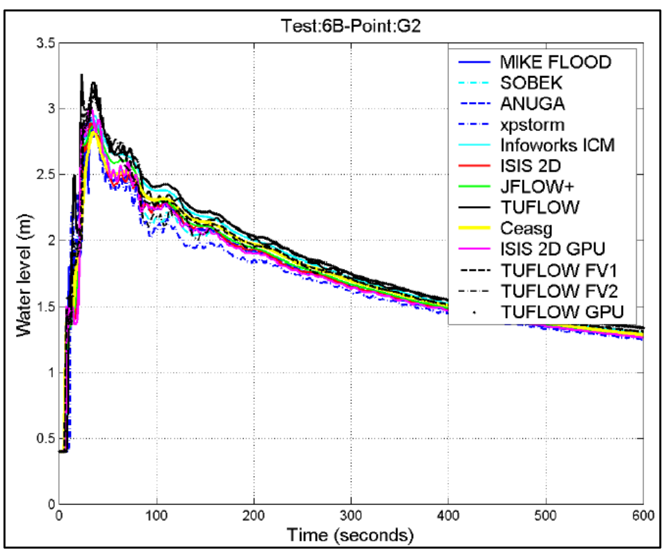

Figure 7-33 Test Point G2 – Water Level versus Time from Report SC120002 (2013)

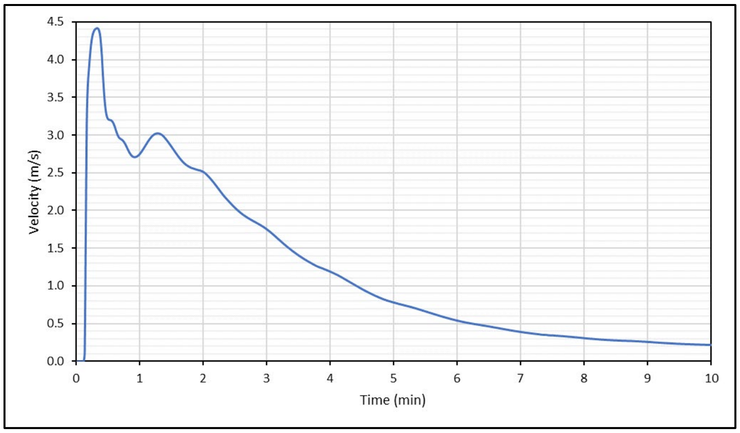

Figure 7-34 Test Point G2 – Velocity versus Time from SRH-2D

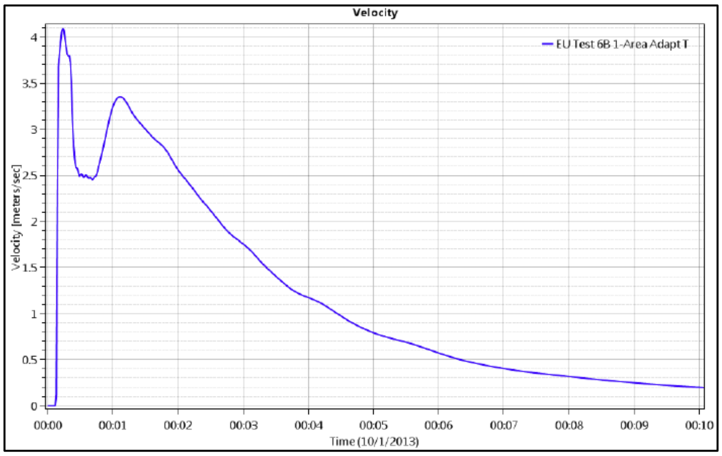

Figure 7-35 Test Point G2 – Velocity versus Time from RD-51 (2018)

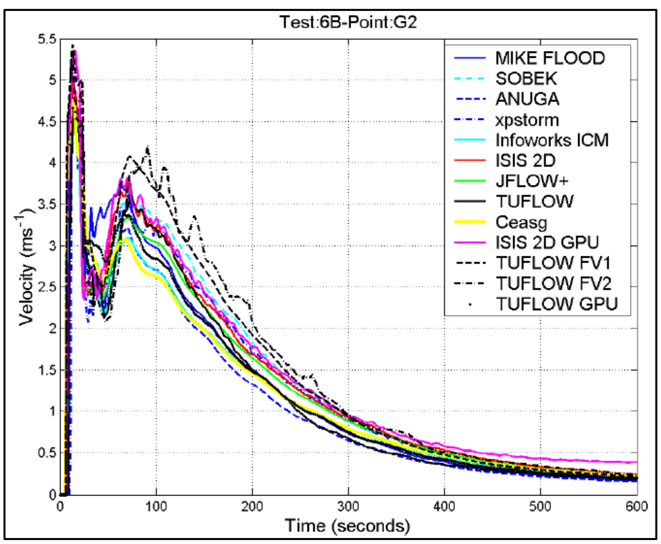

Figure 7-36 Test Point G2 – Velocity versus Time from Report SC120002 (2013)

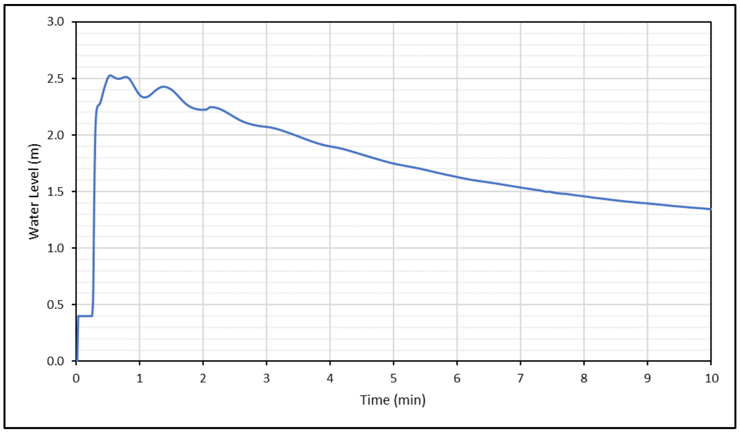

Figure 7-37 Test Point G3 – Water Level versus Time from SRH-2D

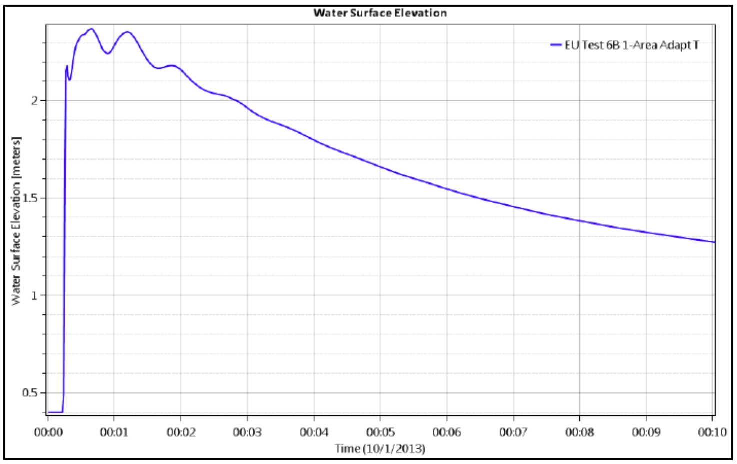

Figure 7-38 Test Point G3 – Water Level versus Time from RD-51 (2018)

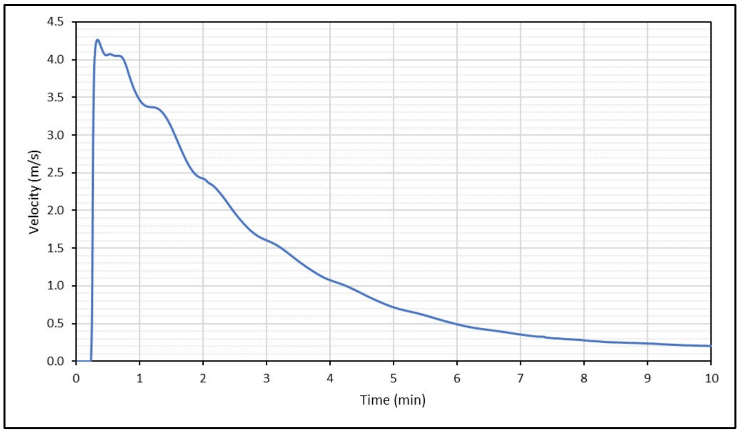

Figure 7-39 Test Point G3 – Velocity versus Time from SRH-2D

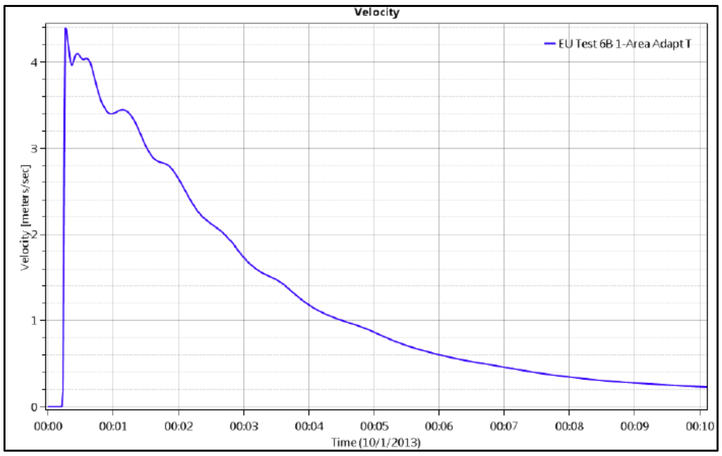

Figure 7-40 Test Point G3 – Velocity versus Time from RD-51 (2018)

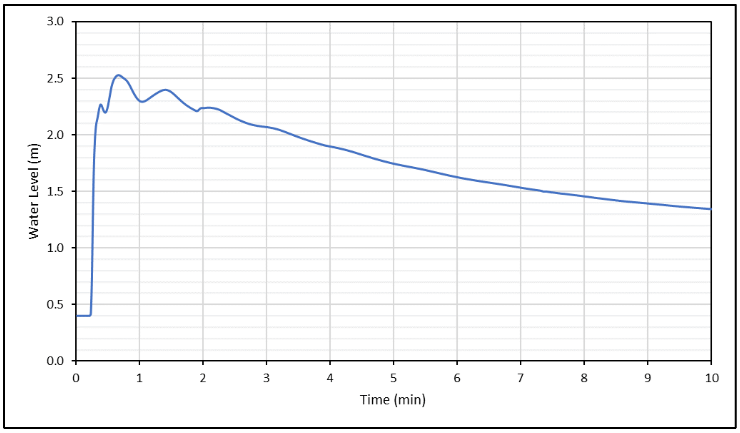

Figure 7-41 Test Point G4 – Water Level versus Time from SRH-2D

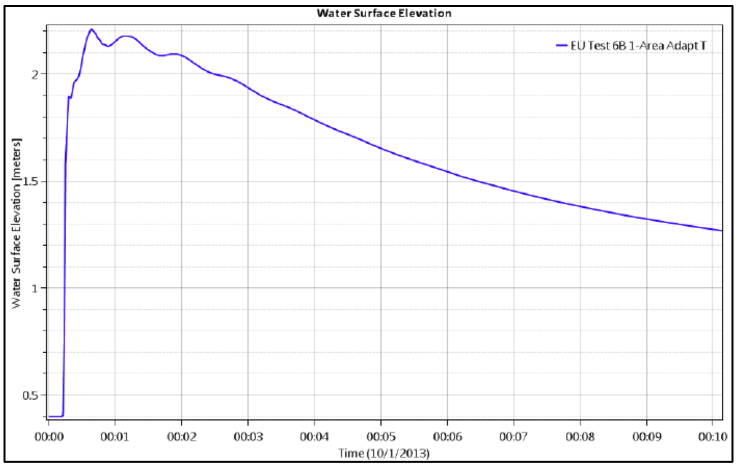

Figure 7-42 Test Point G4 – Water Level versus Time from RD-51 (2018)

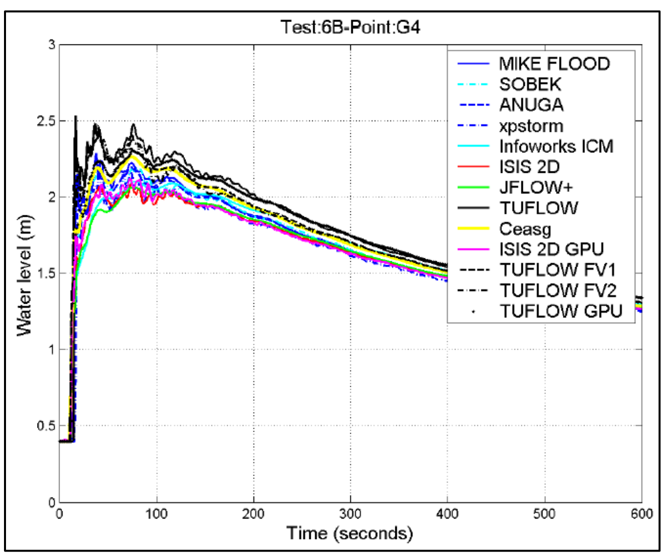

Figure 7-43 Test Point G4 – Water Level versus Time from Report SC120002 (2013)

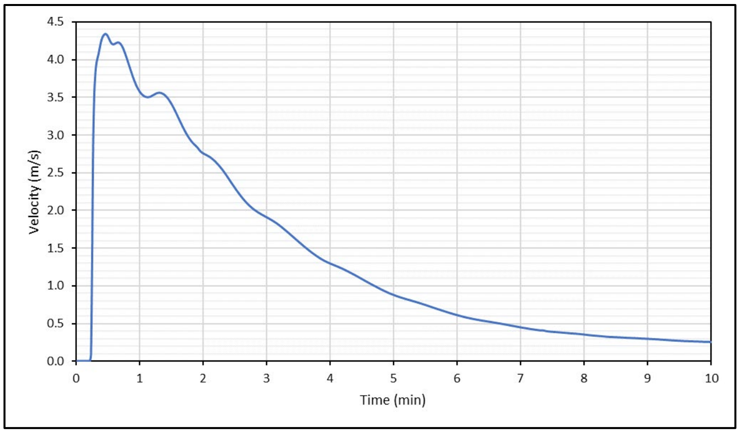

Figure 7-44 Test Point G4 – Velocity versus Time from SRH-2D

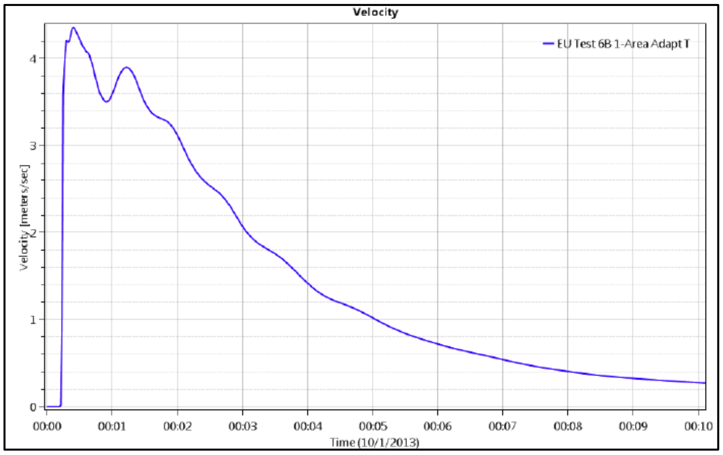

Figure 7-45 Test Point G4 – Velocity versus Time from RD-51 (2018)

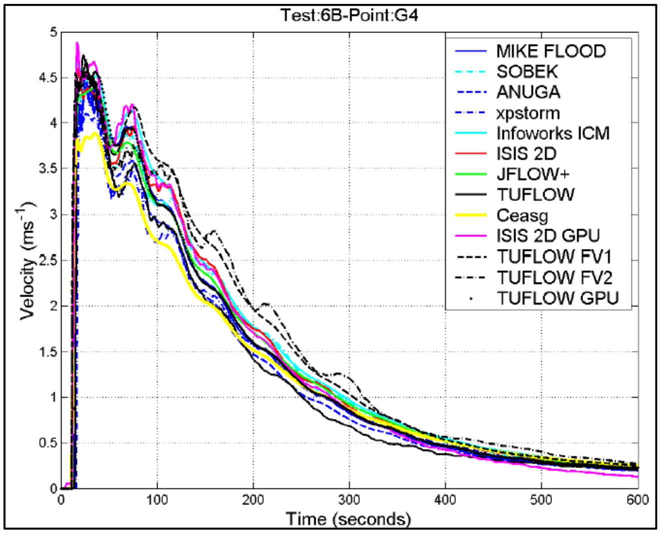

Figure 7-46 Test Point G4 – Velocity versus Time from Report SC120002 (2013)

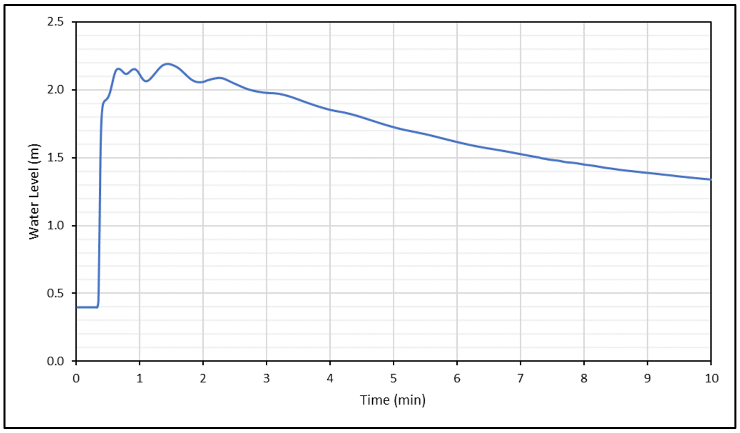

Figure 7-47 Test Point G5 – Water Level versus Time from SRH-2D

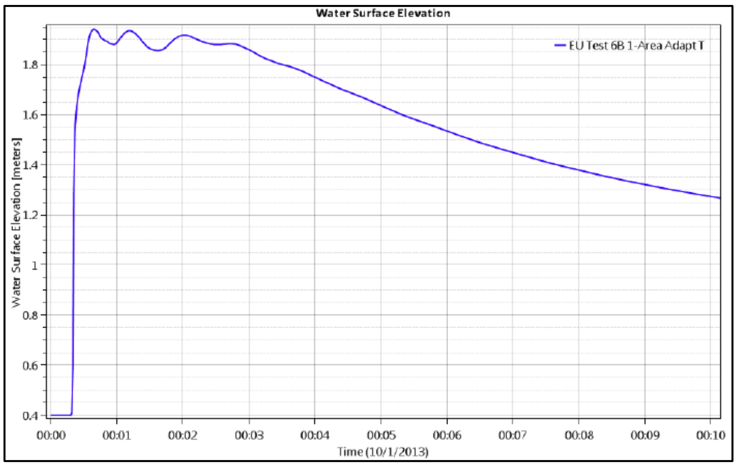

Figure 7-48 Test Point G5 – Water Level versus Time from RD-51 (2018)

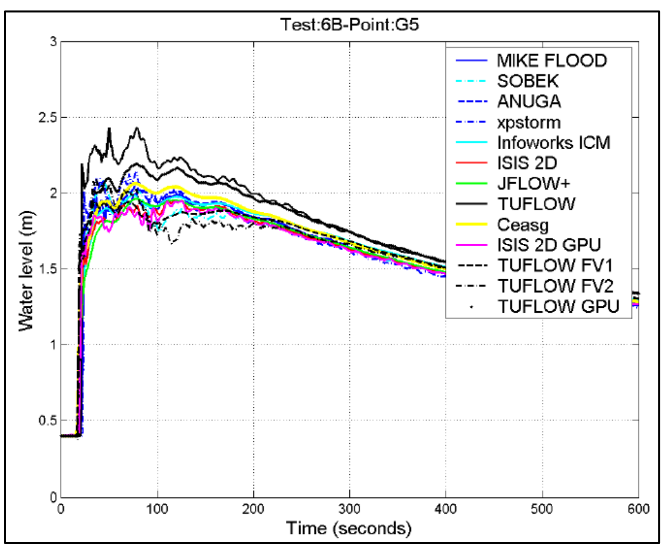

Figure 7-49 Test Point G5 – Water Level versus Time from Report SC120002 (2013)

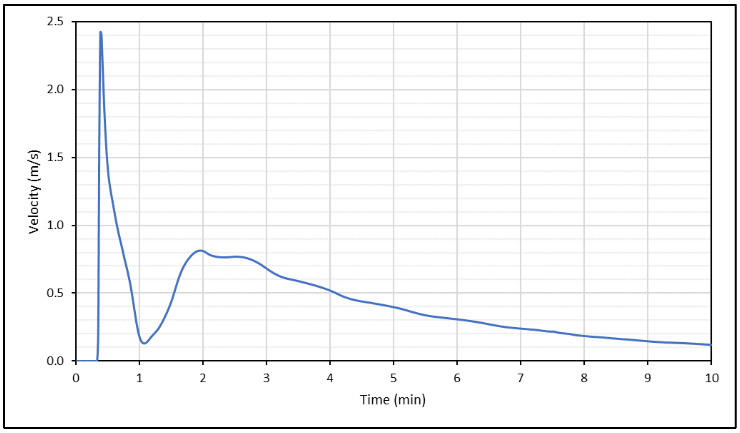

Figure 7-50 Test Point G5 – Velocity versus Time from SRH-2D

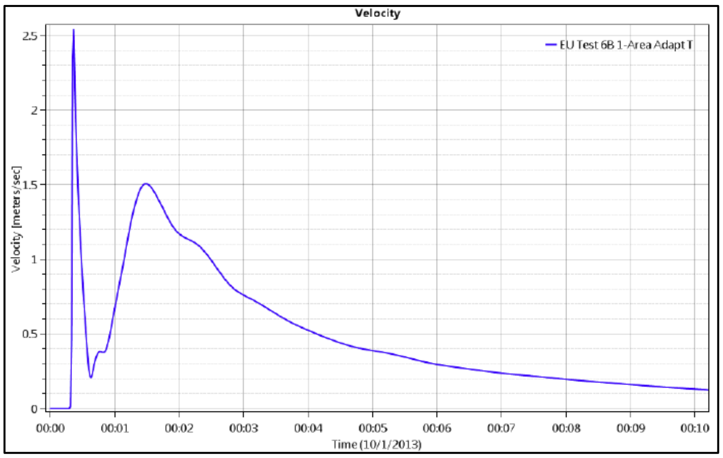

Figure 7-51 Test Point G5 – Velocity versus Time from RD-51 (2018)

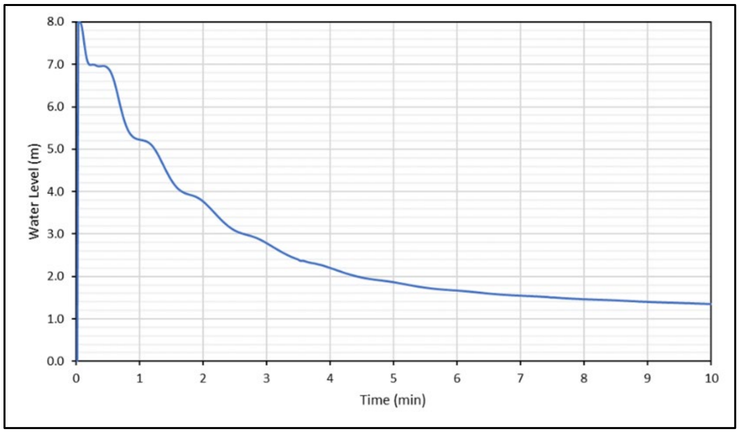

Figure 7-52 Test Point G6 – Water Level versus Time from SRH-2D

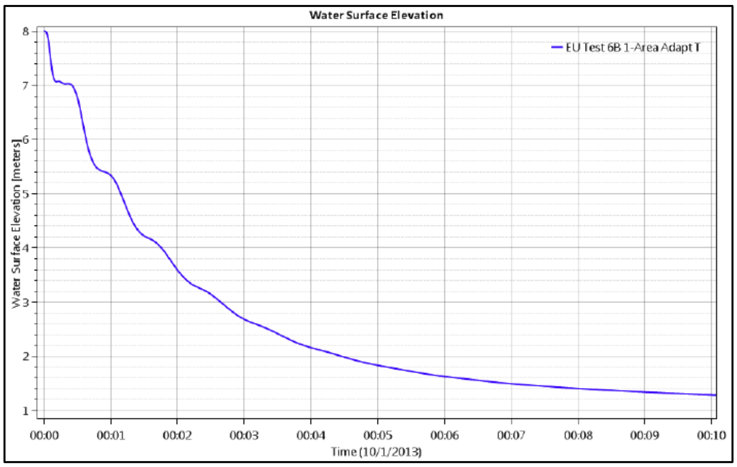

Figure 7-53 Test Point G6 – Water Level versus Time from RD-51 (2018)

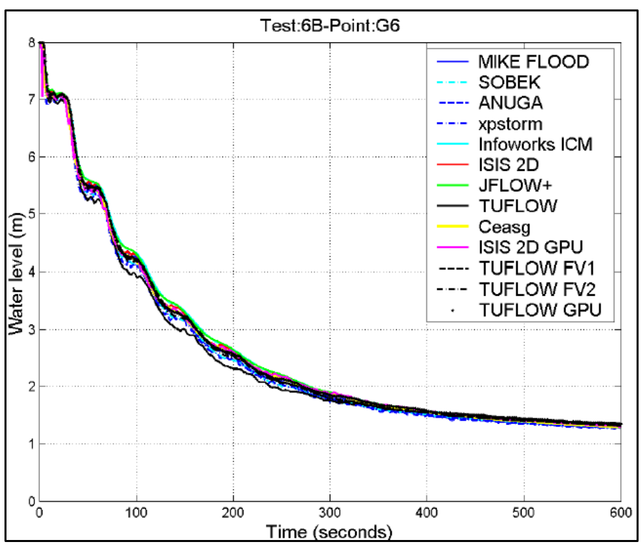

Figure 7-54 Test Point G6 – Water Level versus Time from Report SC120002 (2013)

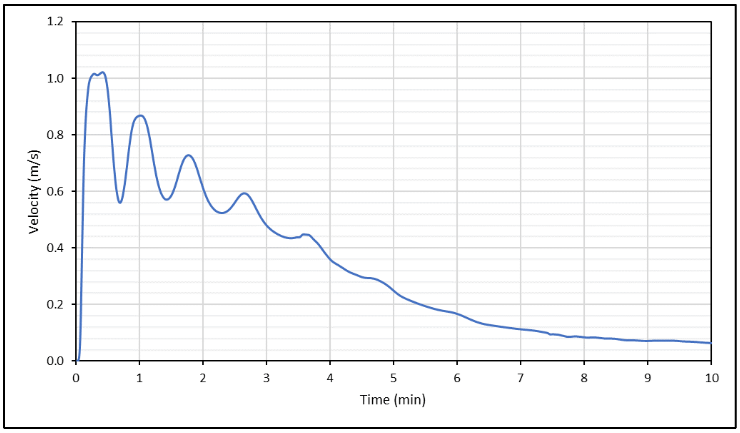

Figure 7-55 Test Point G6 – Velocity versus Time from SRH-2D

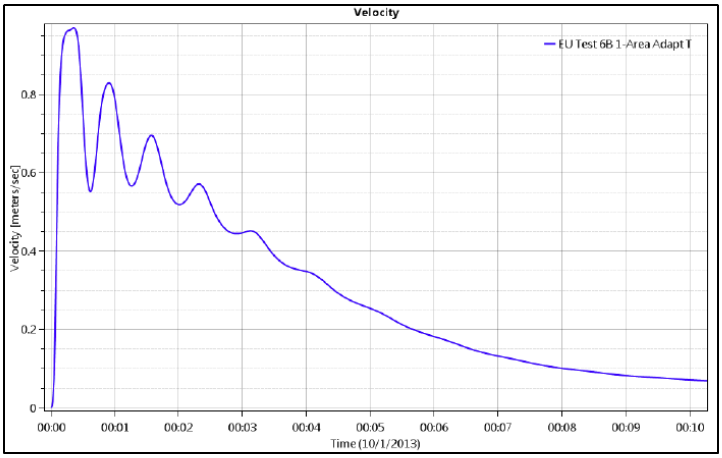

Figure 7-56 Test Point G6 – Velocity versus Time from RD-51 (2018)

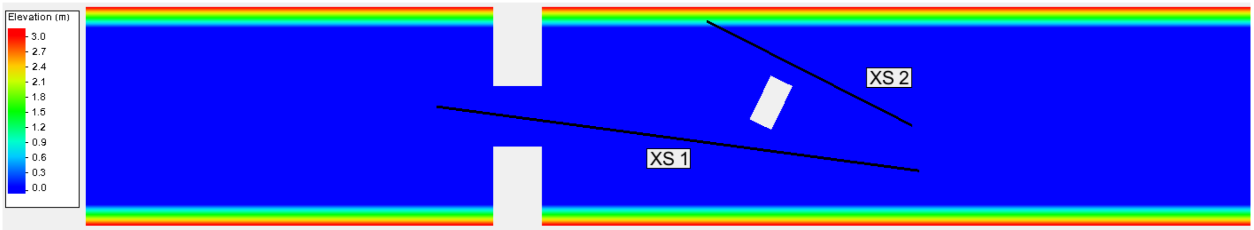

Figure 7-57 Test 6B Elevation Mesh Depicting XS 1 and XS 2 from SRH-2D

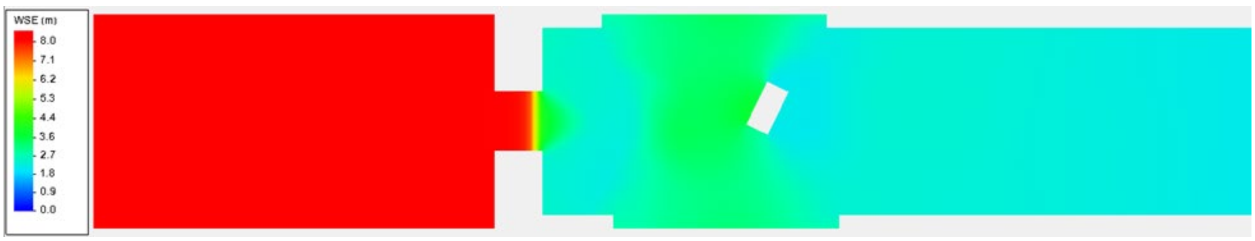

Figure 7-58 Test 6B Maximum Water Surface Elevation (meters) from SRH-2D

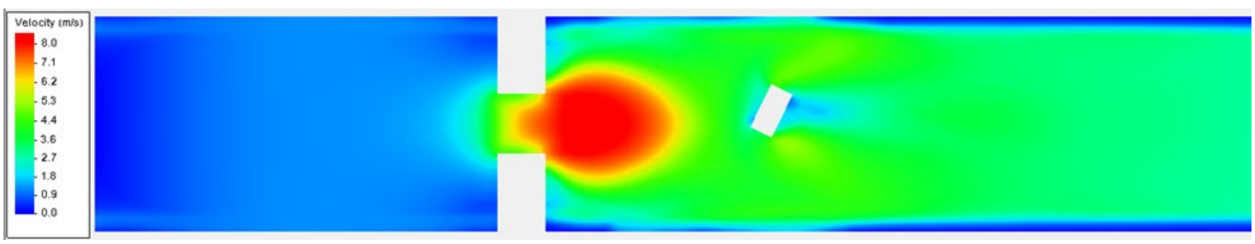

Figure 7-59 Test 6B Maximum Velocity Magnitude (meters per second) from SRH-2D

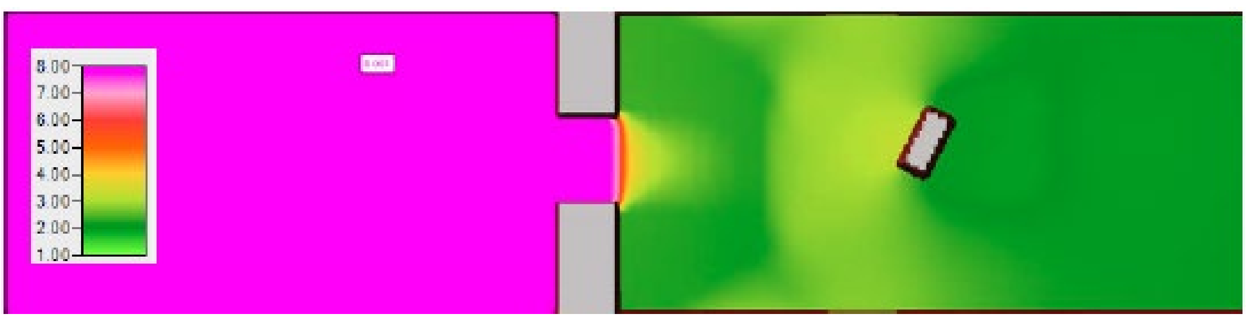

Figure 7-60 Test 6B Maximum Water Surface Elevation (meters) from RD-51 (2018)

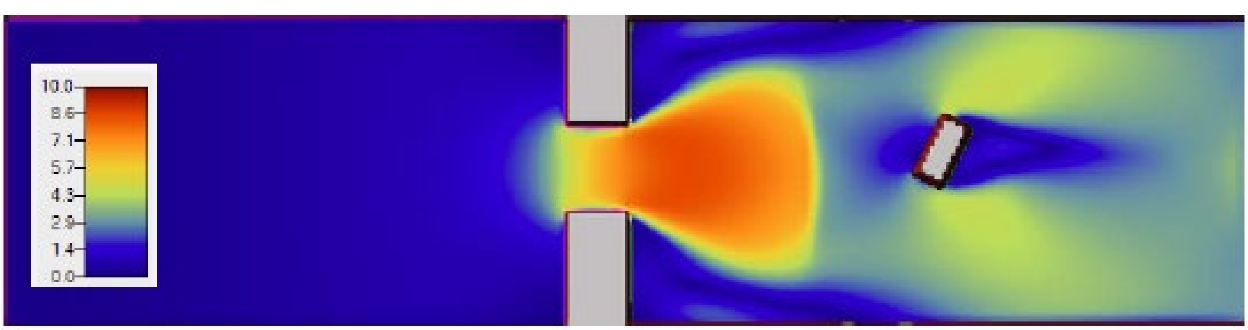

Figure 7-61 Test 6B Maximum Velocity Magnitude (meters per second) from RD-51 (2018)

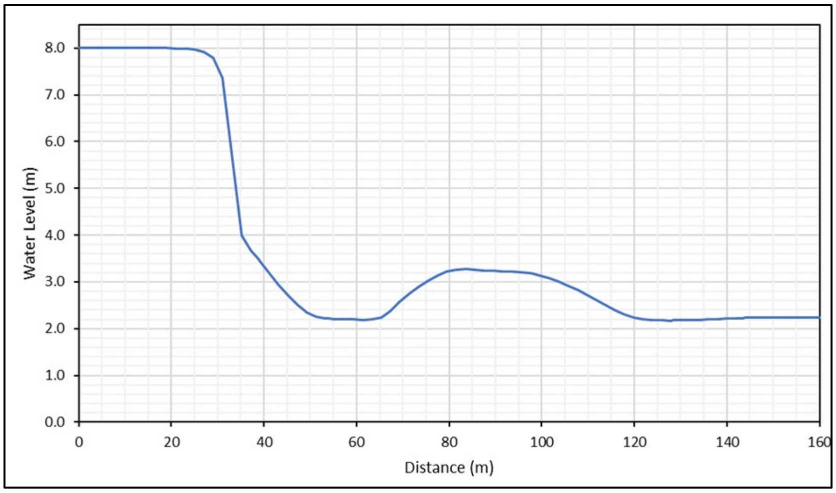

Figure 7-62 Test 6B Maximum Water Surface Elevation Along XS 1 from SRH-2D

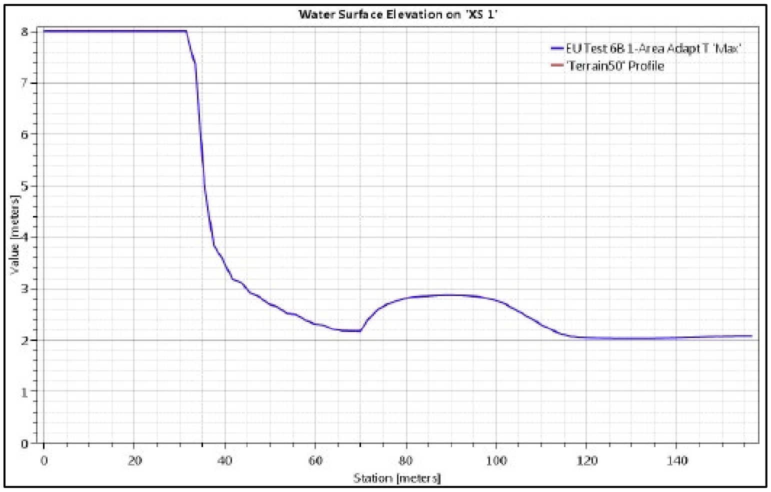

Figure 7-63 Test 6B Maximum Water Surface Elevation Along XS 1 from RD-51 (2018)

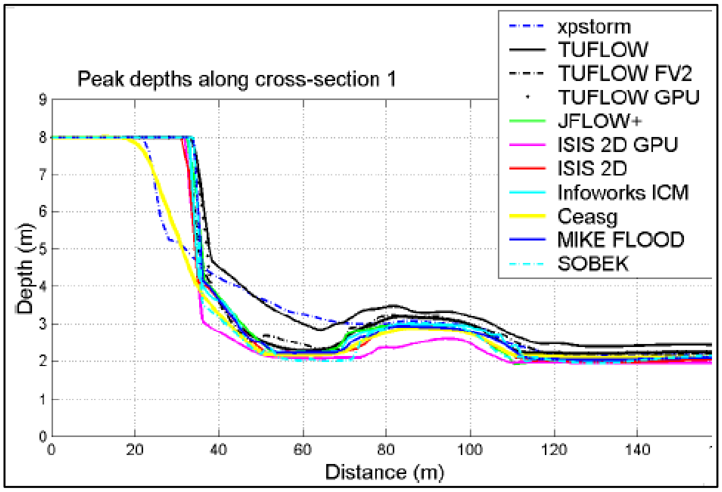

Figure 7-64 Test 6B Maximum Water Surface Elevation Along XS 1 from Report SC120002 (2013)

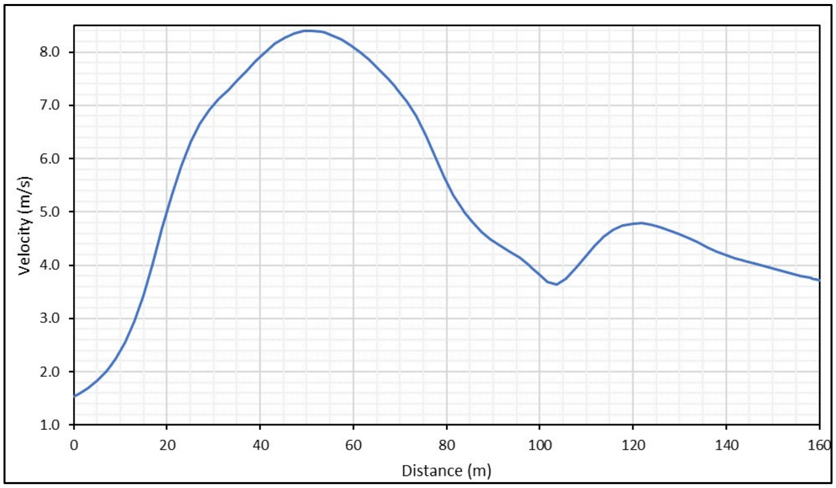

Figure 7-65 Test 6B Maximum Velocity Magnitude Along XS 1 from SRH-2D

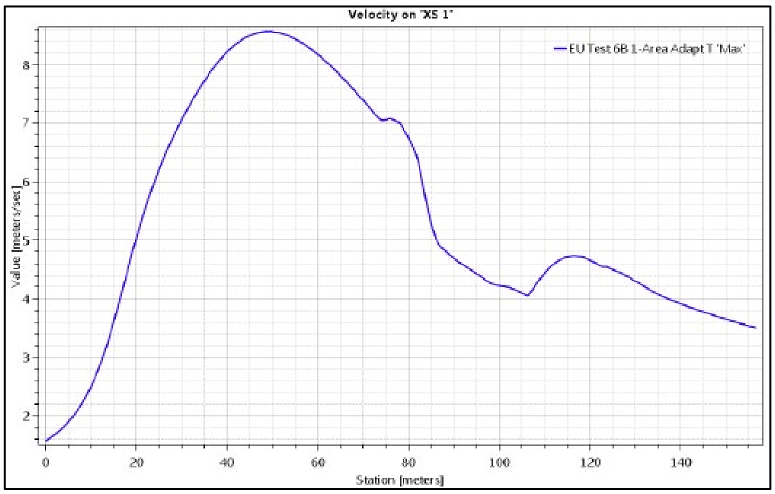

Figure 7-66 Test 6B Maximum Velocity Magnitude Along XS 1 from RD-51 (2018)

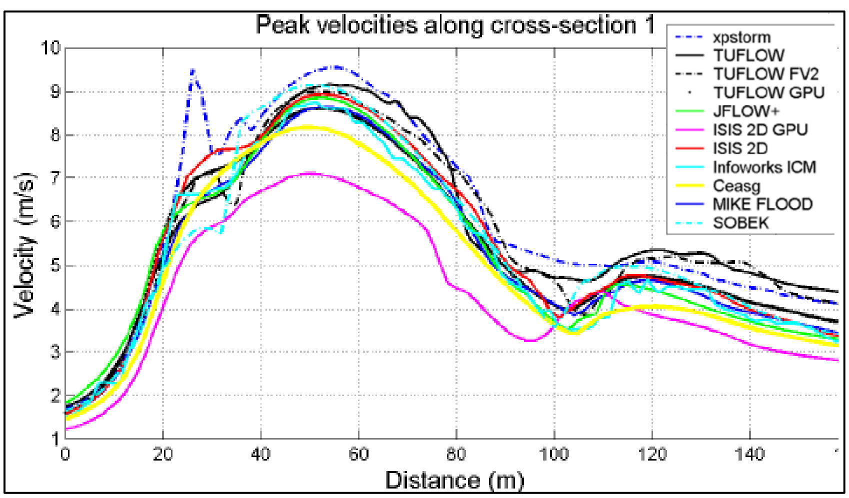

Figure 7-67 Test 6B Maximum Velocity Magnitude Along XS 1 from Report SC120002 (2013)

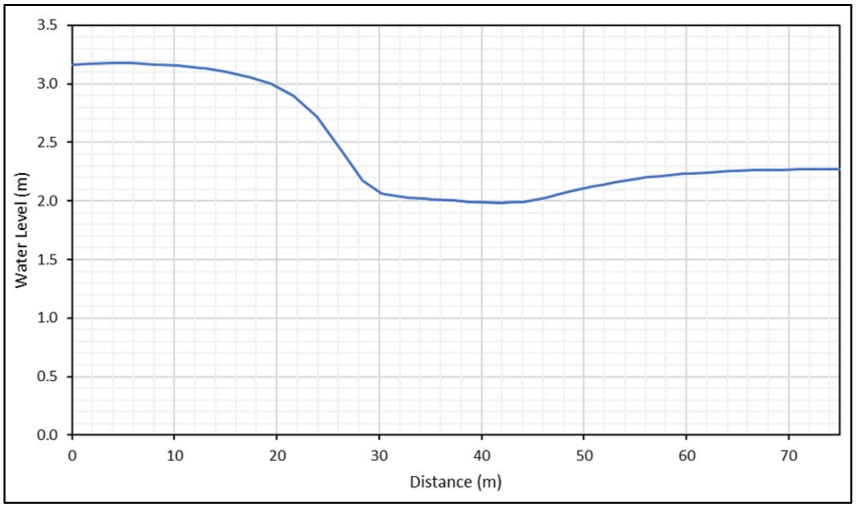

Figure 7-68 Test 6B Maximum Water Surface Elevation Along XS 2 from SRH-2D

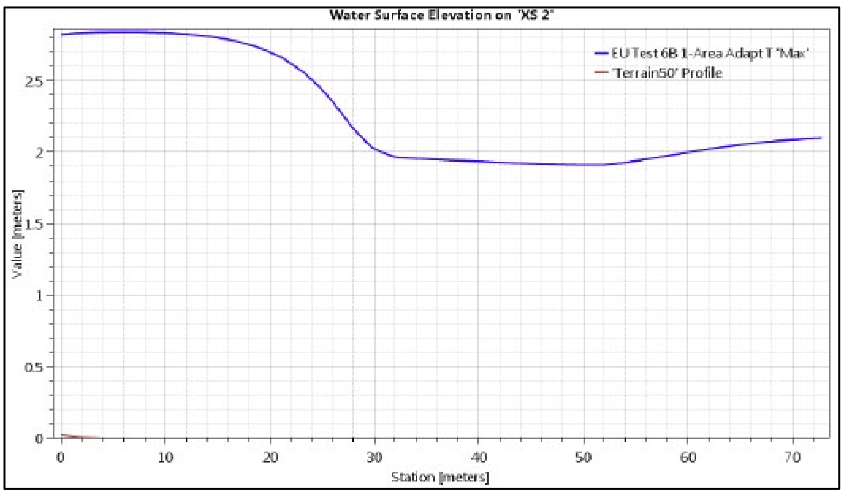

Figure 7-69 Test 6B Maximum Water Surface Elevation Along XS 2 from RD-51 (2018)

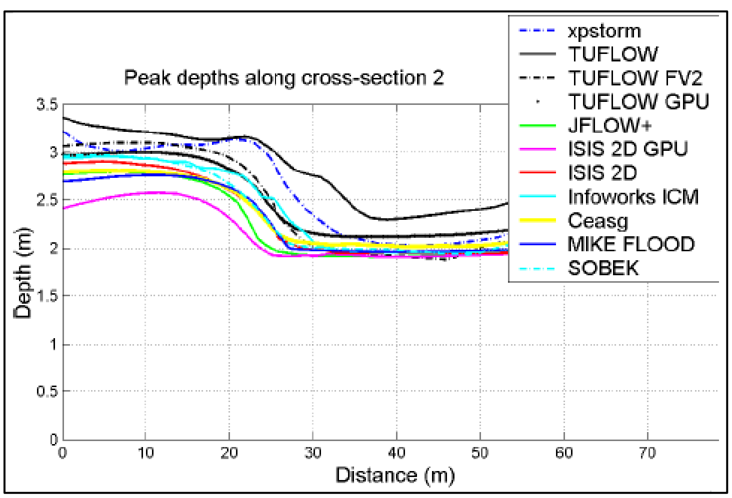

Figure 7-70 Test 6B Maximum Water Surface Elevation Along XS 2 from Report SC120002 (2013)

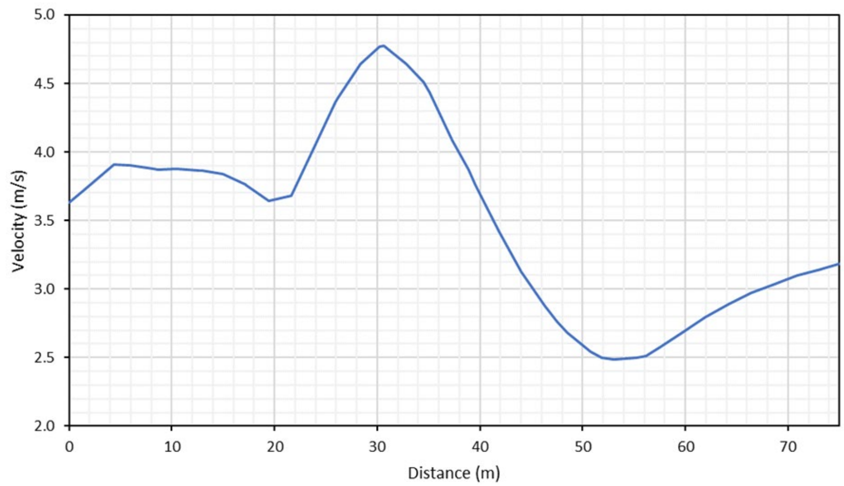

Figure 7-71 Test 6B Maximum Velocity Magnitude Along XS 2 from SRH-2D

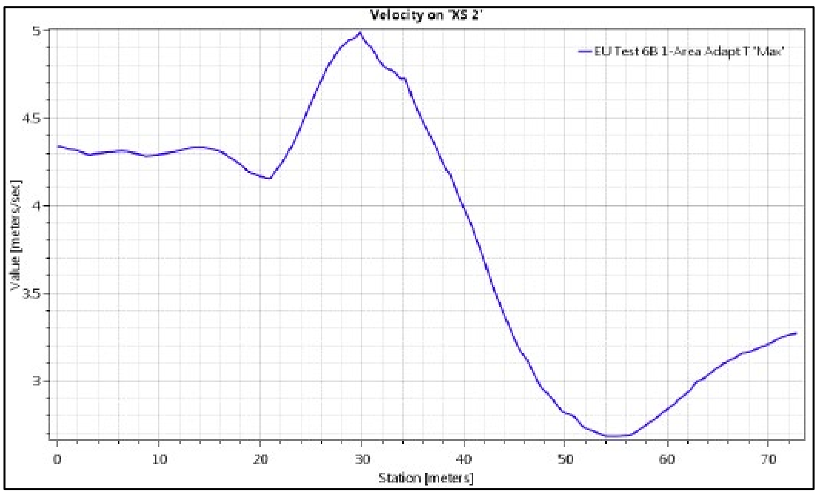

Figure 7-72 Test 6B Maximum Velocity Magnitude Along XS 2 from RD-51 (2018)

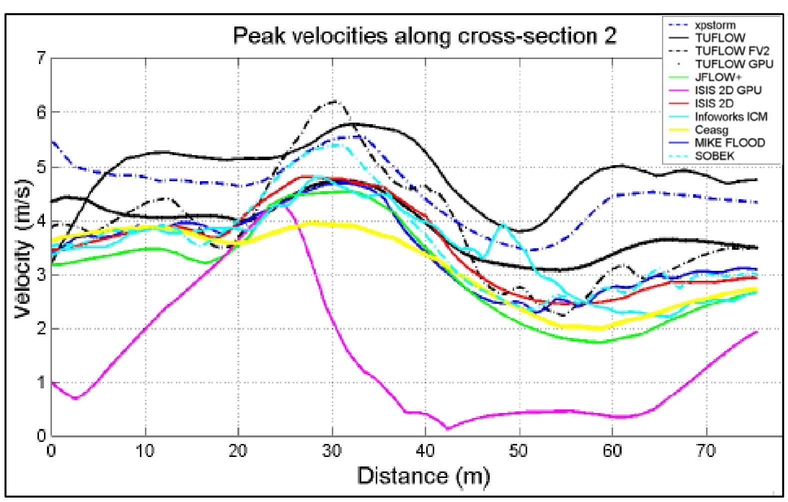

Figure 7-73 Test 6B Maximum Velocity Magnitude Along XS 2 from Report SC120002 (2013)

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8 References

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Soares-Frazao, S. and Zech, Y. (2002) *Dam-break flow experiment: The isolated building test case*. Université catholique de Louvain, Belgium.

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APPENDIX A – Duplicate Figures for 508 Compliance

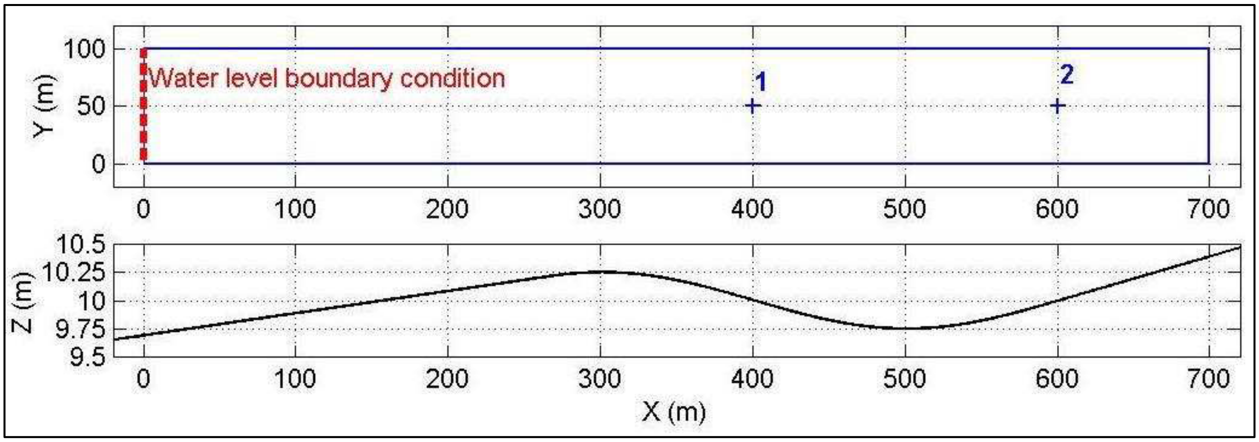


Figure 2-1 Plan (top) and profile (bottom) view of DEM (digital elevation model) used in Benchmark Test 1.

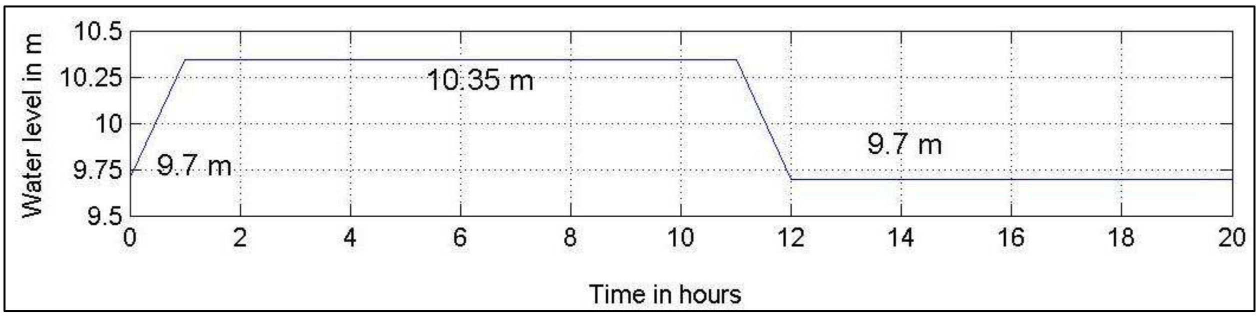


Figure 2-2 Water level hydrograph used as boundary condition.

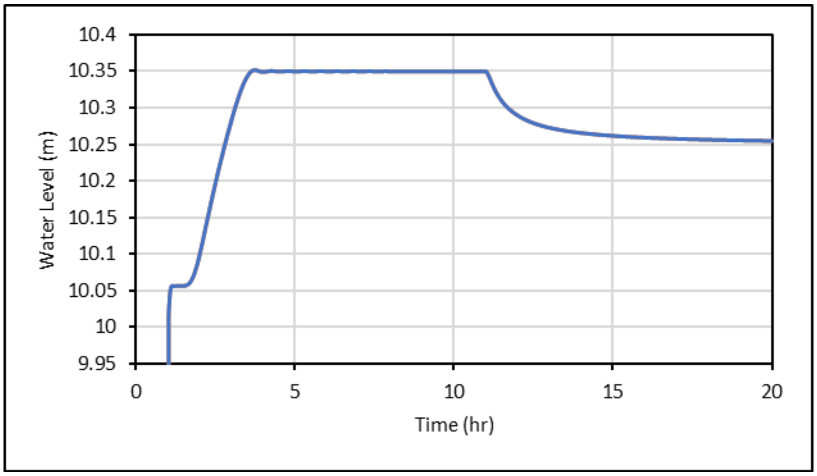


Figure 2-3 Test Point 1 – Water Level versus Time from SRH-2D

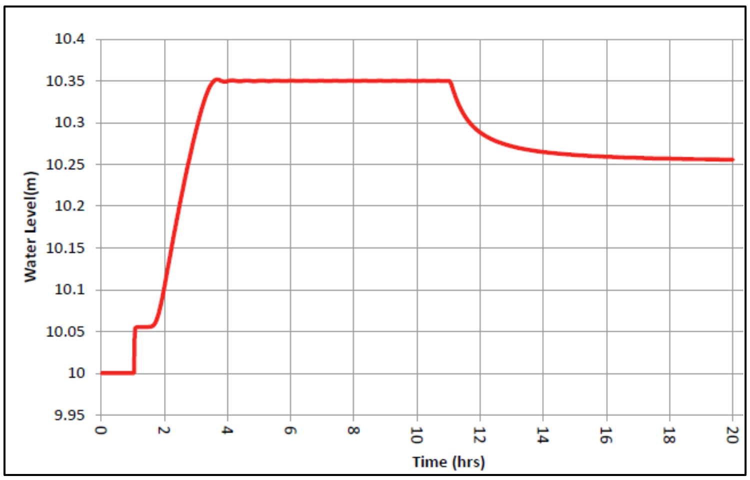


Figure 2-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

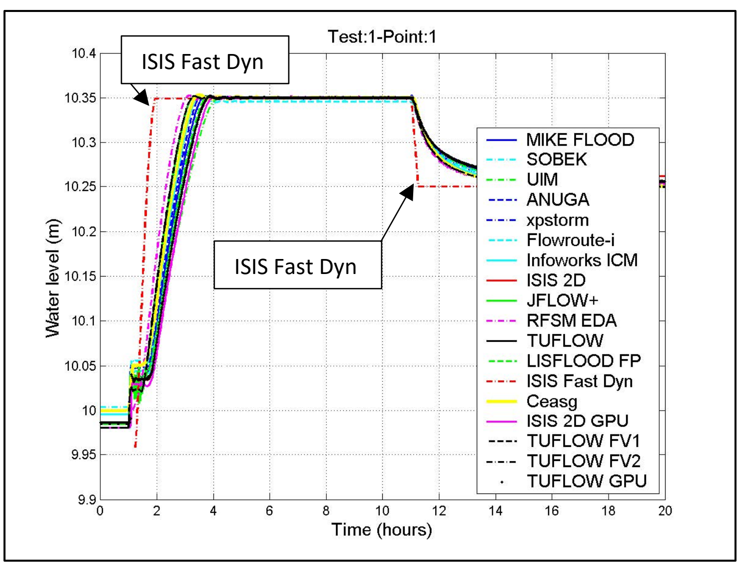


Figure 2-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

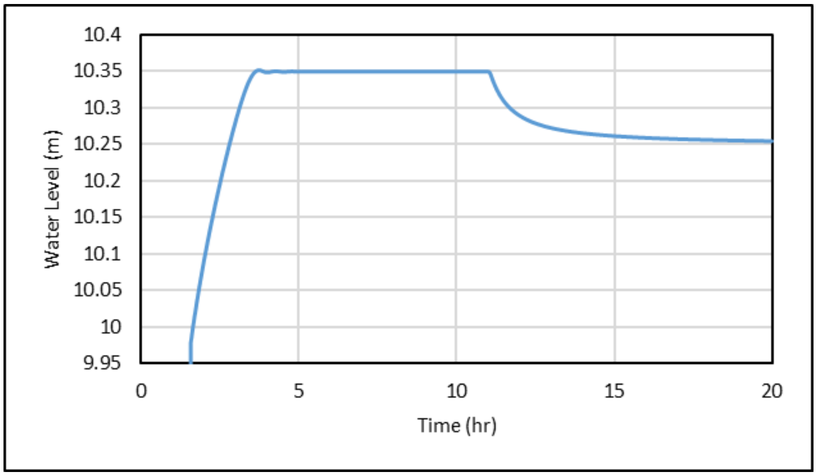


Figure 2-6 Test Point 2 – Water Level versus Time from SRH-2D

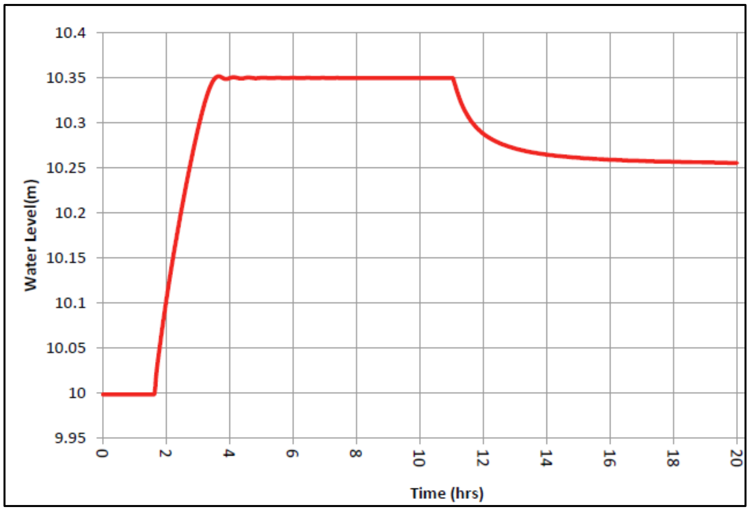


Figure 2-7 Test Point 2 –Water Level versus Time from RD-51 (2018)

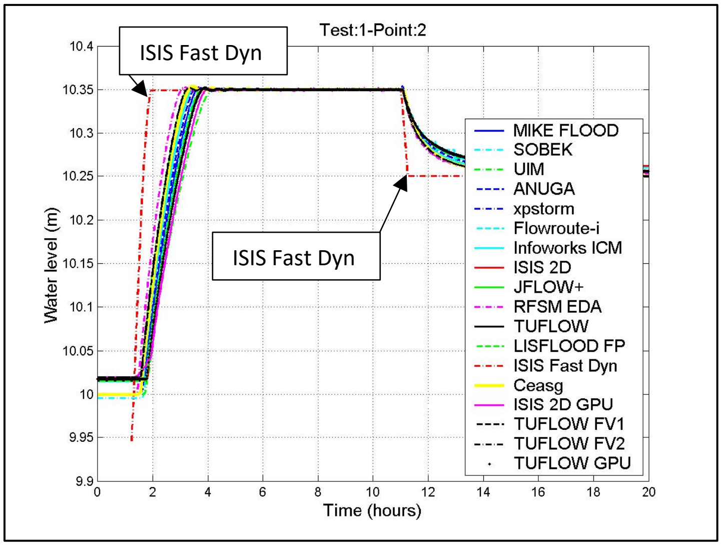


Figure 2-8 Test Point 2 – Water Level versus Time from Report SC120002 (2013)

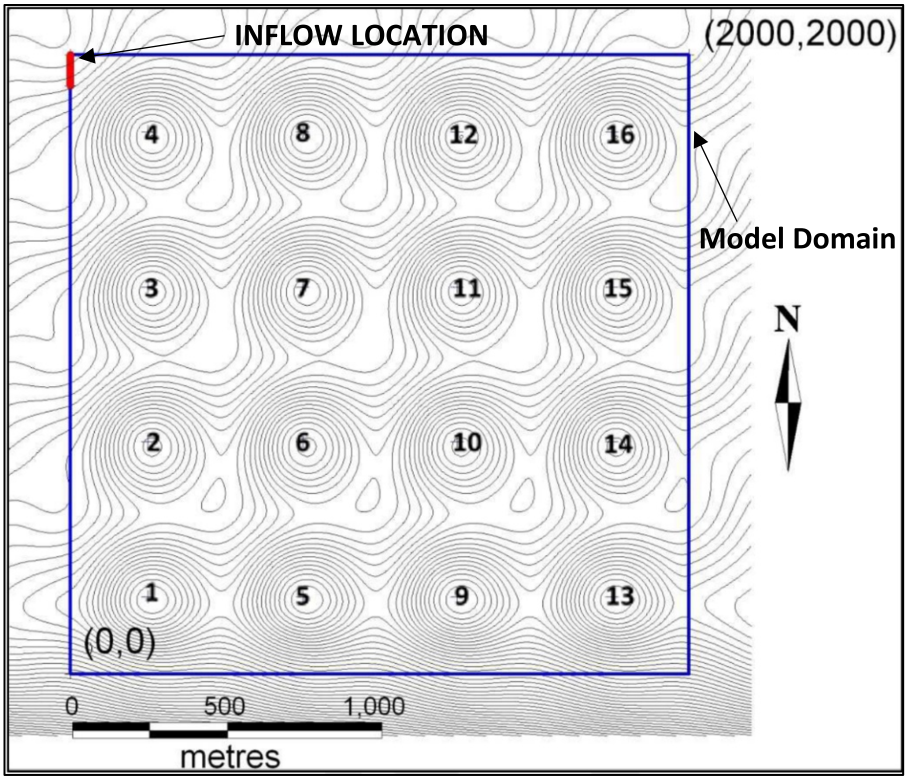


Figure 3-1 Map of the DEM showing the location of the upstream boundary condition (red line), ground elevation contour lines every 0.05 meters, and output point locations (numbers).

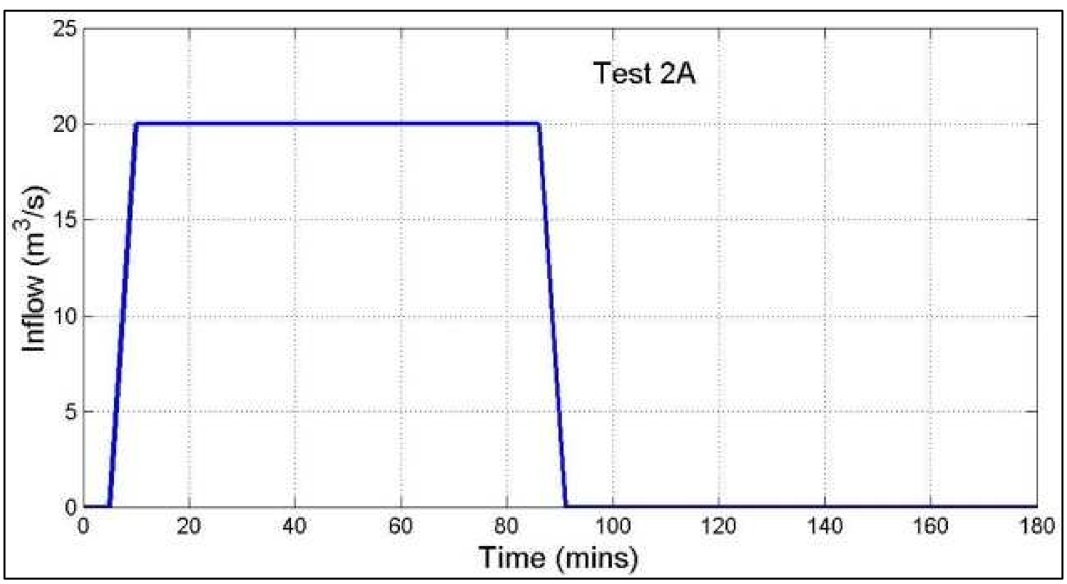


Figure 3-2 Inflow hydrograph used as upstream boundary condition.

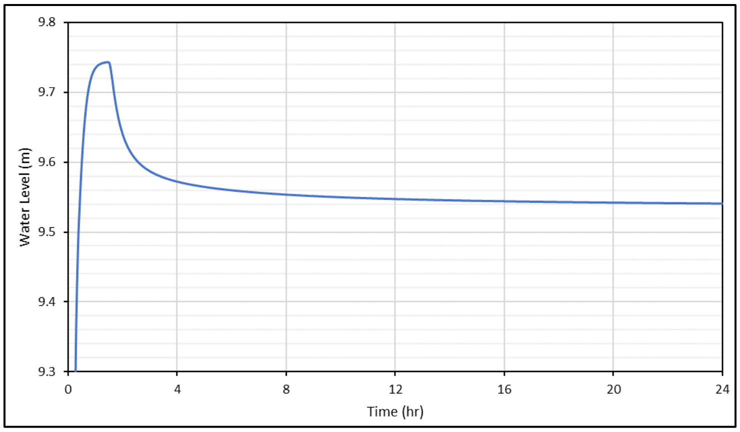


Figure 3-3 Test Point 4 – Water Level versus Time from SRH-2D

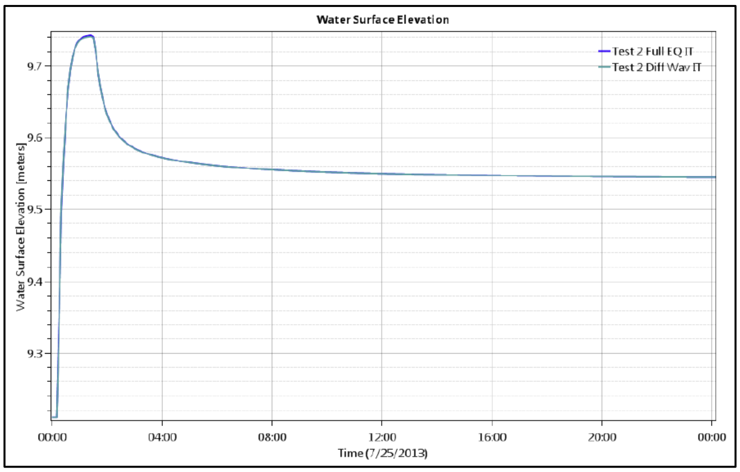


Figure 3-4 Test Point 4 – Water Level versus Time from RD-51 (2018)

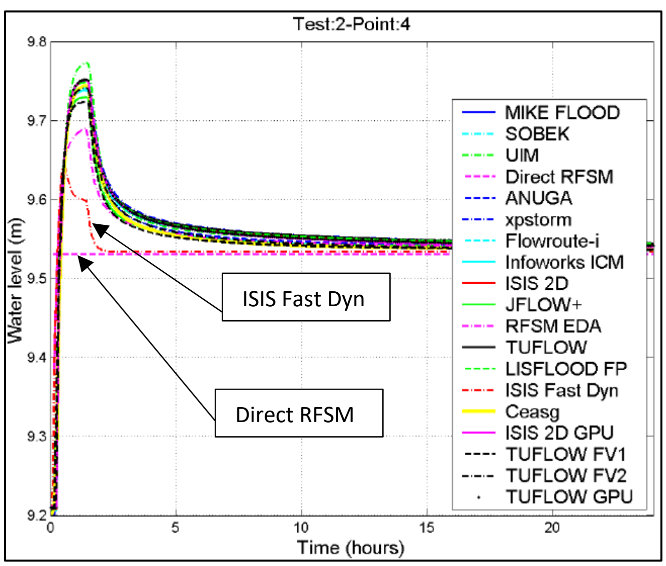


Figure 3-5 Test Point 4 – Water Level versus Time from Report SC120002 (2013)

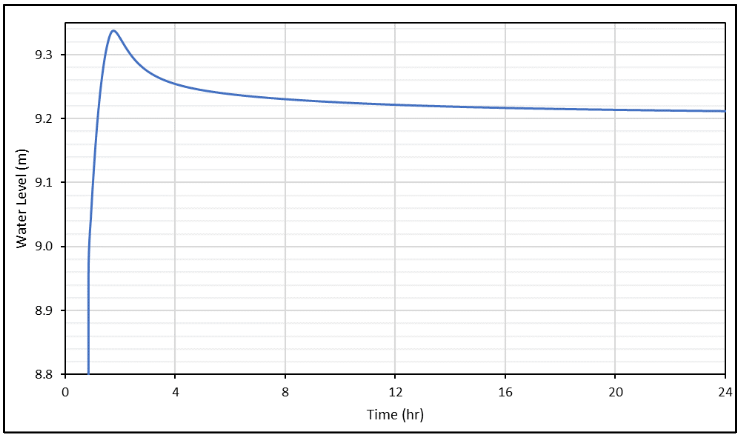


Figure 3-6 Test Point 3 – Water Level versus Time from SRH-2D

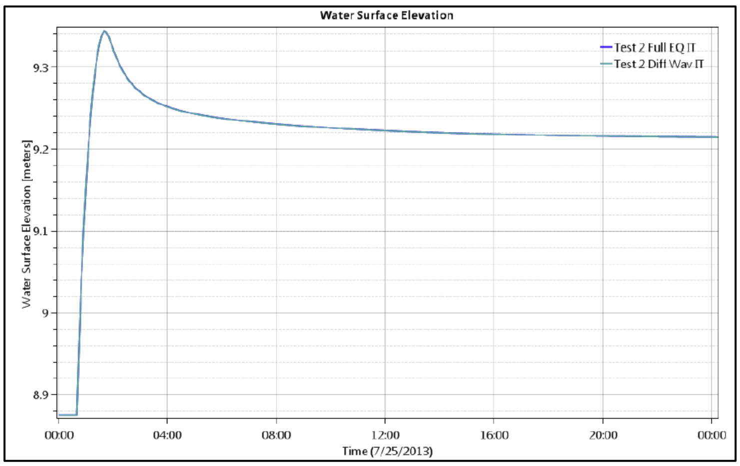


Figure 3-7 Test Point 3 – Water Level versus Time from RD-51 (2018)

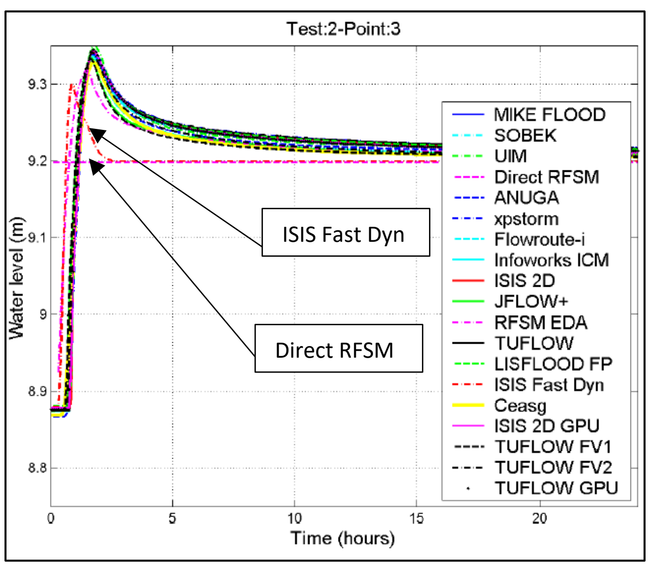


Figure 3-8 Test Point 3 – Water Level versus Time from Report SC120002 (2013)

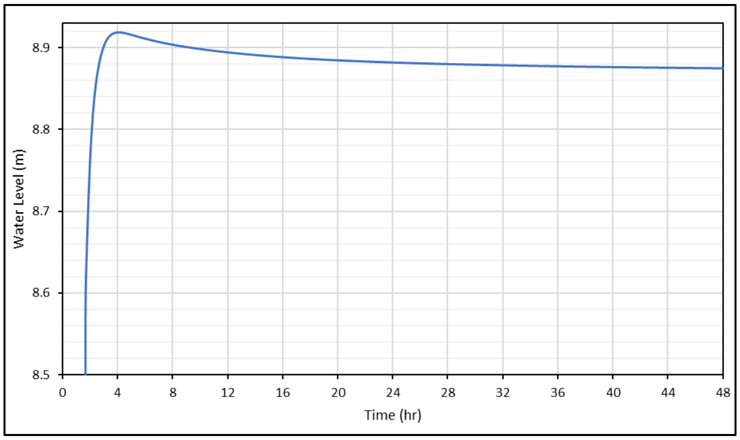
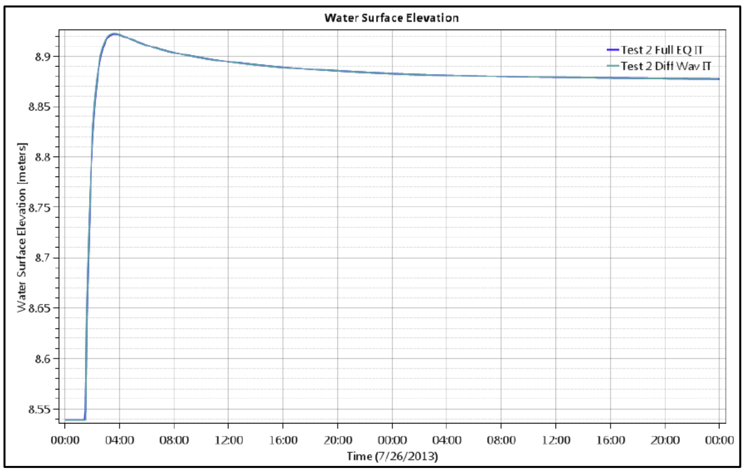


Figure 3-9 Test Point 2 – Water Level versus Time from SRH-2D



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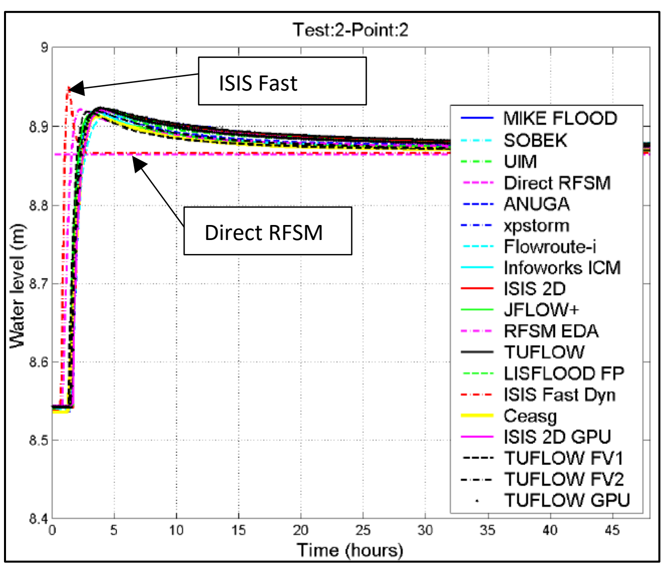

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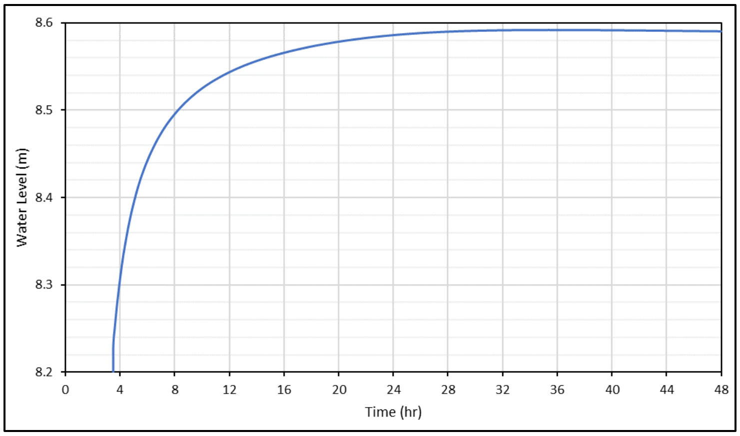


Figure 3-12 Test Point 1 – Water Level versus Time from SRH-2D

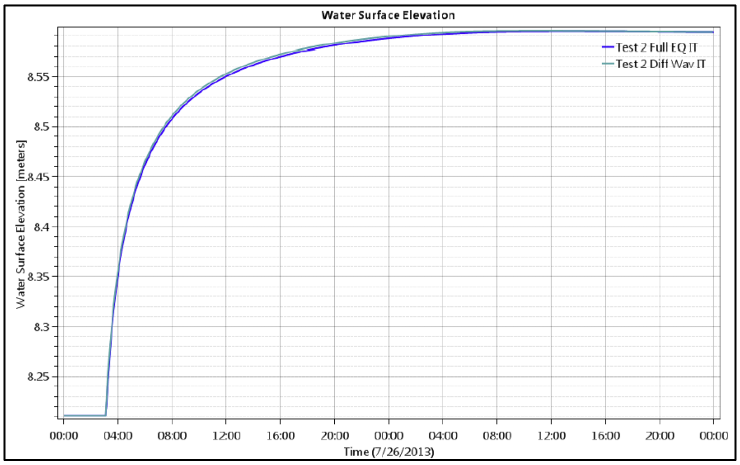


Figure 3-13 Test Point 1 – Water Level versus Time from RD-51 (2018)

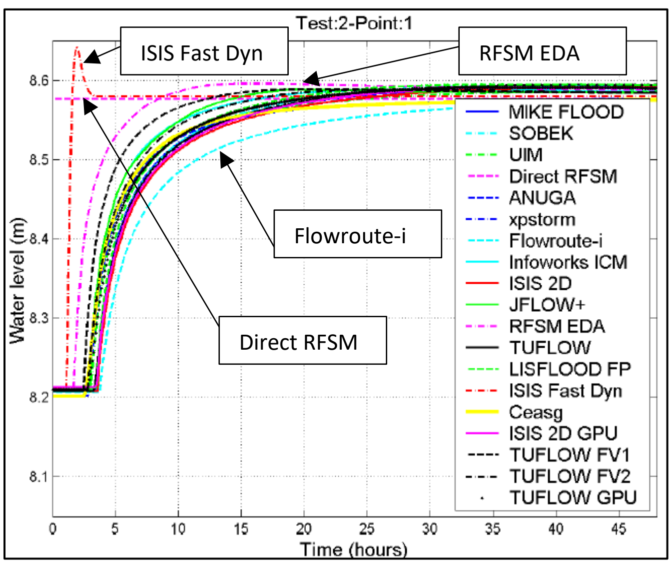


Figure 3-14 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

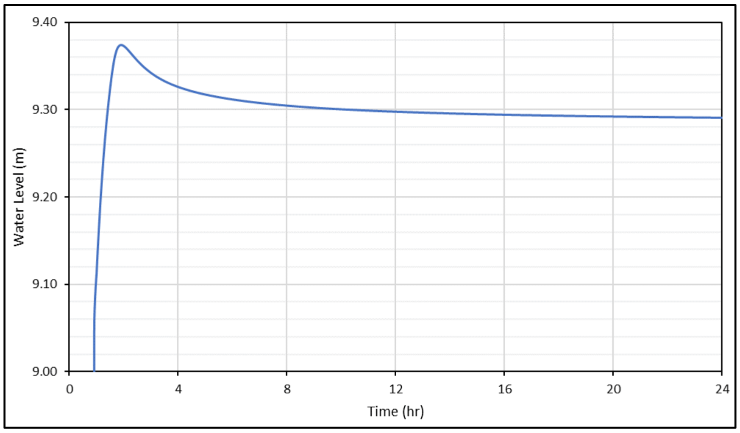


Figure 3-15 Test Point 8 – Water Level versus Time from SRH-2D

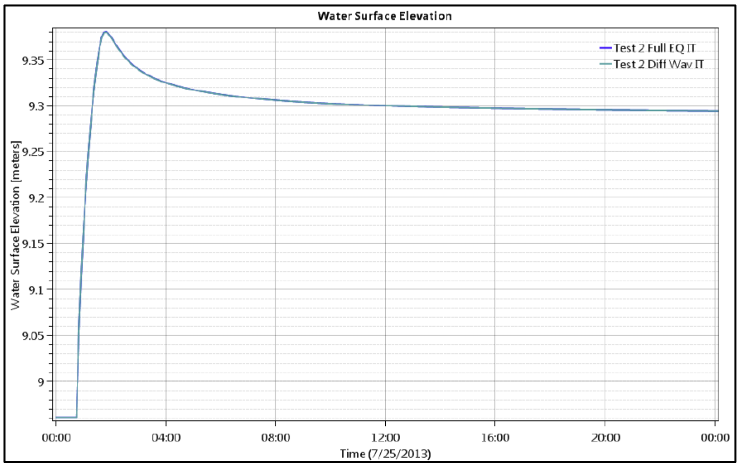


Figure 3-16 Test Point 8 – Water Level versus Time from RD-51 (2018)

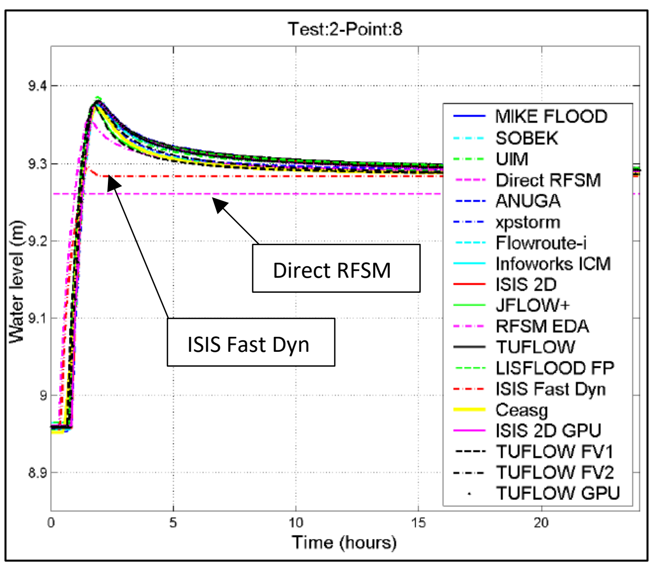


Figure 3-17 Test Point 8 – Water Level versus Time from Report SC120002 (2013)

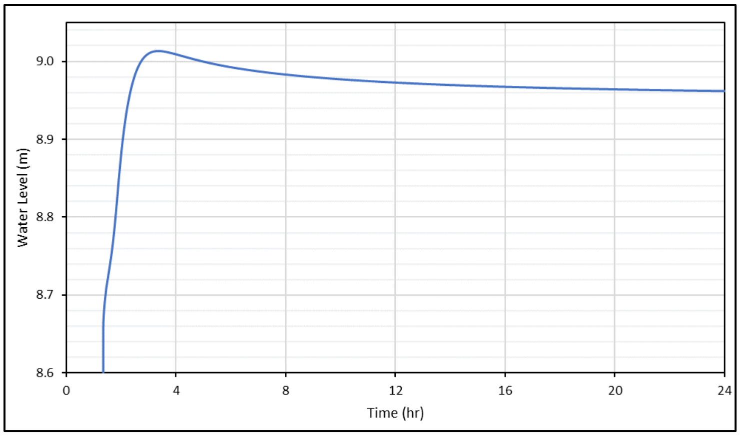


Figure 3-18 Test Point 7 – Water Level versus Time from SRH-2D

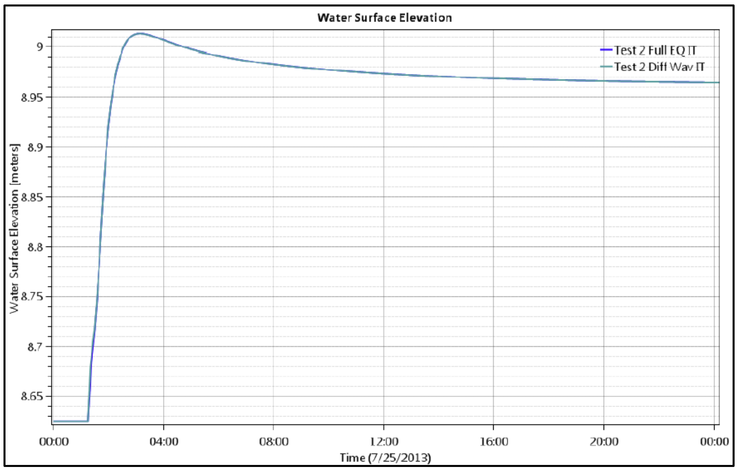


Figure 3-19 Test Point 7 – Water Level versus Time from RD-51 (2018)

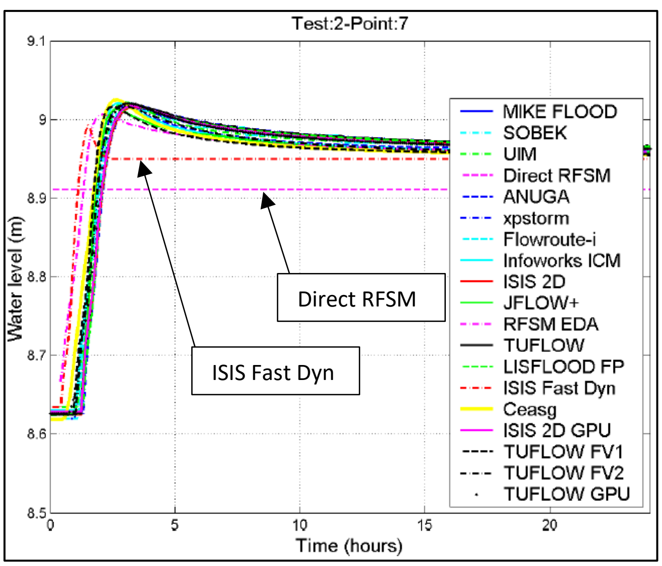


Figure 3-20 Test Point 7 – Water Level versus Time from Report SC120002 (2013)

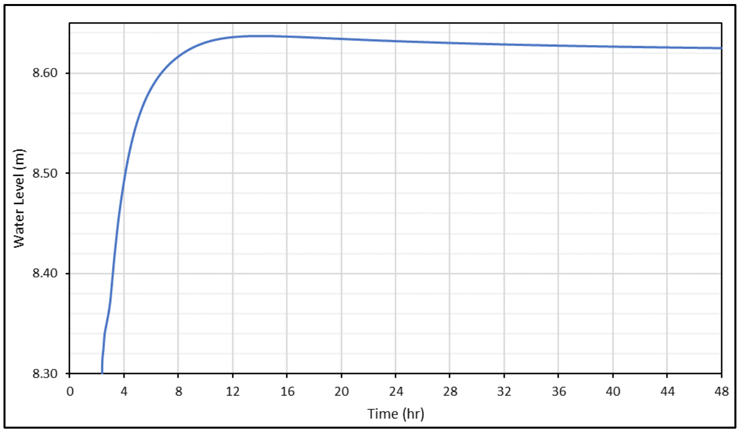


Figure 3-21 Test Point 6 – Water Level versus Time from SRH-2D

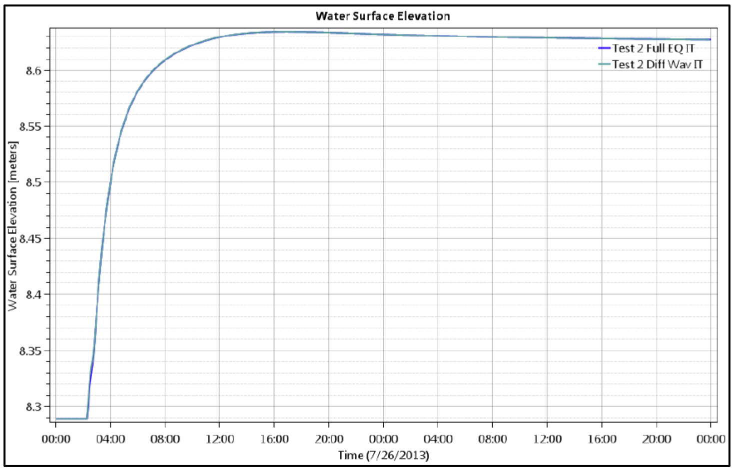
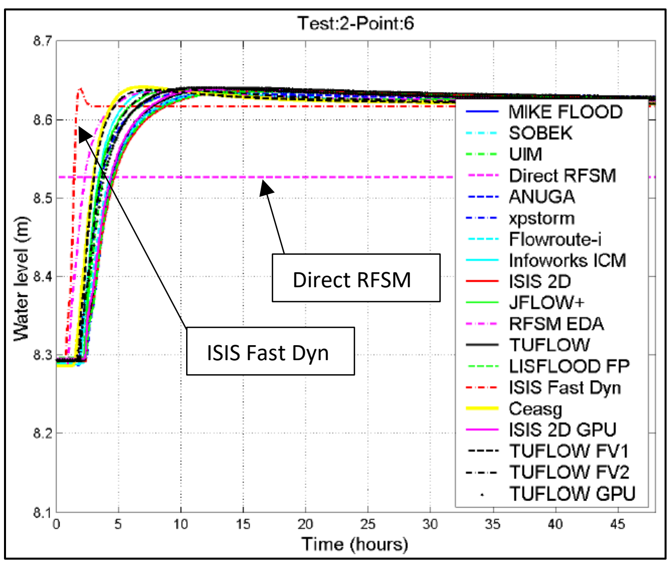


Figure 3-22 Test Point 6 – Water Level versus Time from RD-51 (2018)



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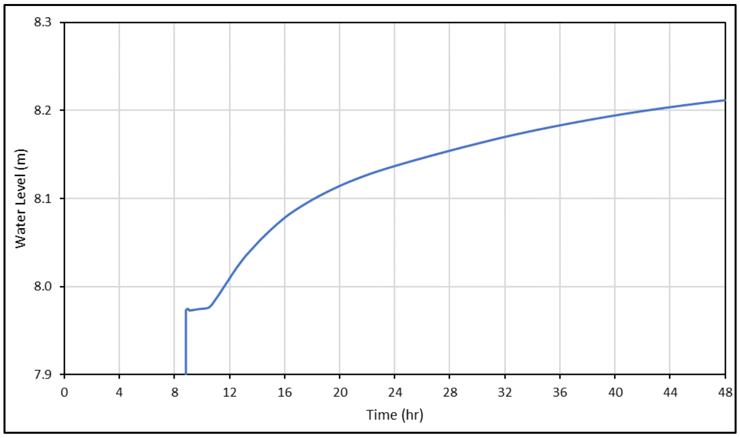

Figure 3-24 Test Point 5 – Water Level versus Time from SRH-2D

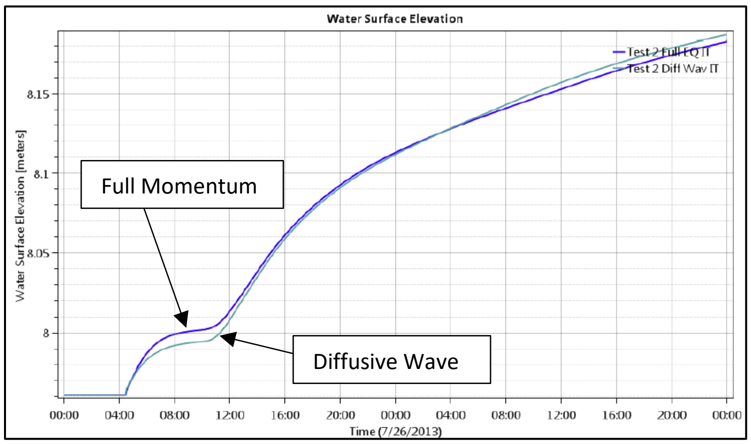

Figure 3-25 Test Point 5 – Water Level versus Time from RD-51 (2018)

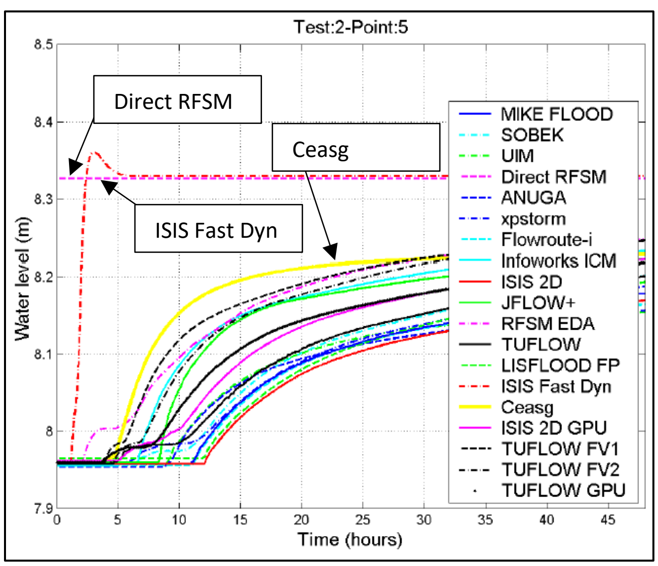

Figure 3-26 Test Point 5 – Water Level versus Time from Report SC120002 (2013)

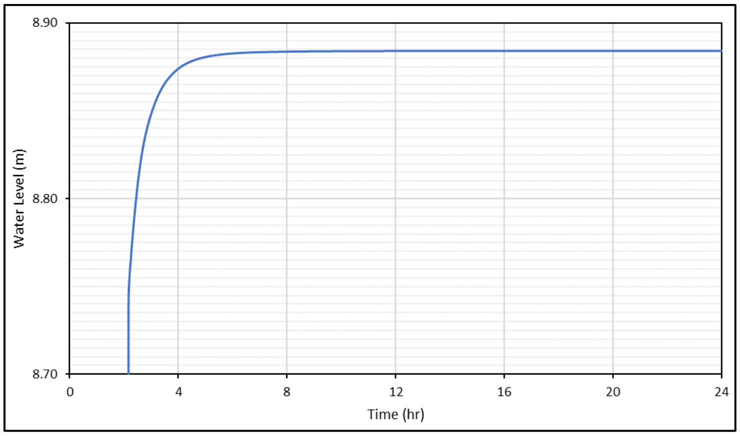

Figure 3-27 Test Point 12 – Water Level versus Time from SRH-2D

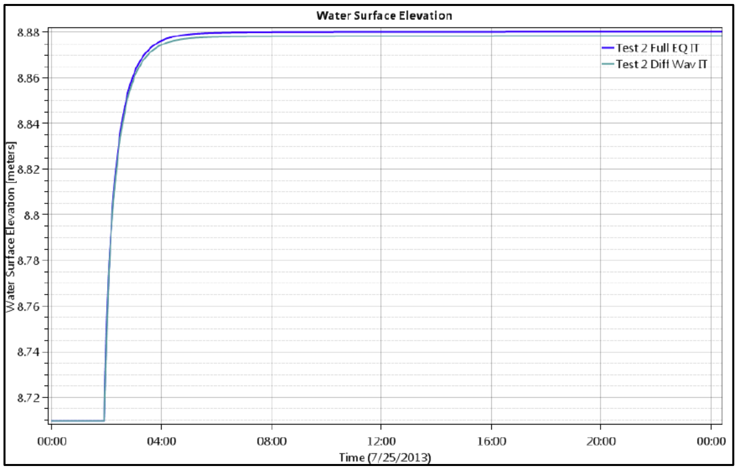

Figure 3-28 Test Point 12 – Water Level versus Time from RD-51 (2018)

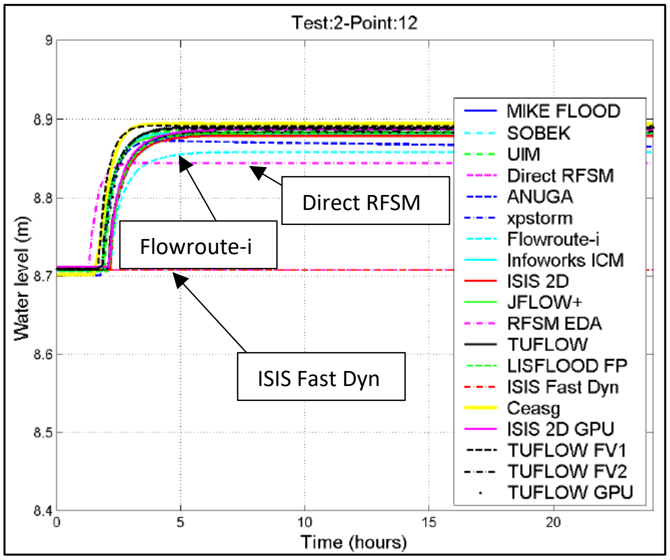

Figure 3-29 Test Point 12 – Water Level versus Time from Report SC120002 (2013)

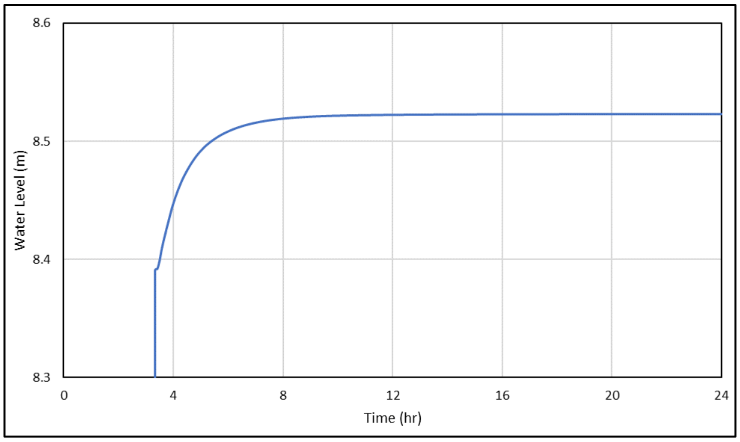

Figure 3-30 Test Point 11 – Water Level versus Time from SRH-2D

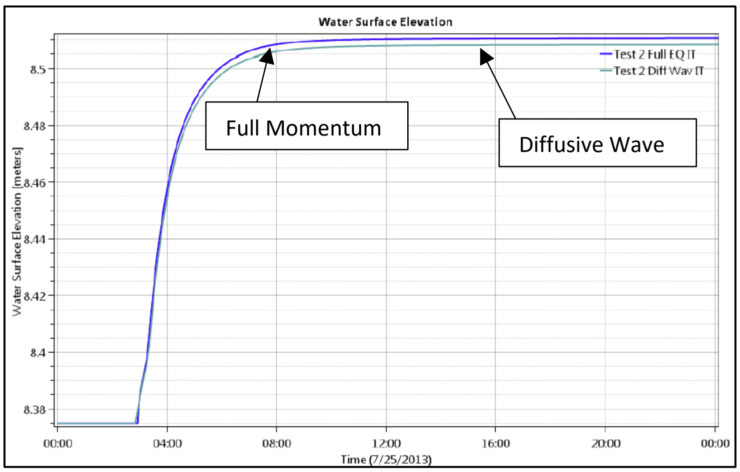

Figure 3-31 Test Point 11 – Water Level versus Time from RD-51 (2018)

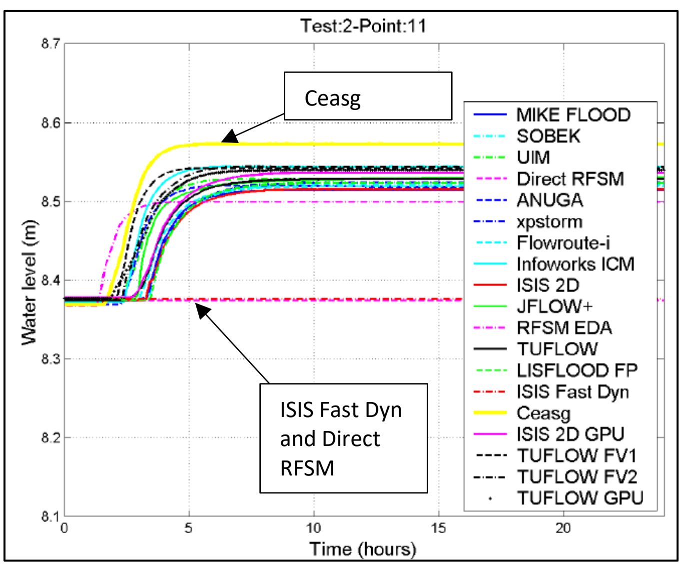

Figure 3-32 Test Point 11 – Water Level versus Time from Report SC120002 (2013)

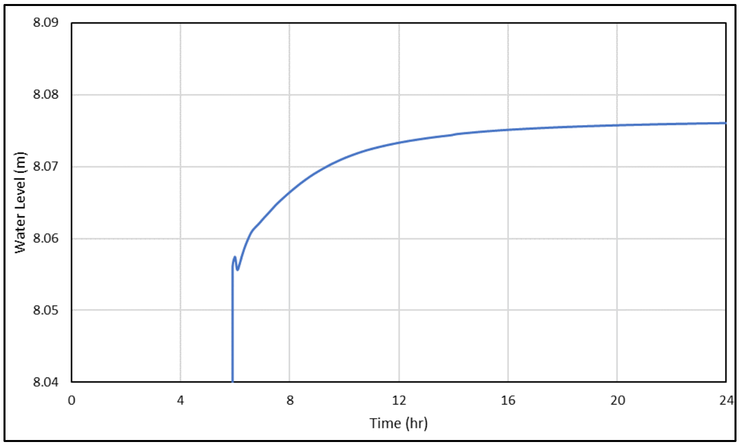

Figure 3-33 Test Point 10 – Water Level versus Time from SRH-2D

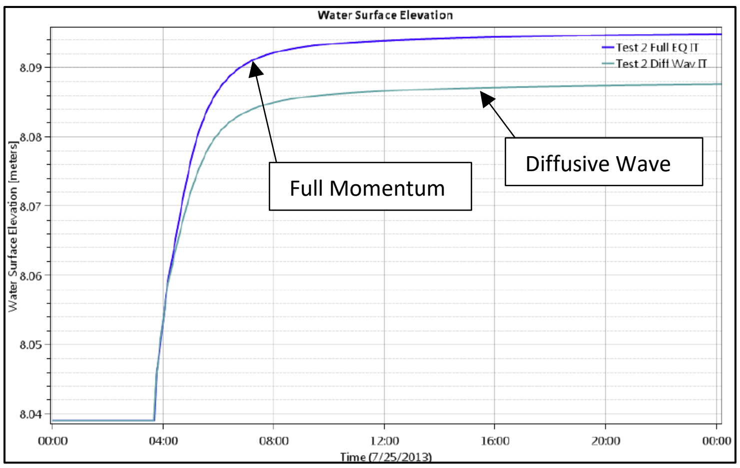

Figure 3-34 Test Point 10 – Water Level versus Time from RD-51 (2018)

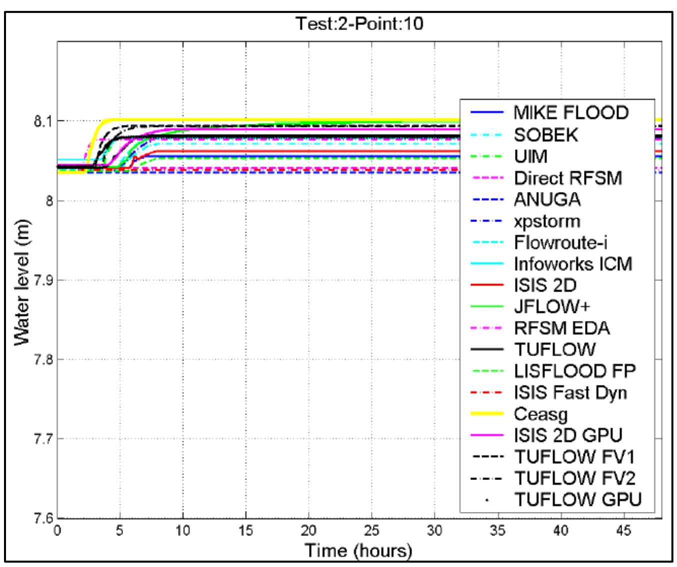

Figure 3-35 Test Point 10 – Water Level versus Time from Report SC120002 (2013)

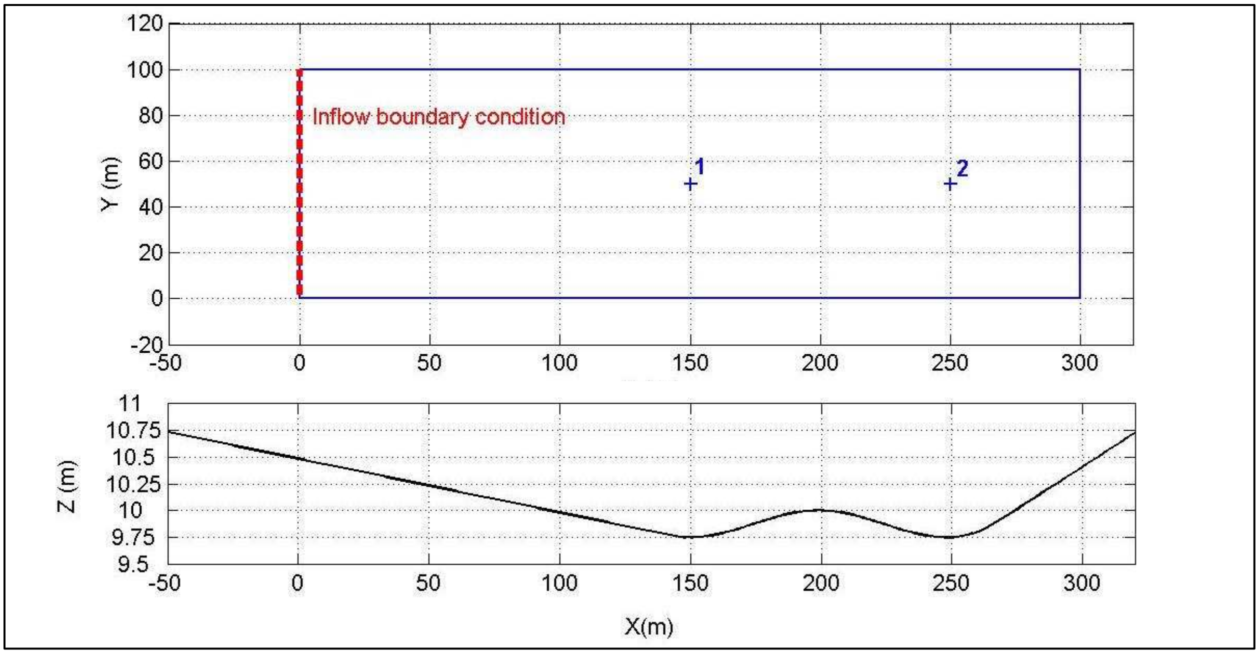

Figure 4-1 Plan (top) and profile (bottom) view of DEM used in Benchmark Test 3.

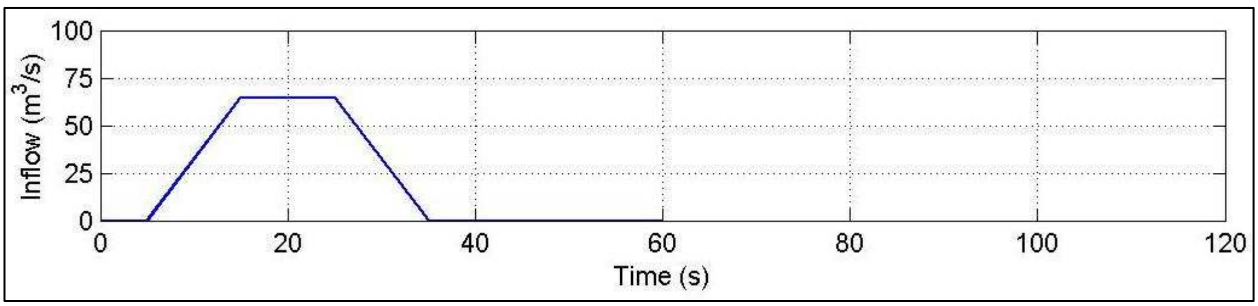

Figure 4-2 Inflow hydrograph used as upstream boundary condition.

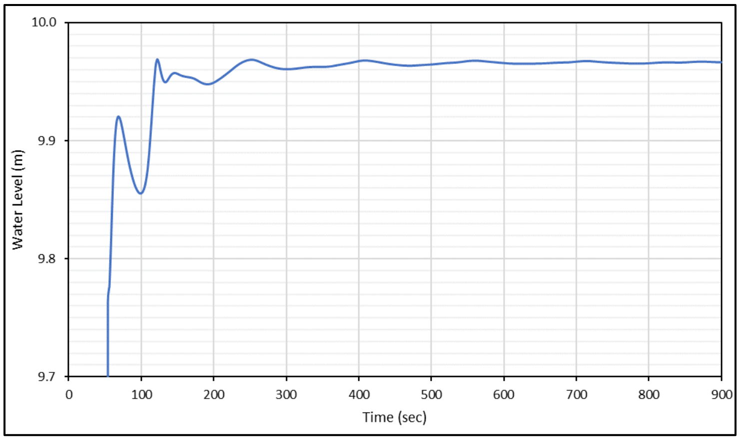

Figure 4-3 Test Point 1 – Water Level versus Time from SRH-2D

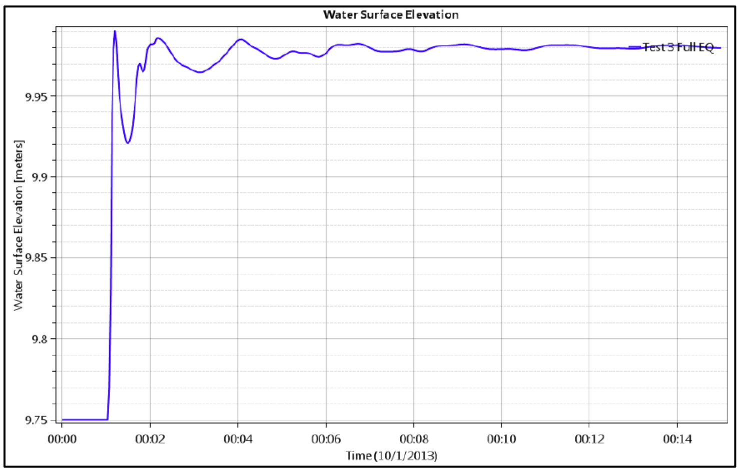

Figure 4-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

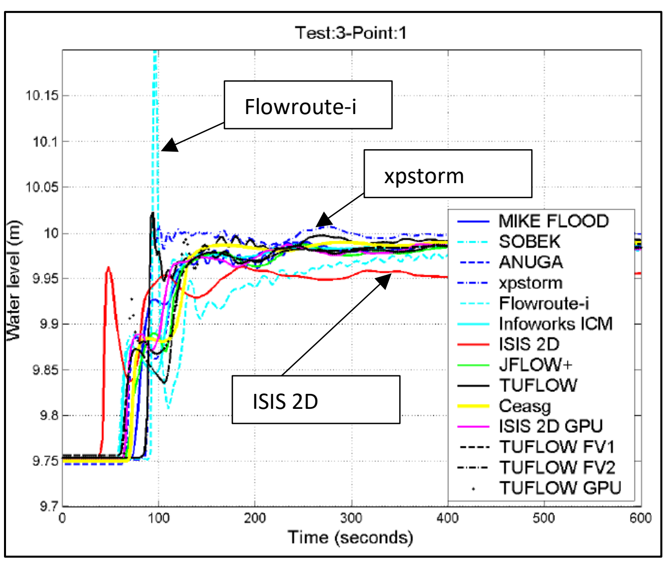

Figure 4-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

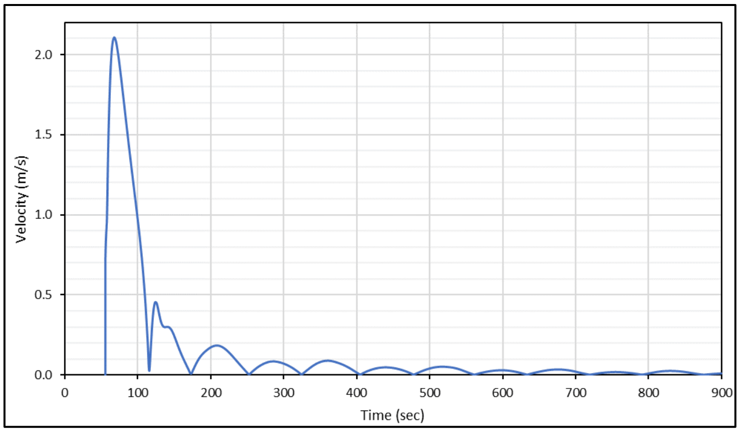

Figure 4-6 Test Point 1 – Velocity versus Time from SRH-2D

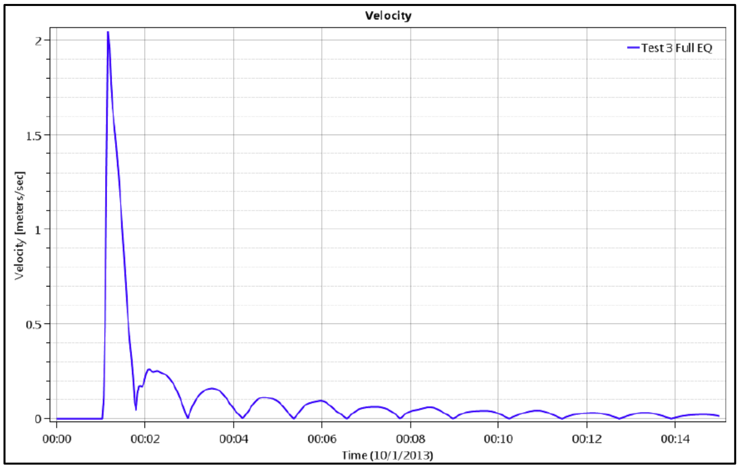

Figure 4-7 Test Point 1 – Velocity versus Time from RD-51 (2018)

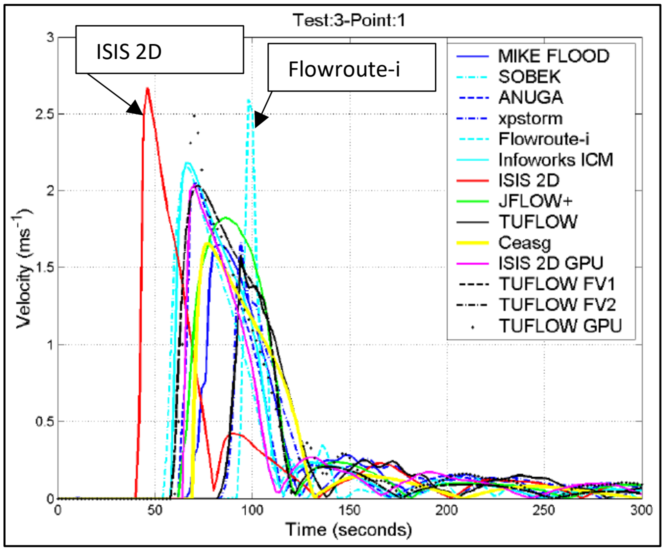

Figure 4-8 Test Point 1 – Velocity versus Time from Report SC120002 (2013)

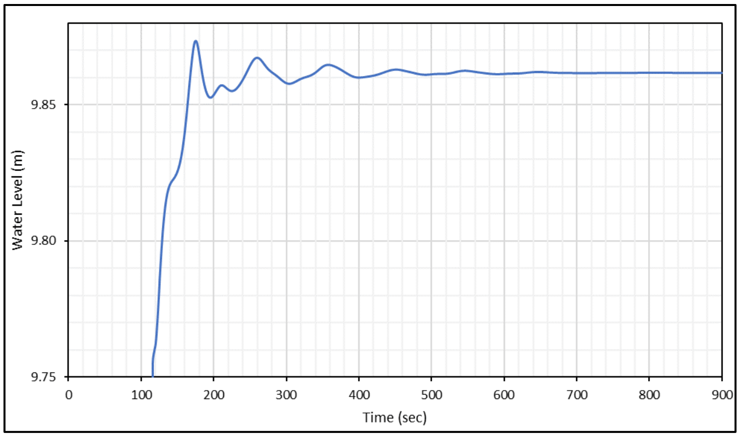

Figure 4-9 Test Point 2 – Water Level versus Time from SRH-2D

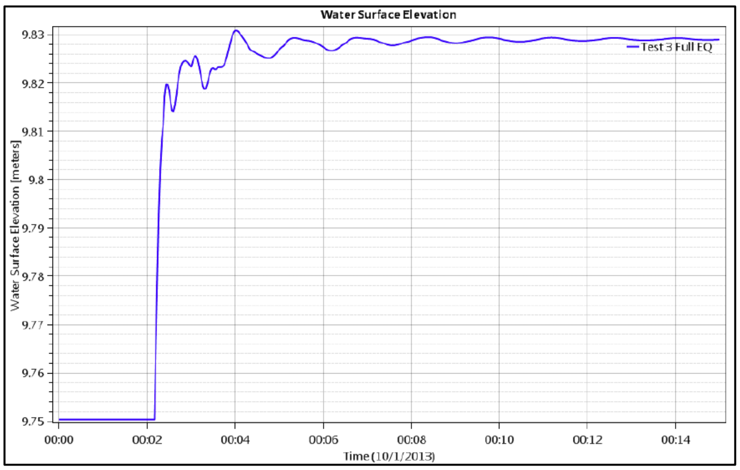

Figure 4-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

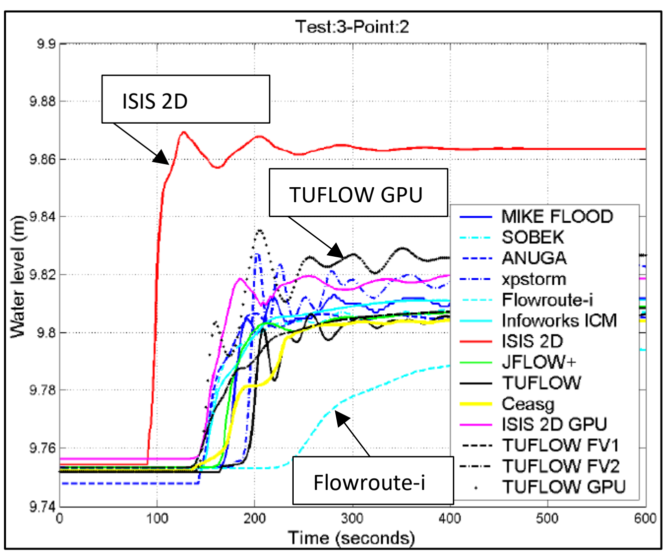

Figure 4-11 Test Point 2 – Water Level versus Time from Report SC120002 (2013)

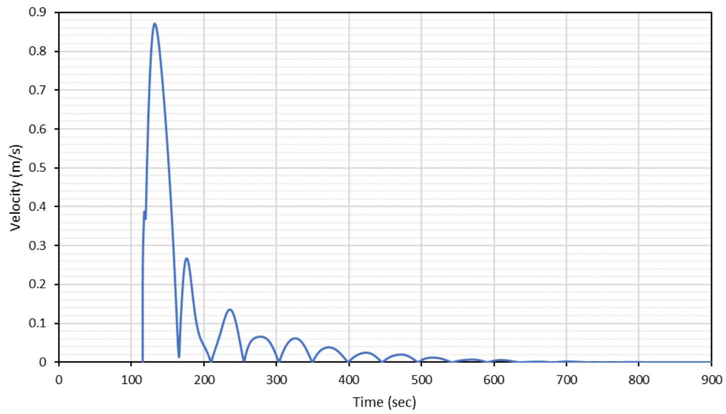

Figure 4-12 Test Point 2 – Velocity versus Time from SRH-2D

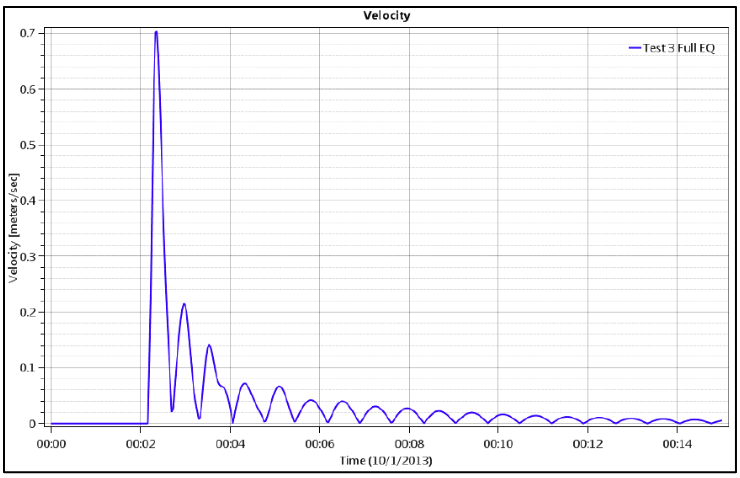

Figure 4-13 Test Point 2 – Velocity versus Time from RD-51 (2018)

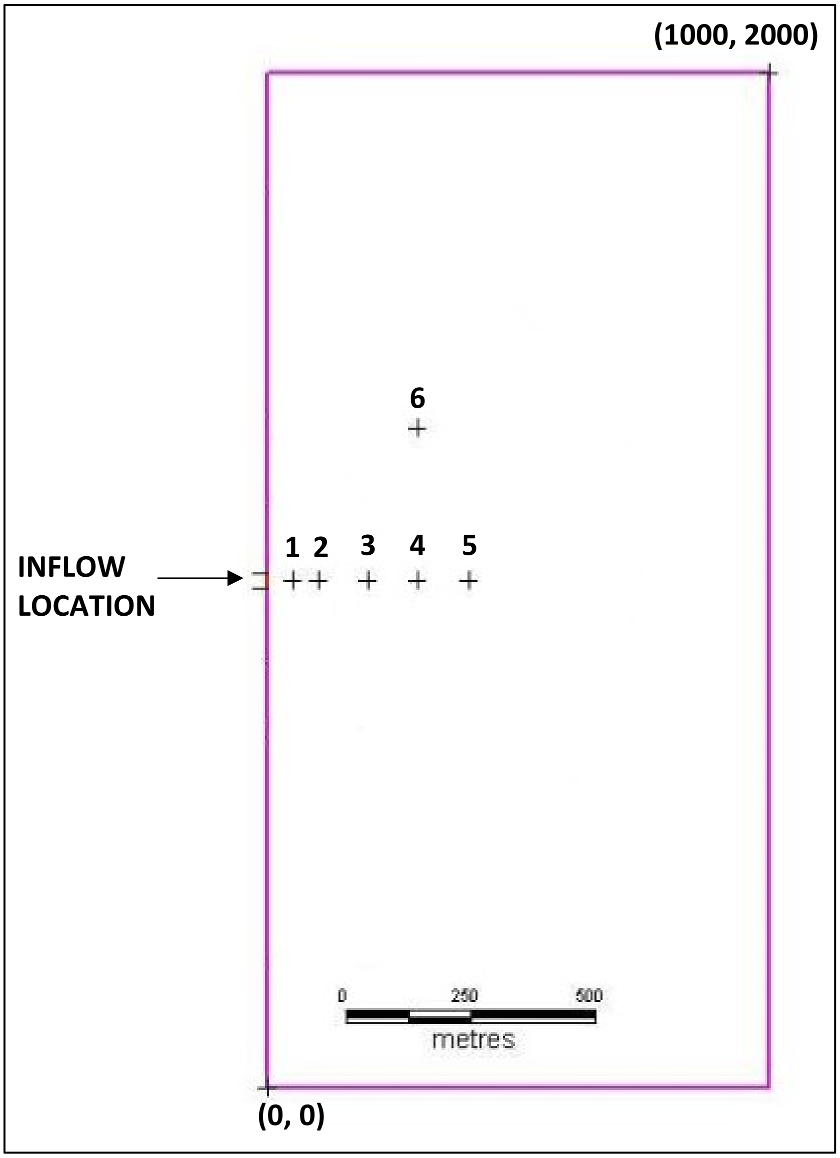

Figure 5-1 Modeled domain, showing the location of the 20 meter inflow hydrograph and output point locations.

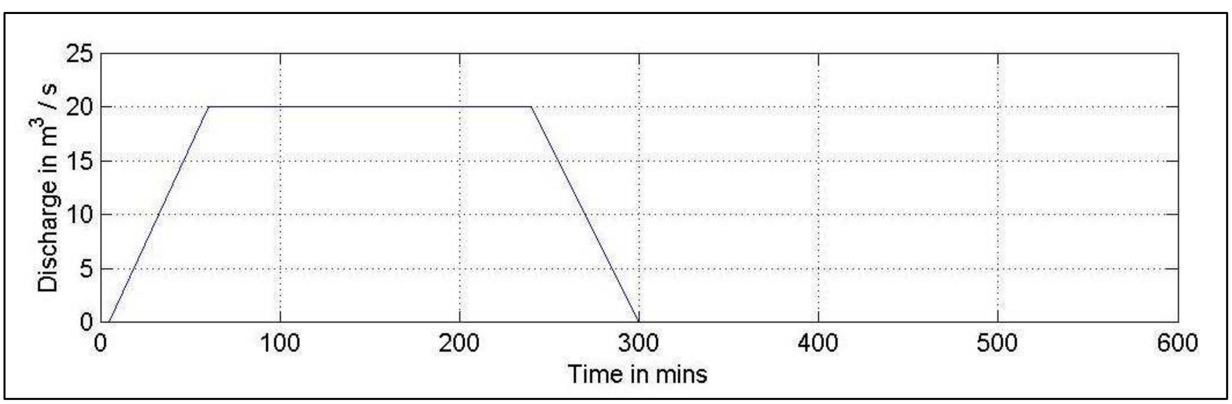

Figure 5-2 Inflow hydrograph used as upstream boundary condition.

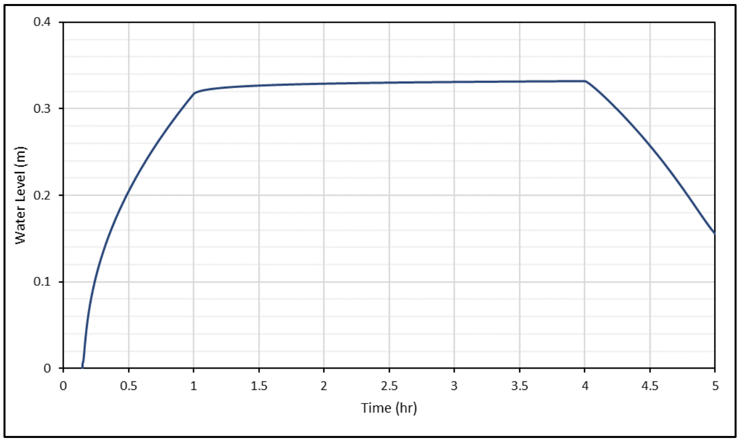

Figure 5-3 Test Point 1 – Water Level versus Time from SRH-2D

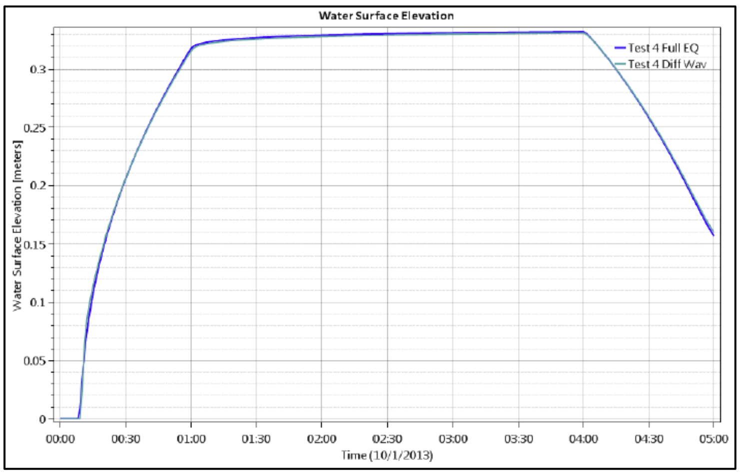

Figure 5-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

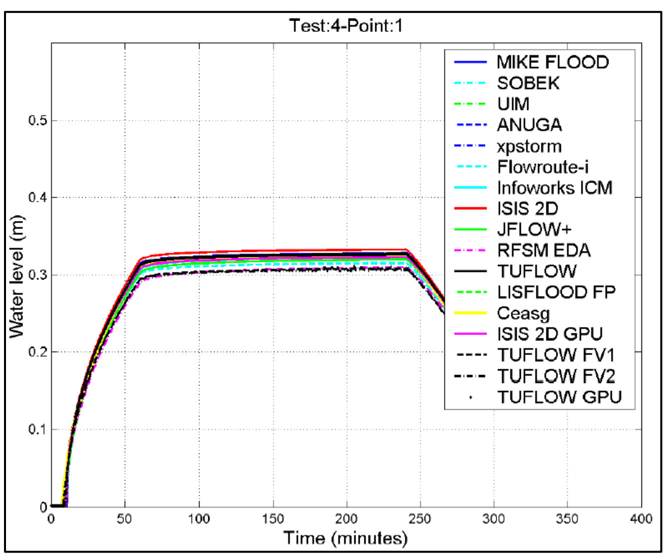

Figure 5-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

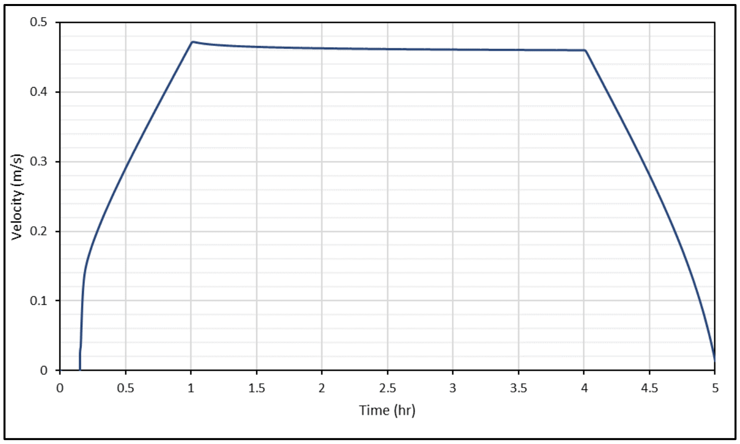

Figure 5-6 Test Point 1 – Velocity versus Time from SRH-2D

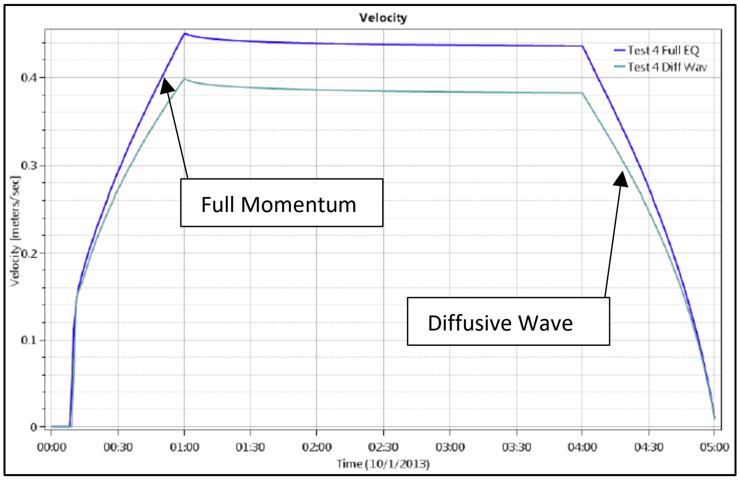

Figure 5-7 Test Point 1 – Velocity versus Time from RD-51 (2018)

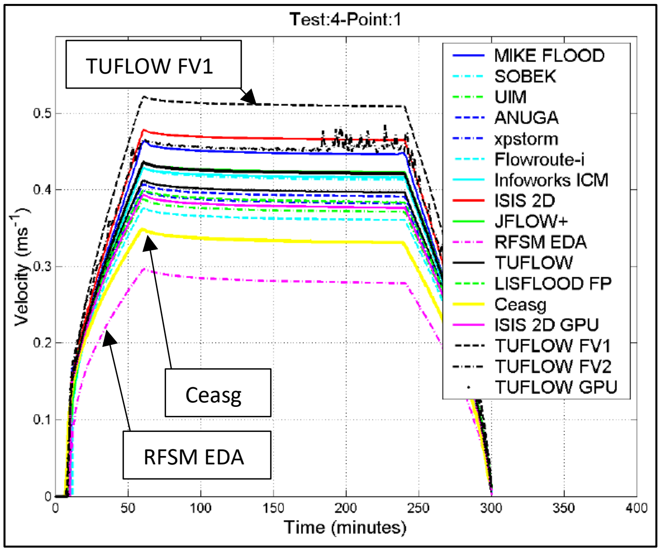

Figure 5-8 Test Point 1 – Velocity versus Time from Report SC120002 (2013)

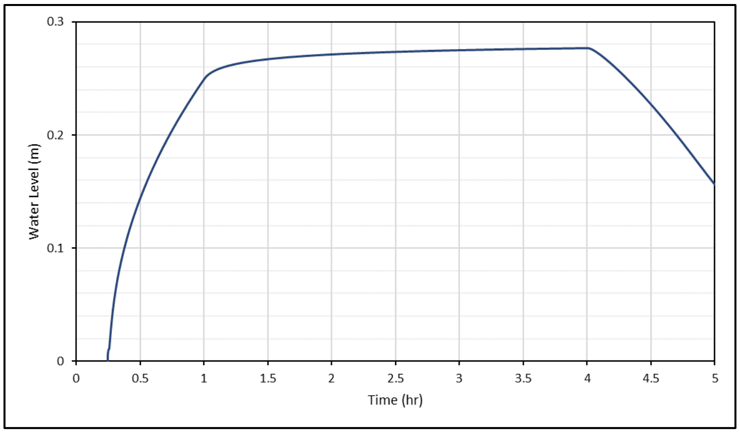

Figure 5-9 Test Point 2 – Water Level versus Time from SRH-2D

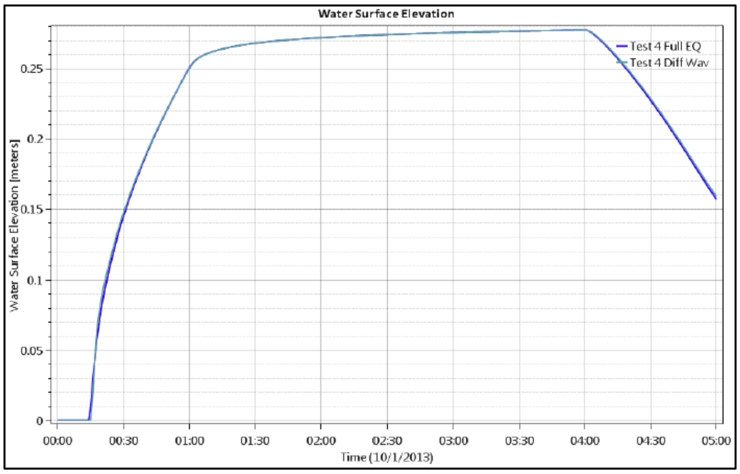

Figure 5-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

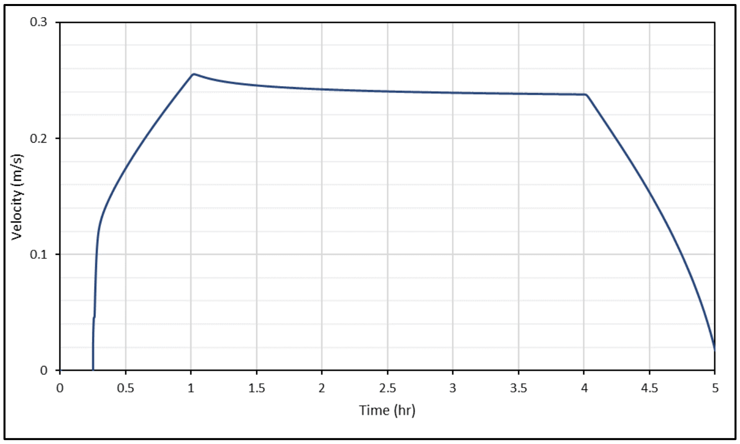

Figure 5-11 Test Point 2 – Velocity versus Time from SRH-2D

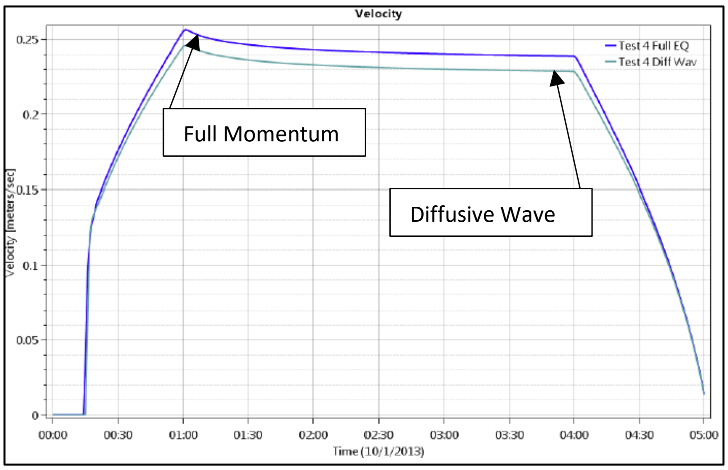

Figure 5-12 Test Point 2 – Velocity versus Time from RD-51 (2018)

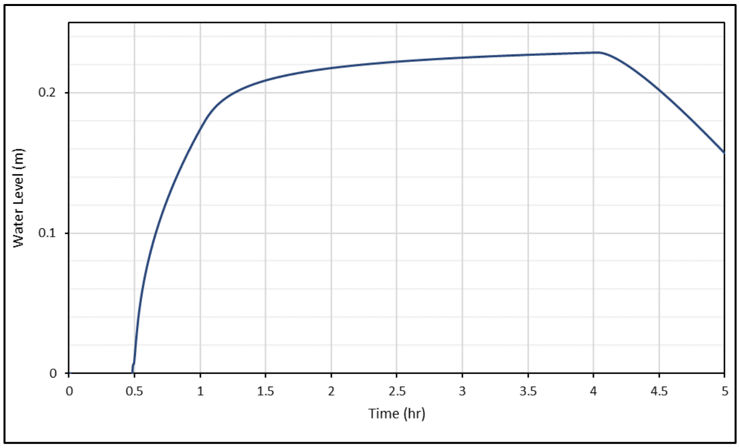

Figure 5-13 Test Point 3 – Water Level versus Time from SRH-2D

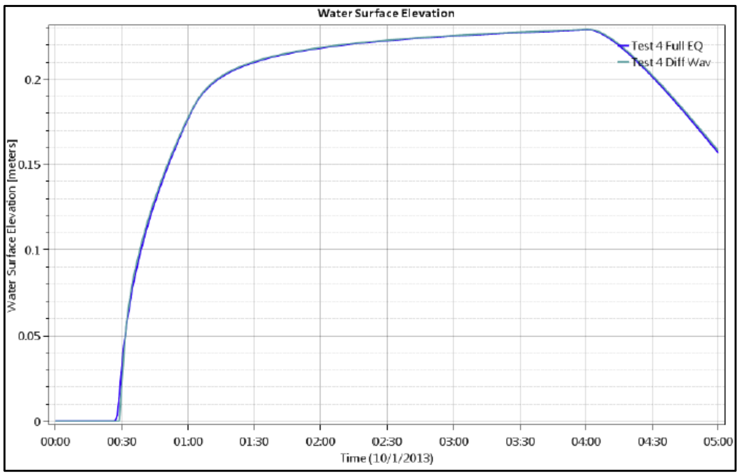

Figure 5-14 Test Point 3 – Water Level versus Time from RD-51 (2018)

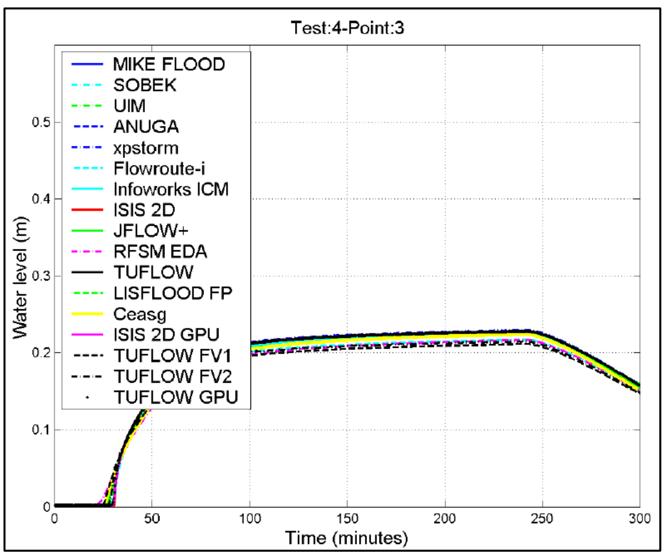

Figure 5-15 Test Point 3 – Water Level versus Time from Report SC120002 (2013)

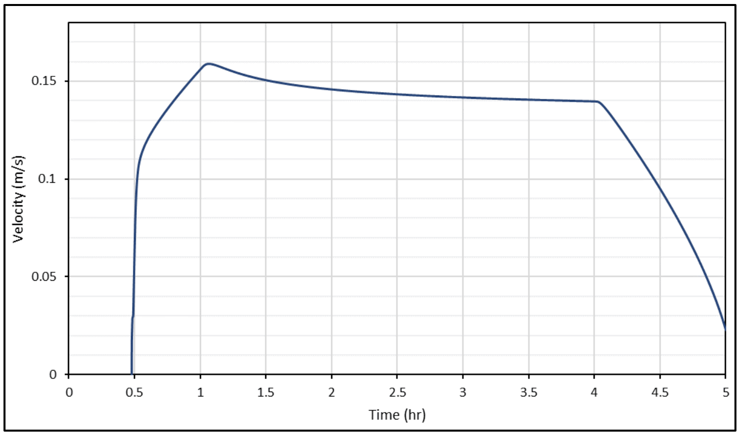

Figure 5-16 Test Point 3 – Velocity versus Time from SRH-2D

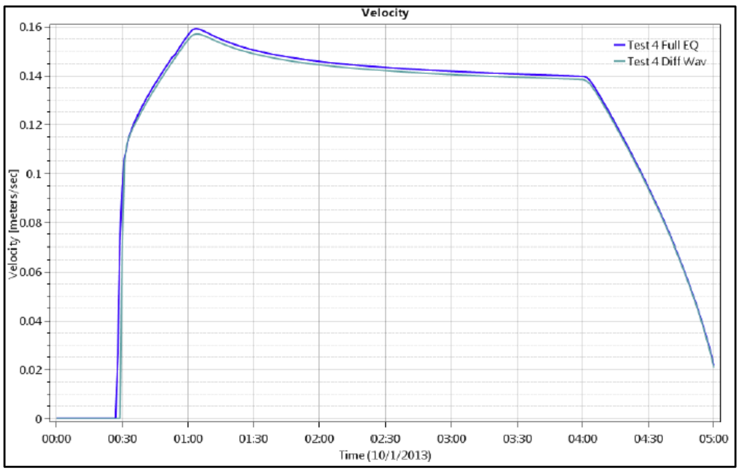

Figure 5-17 Test Point 3 – Velocity versus Time from RD-51 (2018)

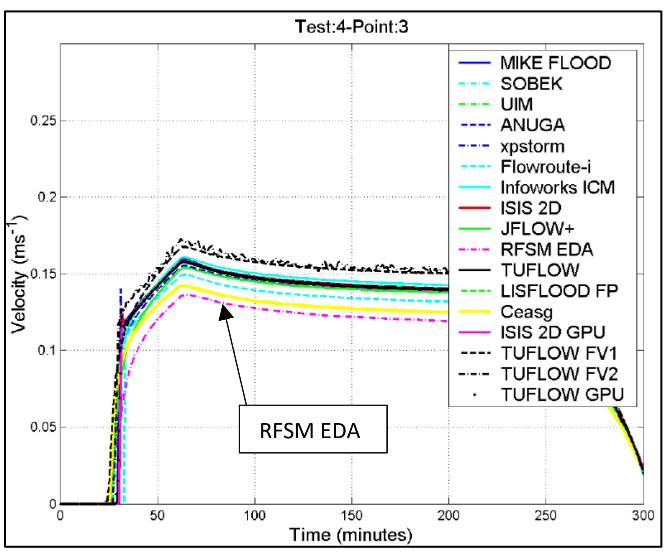

Figure 5-18 Test Point 3 – Velocity versus Time from Report SC120002 (2013)

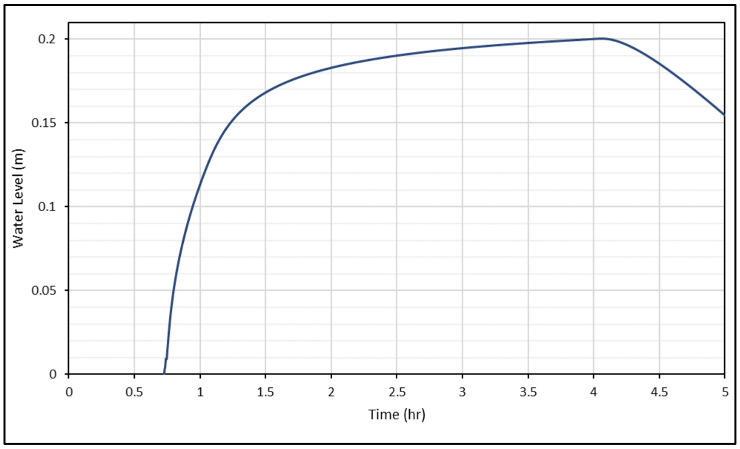

Figure 5-19 Test Point 4 – Water Level versus Time from SRH-2D

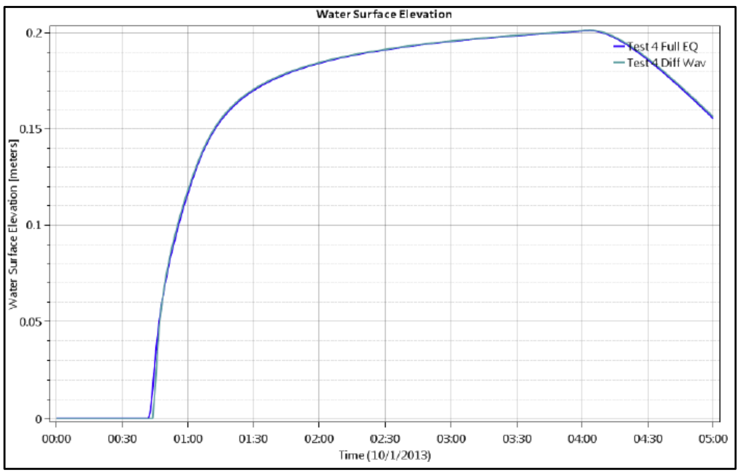

Figure 5-20 Test Point 4 – Water Level versus Time from RD-51 (2018)

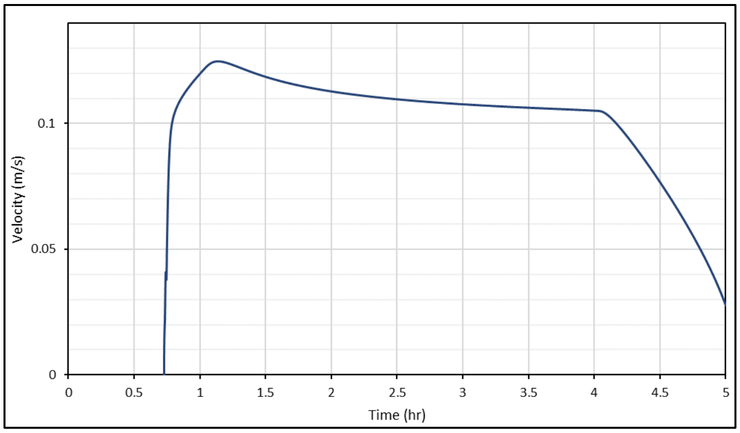

Figure 5-21 Test Point 4 – Velocity versus Time from SRH-2D

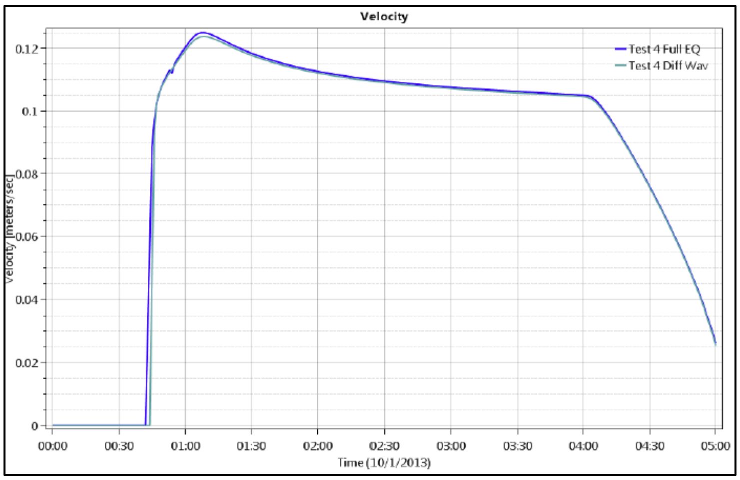

Figure 5-22 Test Point 4 – Velocity versus Time from RD-51 (2018)

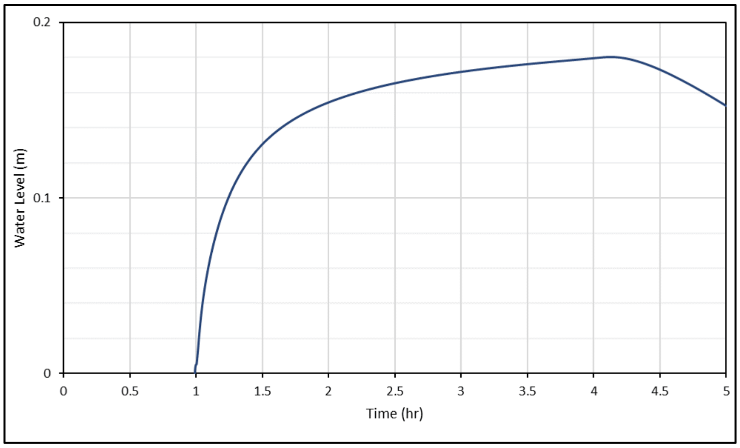

Figure 5-23 Test Point 5 – Water Level versus Time from SRH-2D

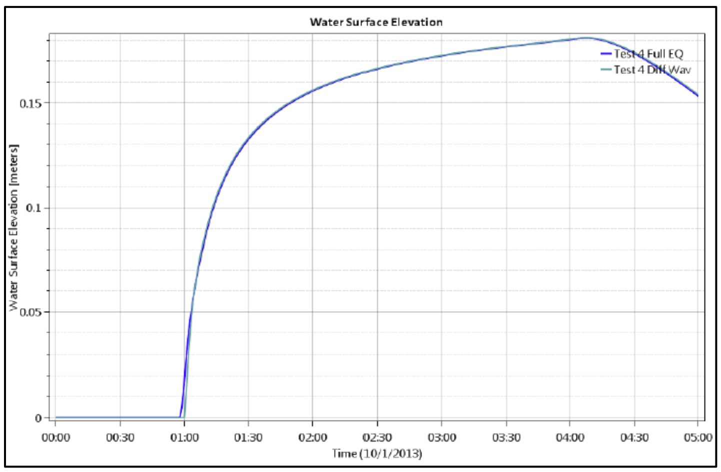

Figure 5-24 Test Point 5 – Water Level versus Time from RD-51 (2018)

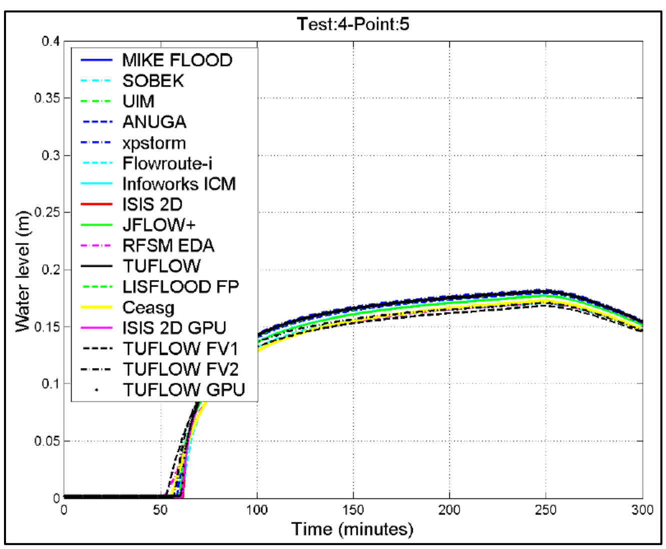

Figure 5-25 Test Point 5 – Water Level versus Time from Report SC120002 (2013)

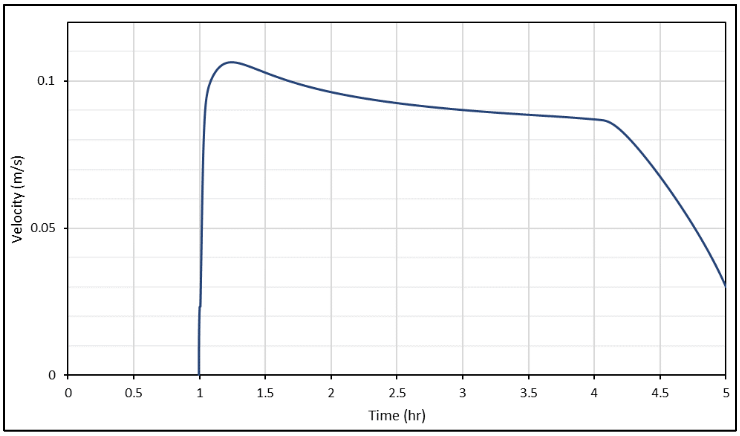

Figure 5-26 Test Point 5 – Velocity versus Time from SRH-2D

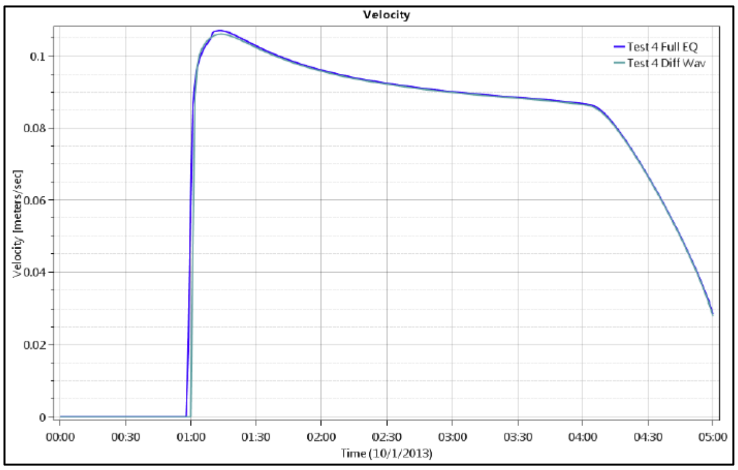

Figure 5-27 Test Point 5 – Velocity versus Time from RD-51 (2018)

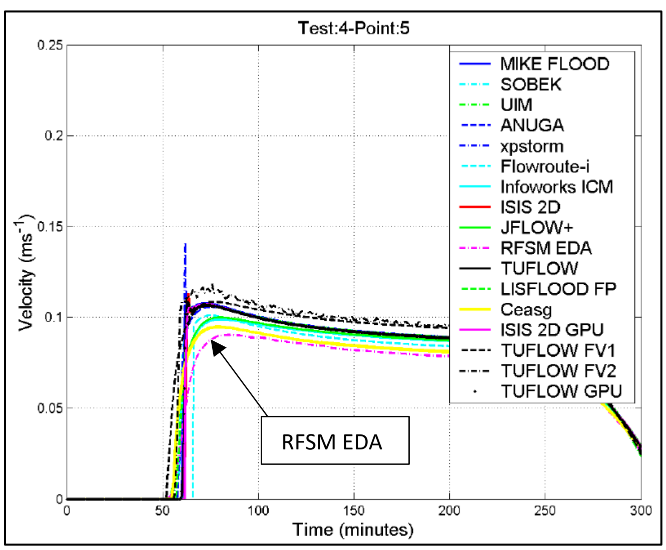

Figure 5-28 Test Point 5 – Velocity versus Time from Report SC120002 (2013)

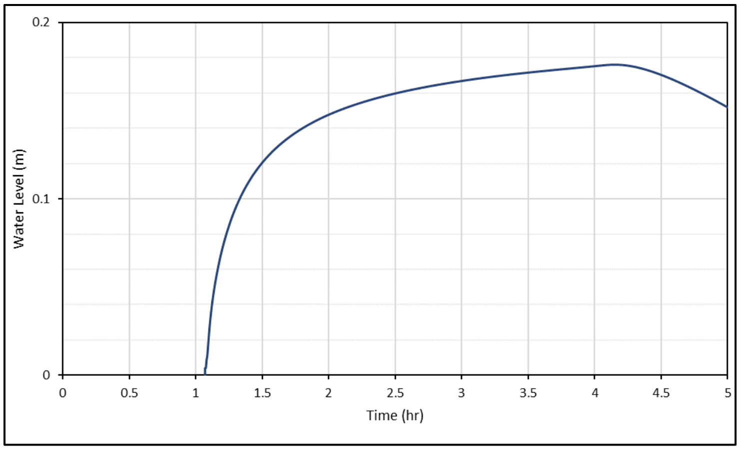

Figure 5-29 Test Point 6 – Water Level versus Time from SRH-2D

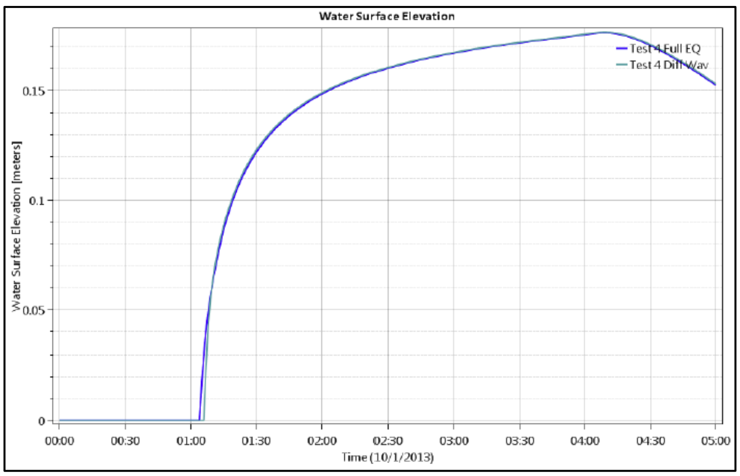

Figure 5-30 Test Point 6 – Water Level versus Time from RD-51 (2018)

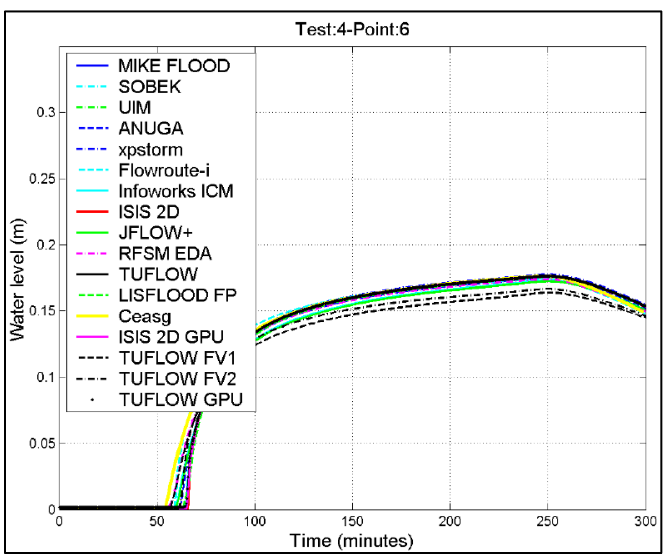

Figure 5-31 Test Point 6 – Water Level versus Time from Report SC120002 (2013)

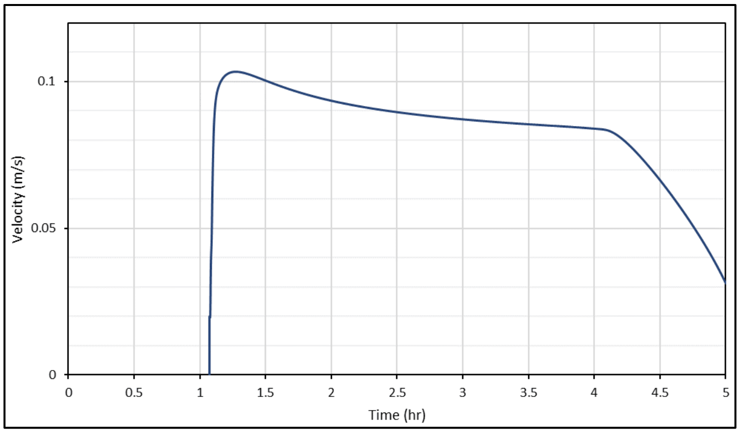

Figure 5-32 Test Point 6 – Velocity versus Time from SRH-2D

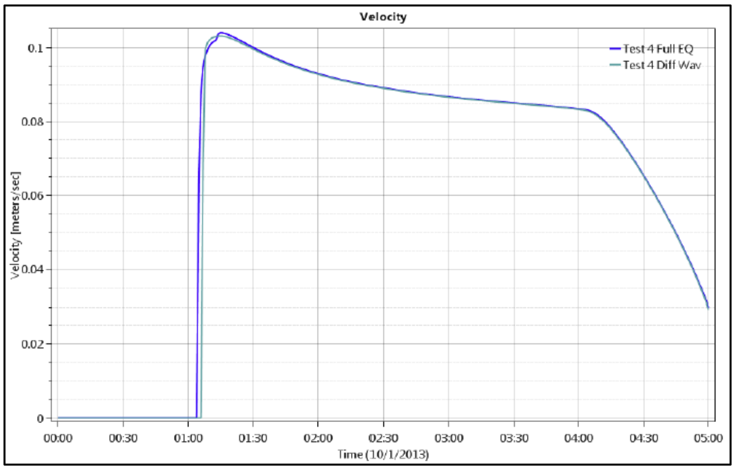

Figure 5-33 Test Point 6 – Velocity versus Time from RD-51 (2018)

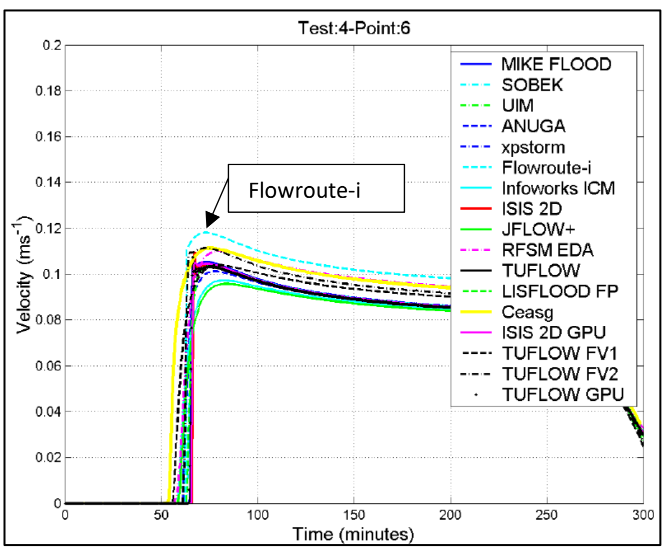

Figure 5-34 Test Point 6 – Velocity versus Time from Report SC120002 (2013)

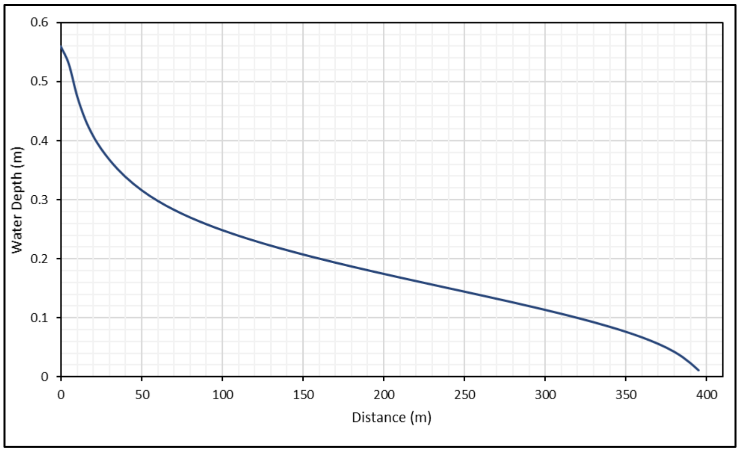

Figure 5-35 Cross Section from Inflow to Point 5 – Water Level versus Distance at 1 Hour from SRH-2D

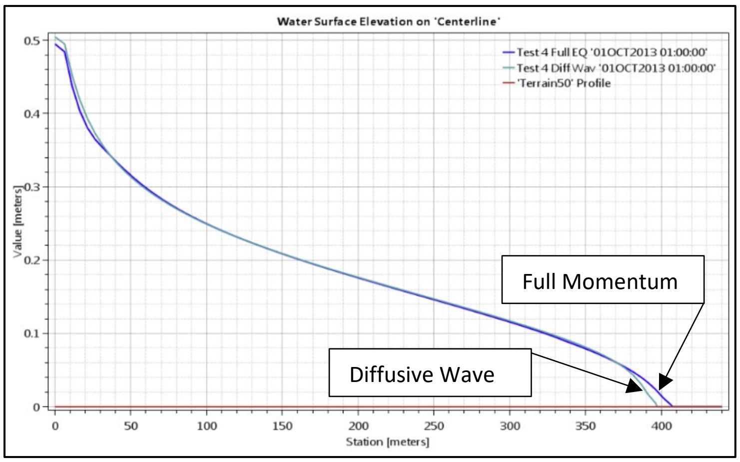

Figure 5-36 Cross Section from Inflow to Point 5 – Water Level versus Distance at 1 Hour from RD-51 (2018)

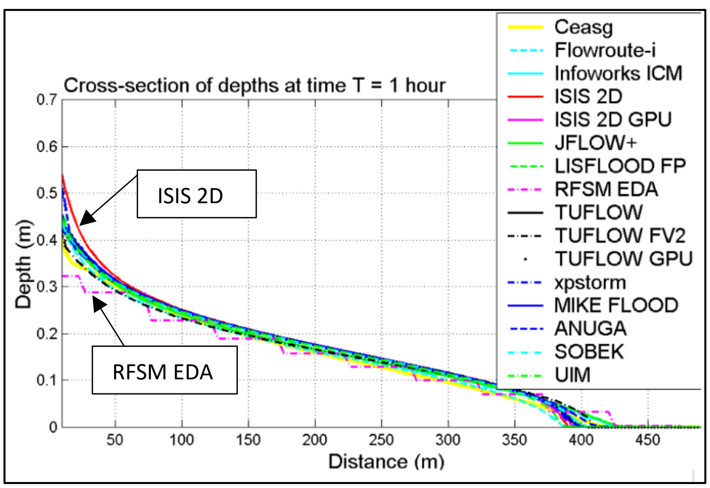

Figure 5-37 Cross Section from Inflow to Point 5 – Water Level versus Distance at 1 Hour from Report SC120002 (2013)

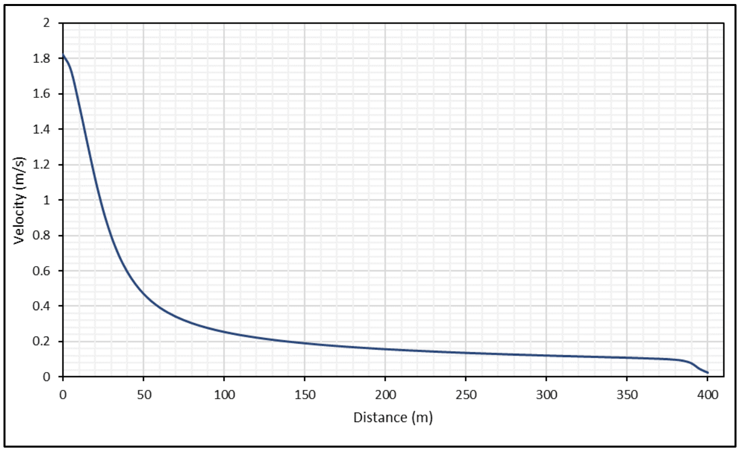

Figure 5-38 Cross Section from Inflow to Point 5 – Velocity versus Distance at 1 Hour from SRH-2D

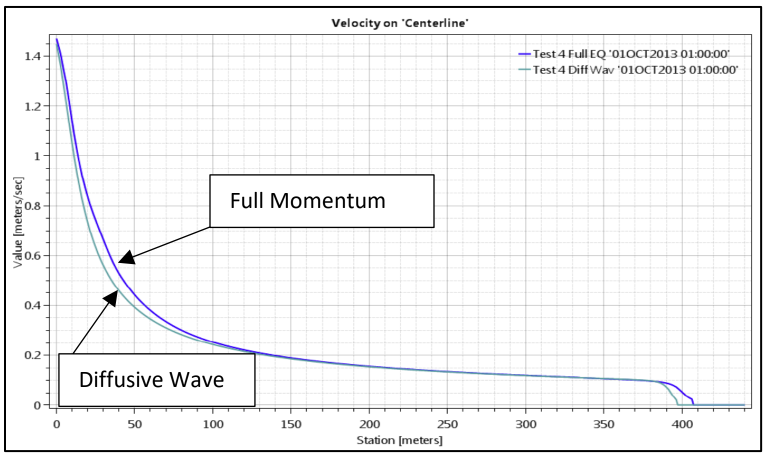

Figure 5-39 Cross Section from Inflow to Point 5 – Velocity versus Distance at 1 Hour from RD-51 (2018)

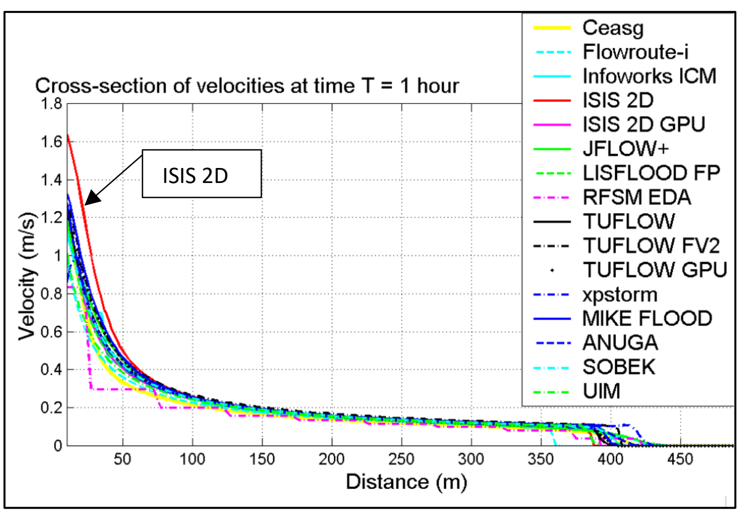

Figure 5-40 Cross Section from Inflow to Point 5 – Velocity versus Distance at 1 Hour from Report SC120002 (2013)

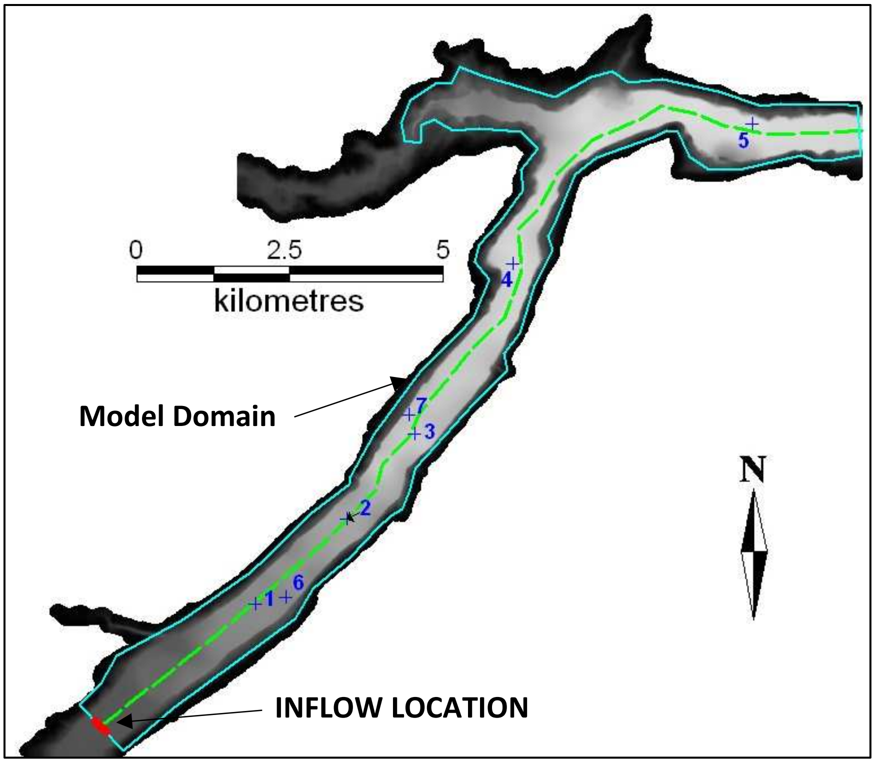

Figure 6-1 Plan view of DEM used in Benchmark Test 5 including output point locations. The red line indicates the location of the boundary condition, and the cyan polygon represents the extents of the model's domain.

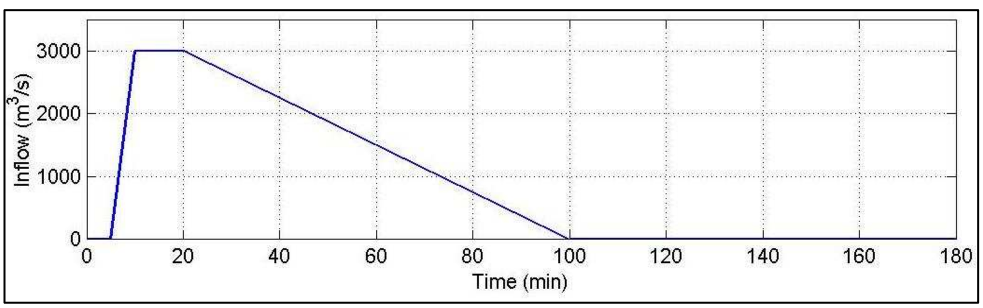

Figure 6-2 Inflow hydrograph used as upstream boundary condition.

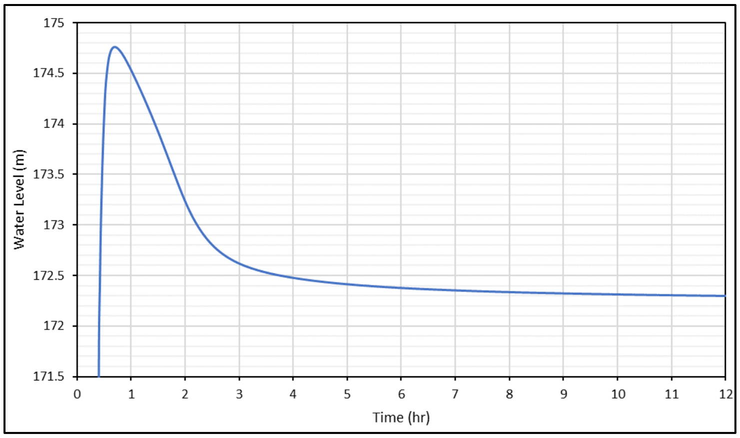

Figure 6-3 Test Point 1 – Water Level versus Time from SRH-2D

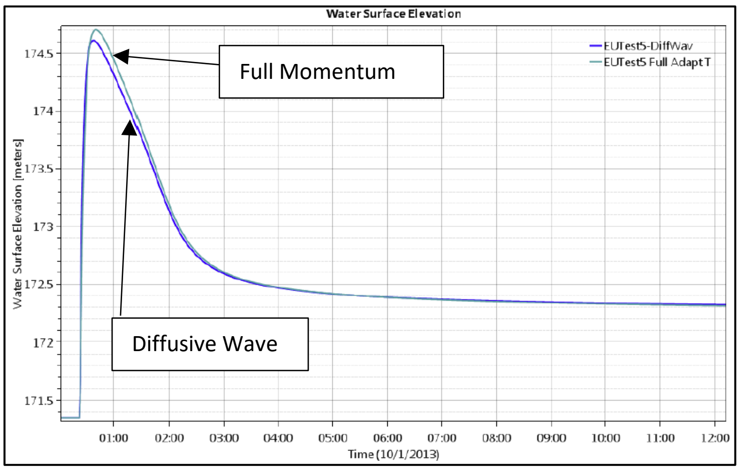

Figure 6-4 Test Point 1 – Water Level versus Time from RD-51 (2018)

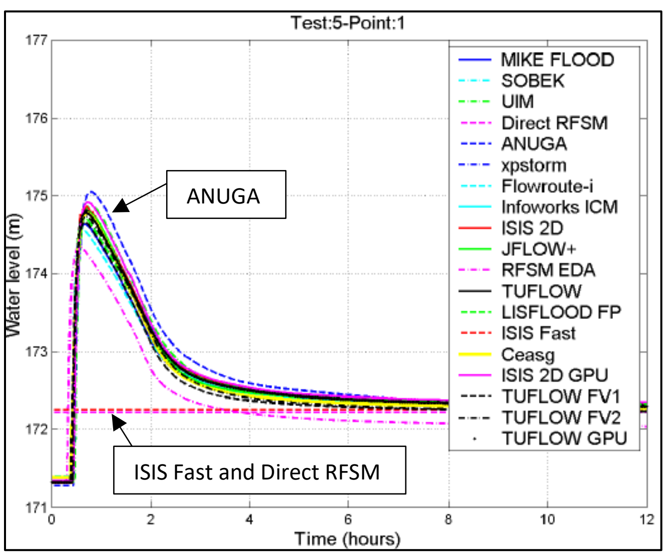

Figure 6-5 Test Point 1 – Water Level versus Time from Report SC120002 (2013)

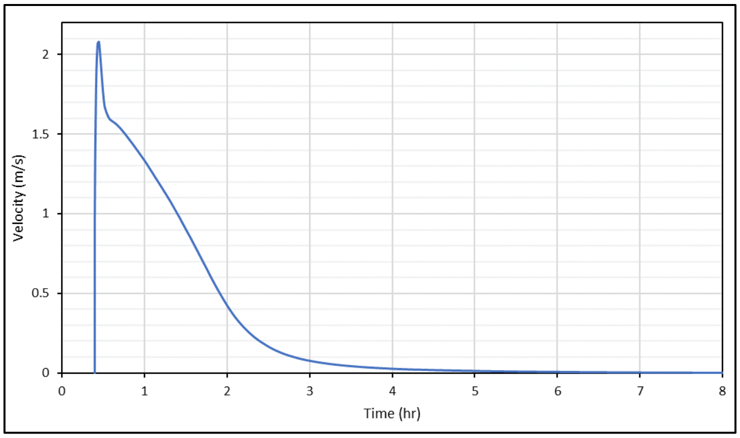

Figure 6-6 Test Point 1 – Velocity versus Time from SRH-2D

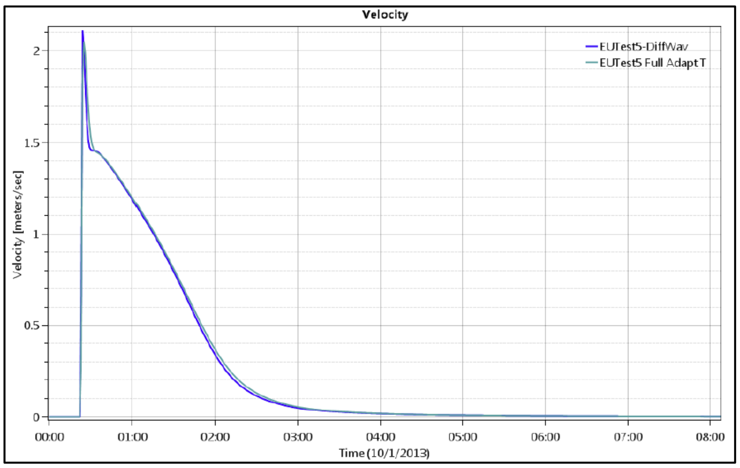

Figure 6-7 Test Point 1 – Velocity versus Time from RD-51 (2018)

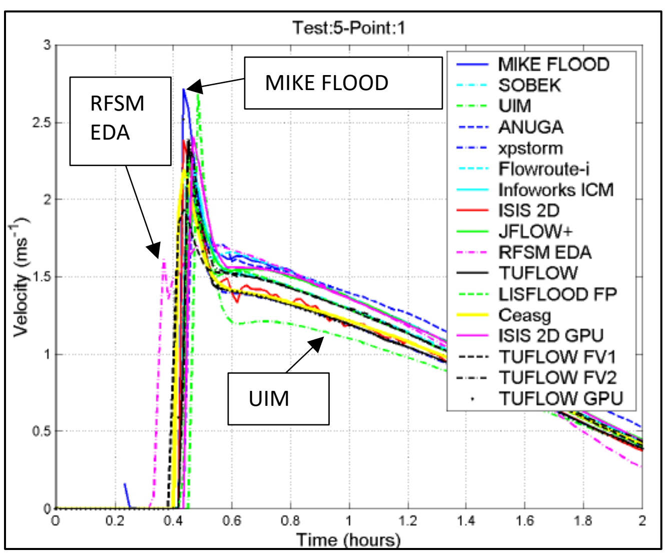

Figure 6-8 Test Point 1 – Velocity versus Time from Report SC120002 (2013)

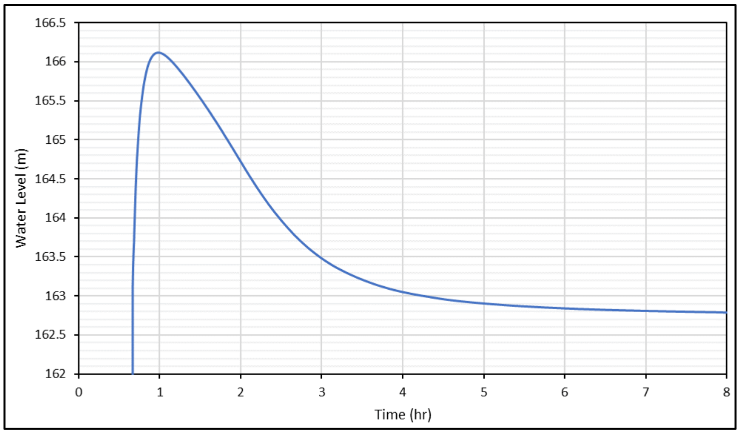

Figure 6-9 Test Point 2 – Water Level versus Time from SRH-2D

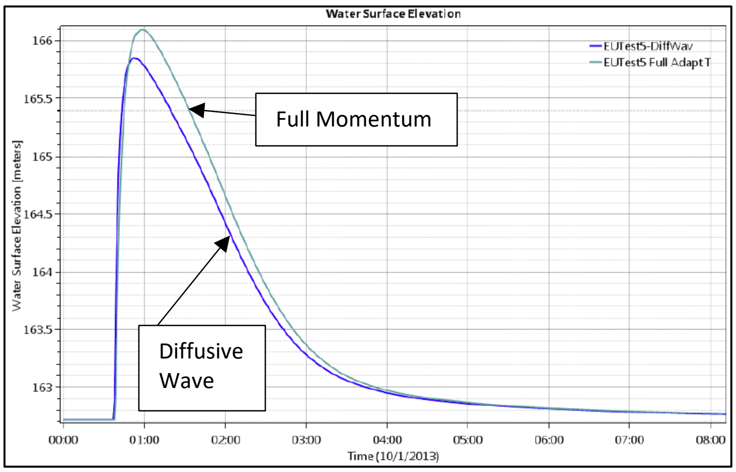

Figure 6-10 Test Point 2 – Water Level versus Time from RD-51 (2018)

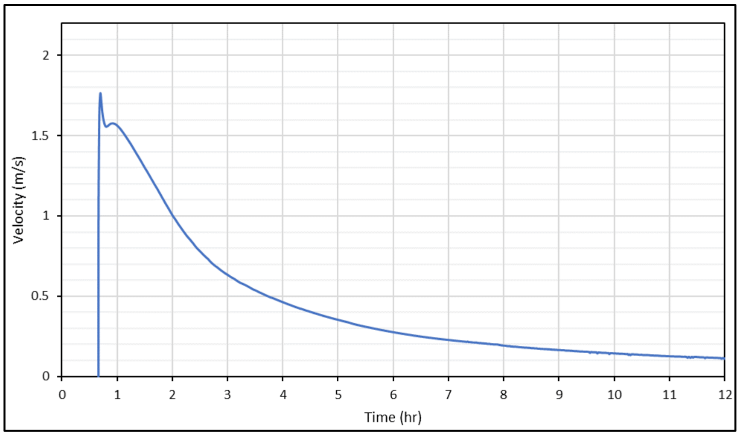

Figure 6-11 Test Point 2 – Velocity versus Time from SRH-2D

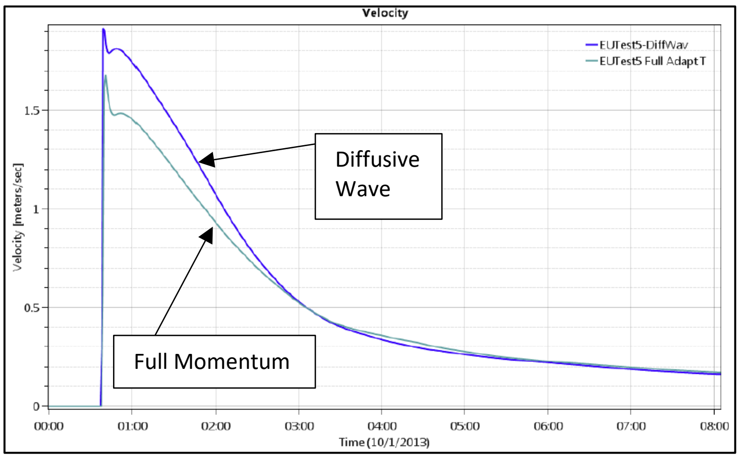

Figure 6-12 Test Point 2 – Velocity versus Time from RD-51 (2018)

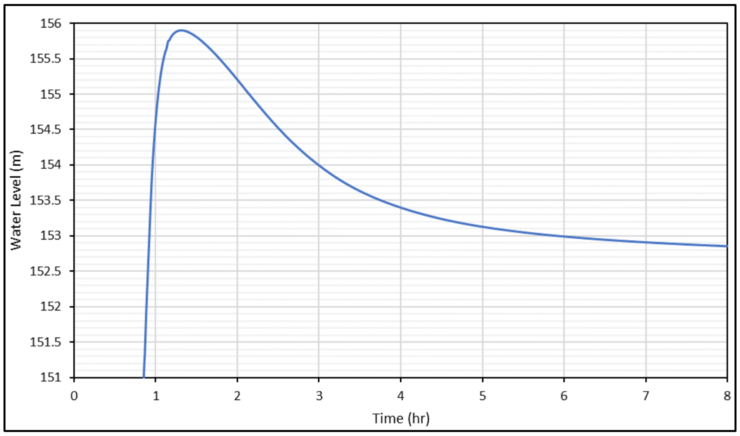

Figure 6-13 Test Point 3 – Water Level versus Time from SRH-2D

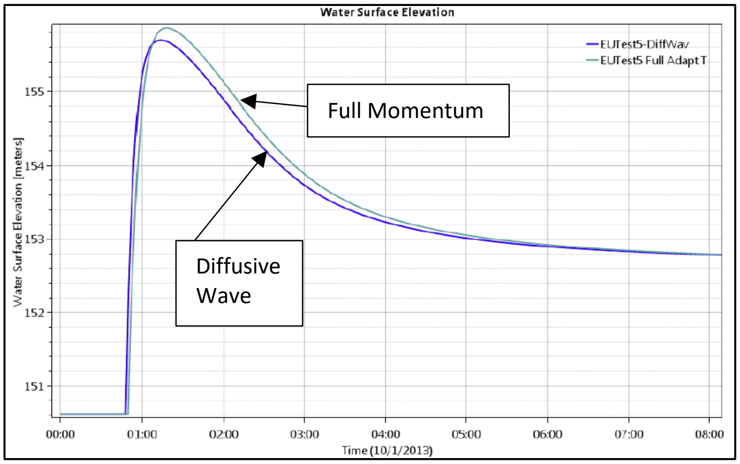

Figure 6-14 Test Point 3 – Water Level versus Time from RD-51 (2018)

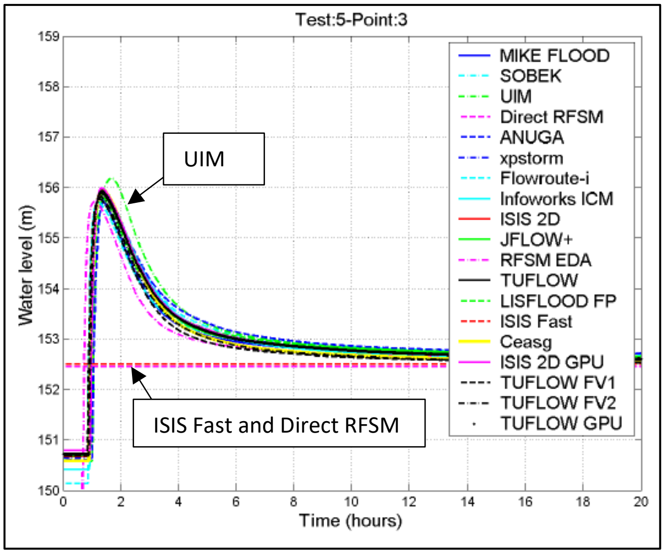

Figure 6-15 Test Point 3 – Water Level versus Time from Report SC120002 (2013)

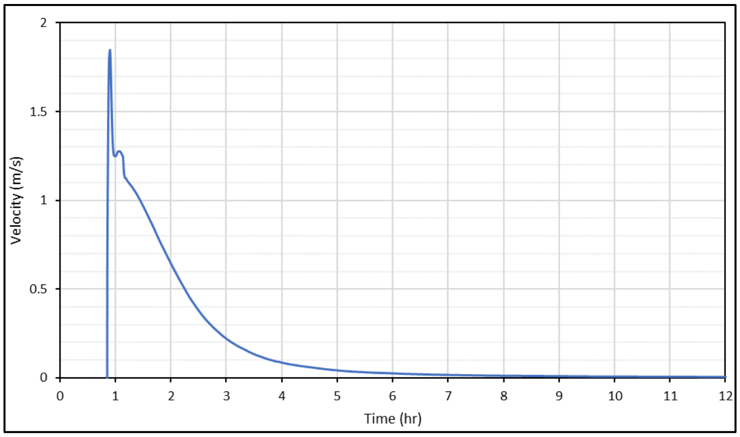

Figure 6-16 Test Point 3 – Velocity versus Time from SRH-2D

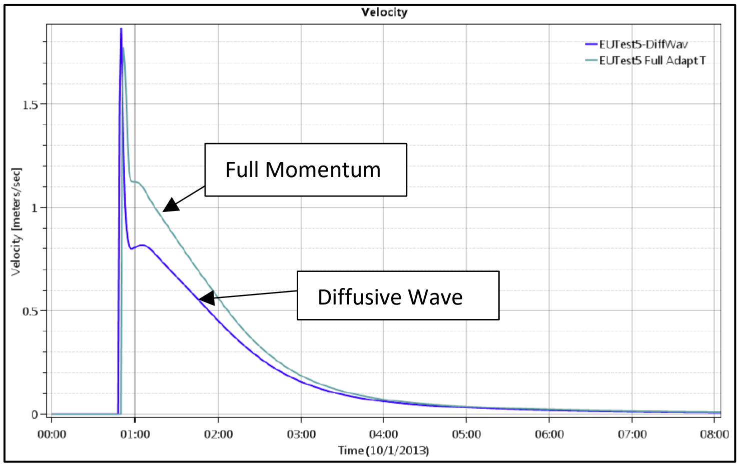

Figure 6-17 Test Point 3 – Velocity versus Time from RD-51 (2018)

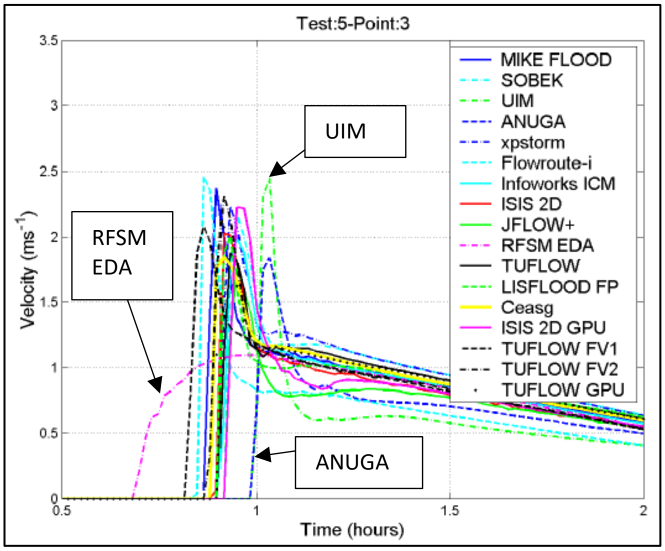

Figure 6-18 Test Point 3 – Velocity versus Time from Report SC120002 (2013)

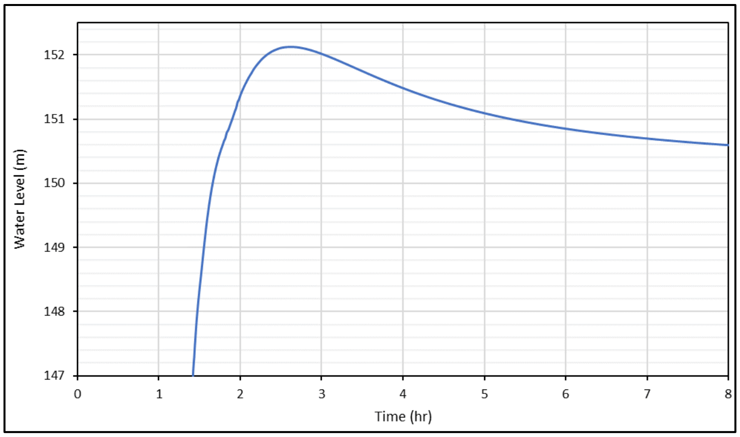

Figure 6-19 Test Point 4 – Water Level versus Time from SRH-2D

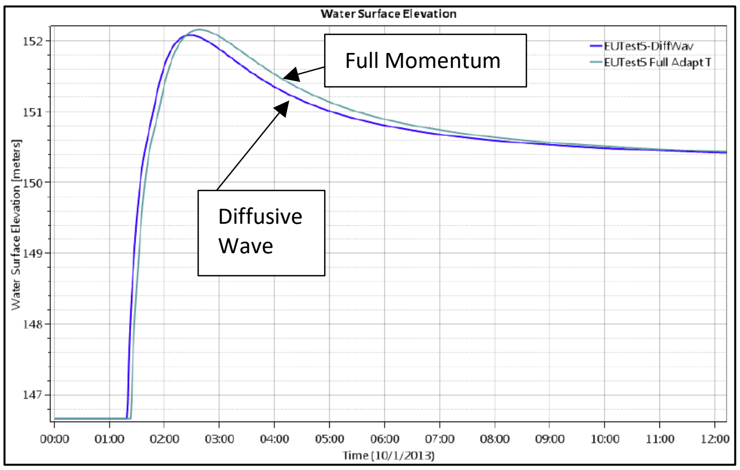

Figure 6-20 Test Point 4 – Water Level versus Time from RD-51 (2018)

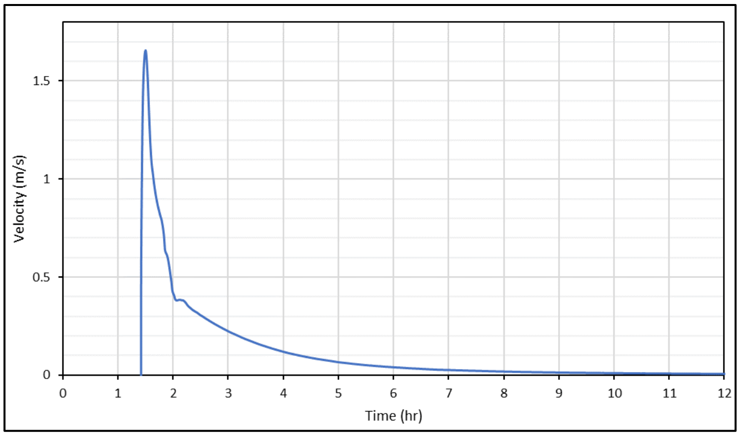

Figure 6-21 Test Point 4 – Velocity versus Time from SRH-2D

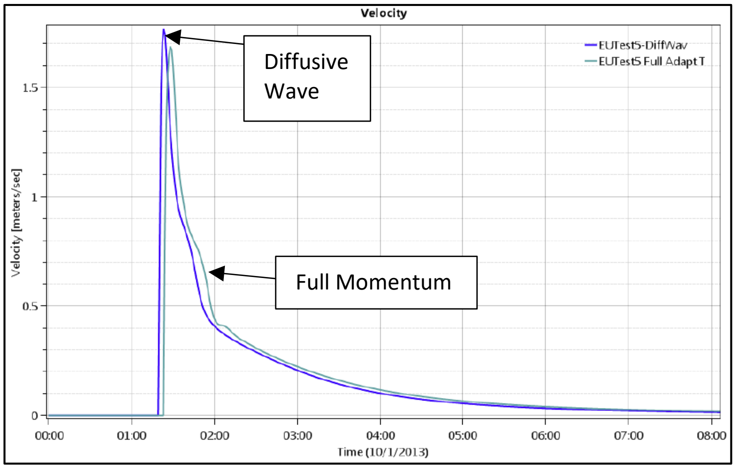

Figure 6-22 Test Point 4 – Velocity versus Time from RD-51 (2018)

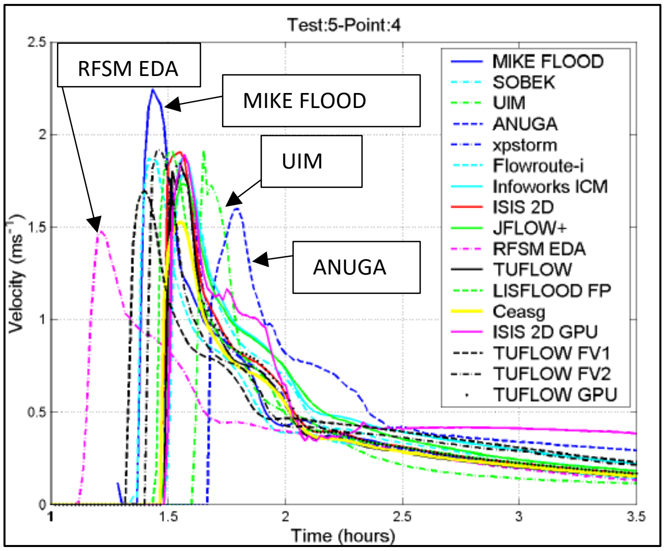

Figure 6-23 Test Point 4 – Velocity versus Time from Report SC120002 (2013)

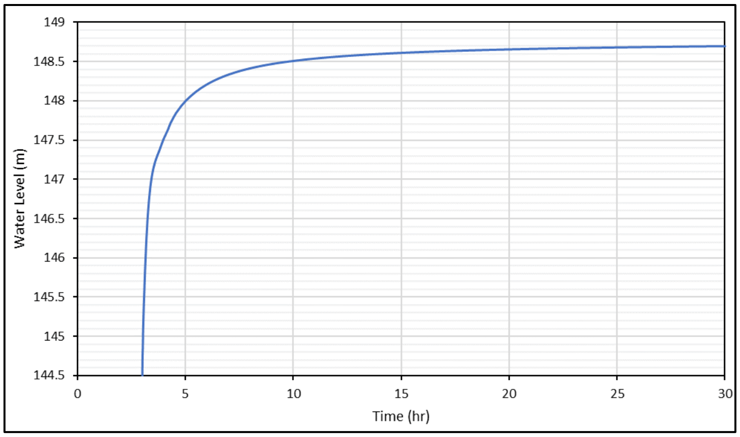

Figure 6-24 Test Point 5 – Water Level versus Time from SRH-2D

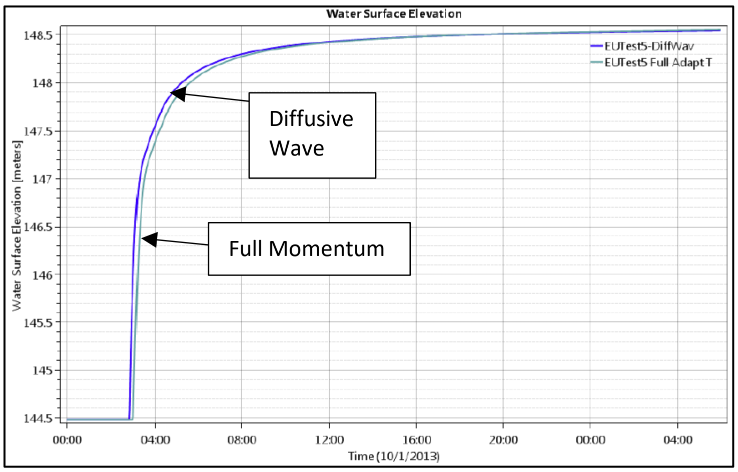

Figure 6-25 Test Point 5 – Water Level versus Time from RD-51 (2018)

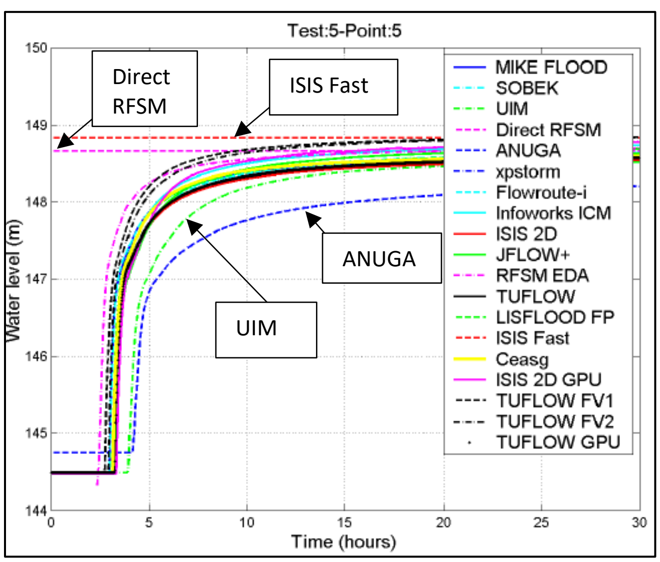

Figure 6-26 Test Point 5 – Water Level versus Time from Report SC120002 (2013)

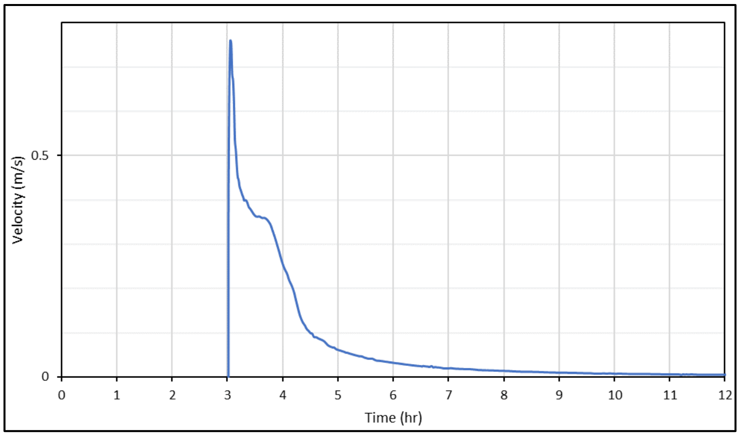

Figure 6-27 Test Point 5 – Velocity versus Time from SRH-2D

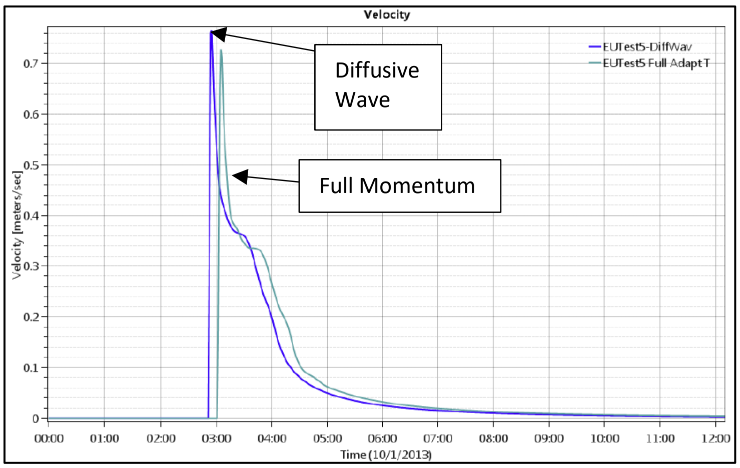

Figure 6-28 Test Point 5 – Velocity versus Time from RD-51 (2018)

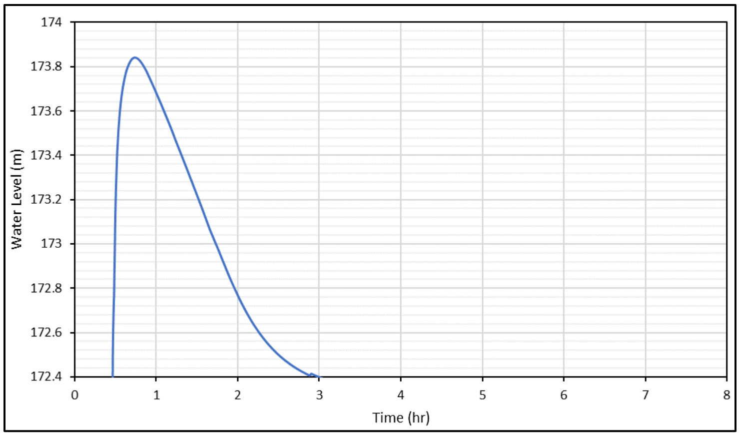

Figure 6-29 Test Point 6 – Water Level versus Time from SRH-2D

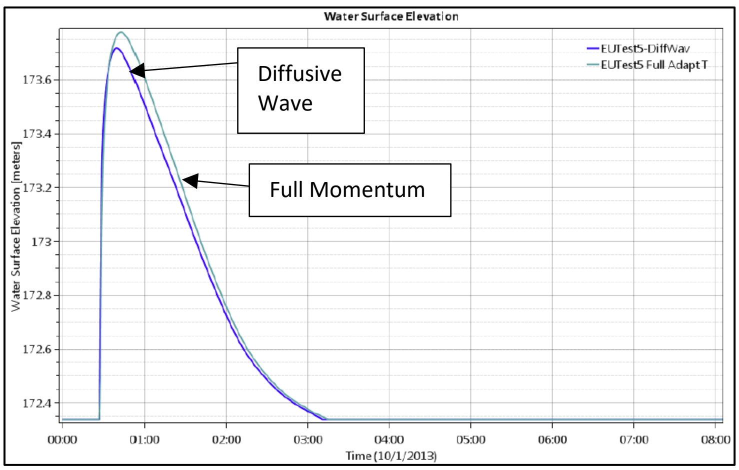

Figure 6-30 Test Point 6 – Water Level versus Time from RD-51 (2018)

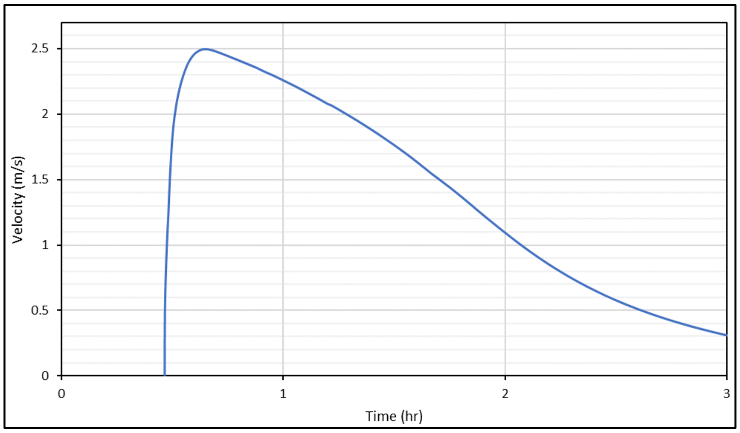

Figure 6-31 Test Point 6 – Velocity versus Time from SRH-2D

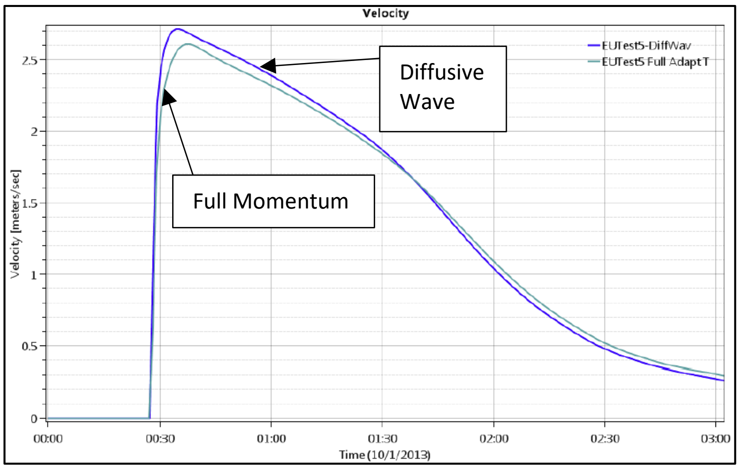

Figure 6-32 Test Point 6 – Velocity versus Time from RD-51 (2018)

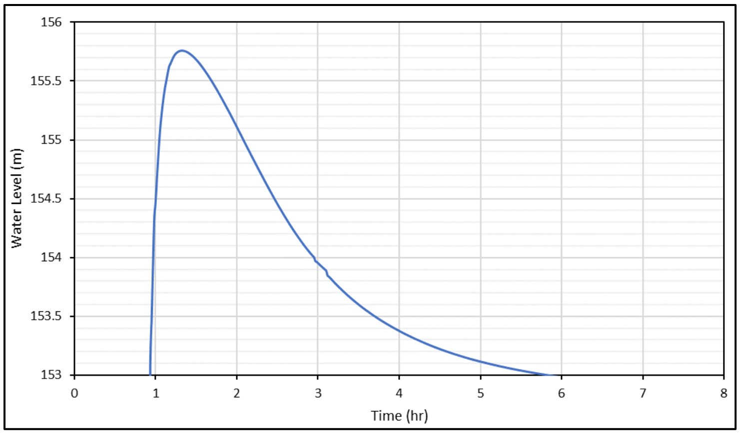

Figure 6-33 Test Point 7 – Water Level versus Time from SRH-2D

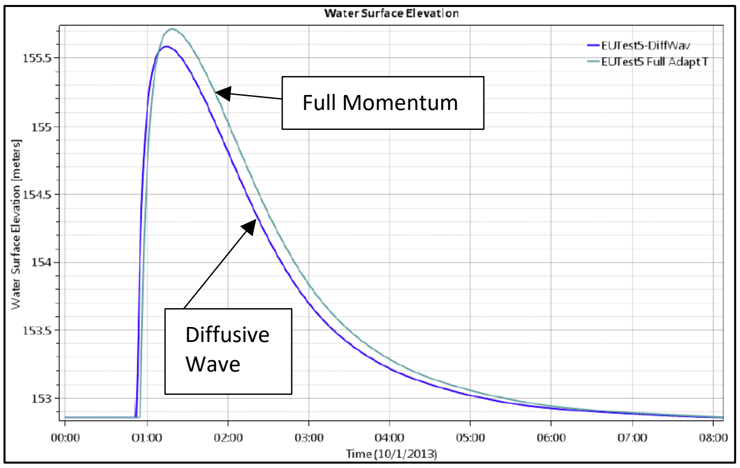

Figure 6-34 Test Point 7 – Water Level versus Time from RD-51 (2018)

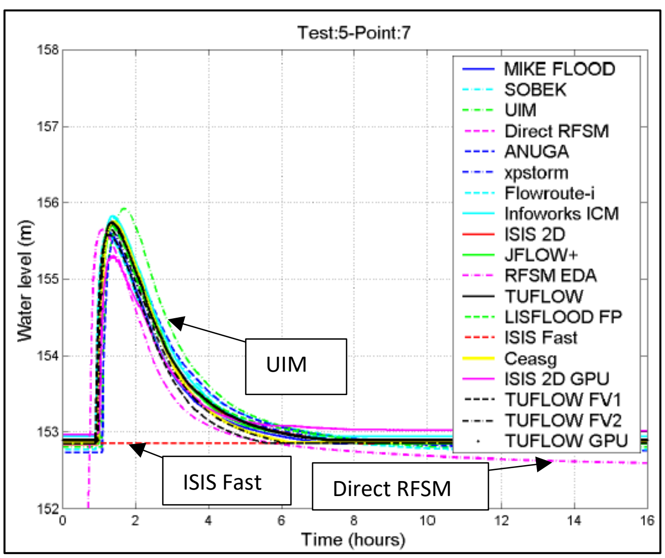

Figure 6-35 Test Point 7 – Water Level versus Time from Report SC120002 (2013)

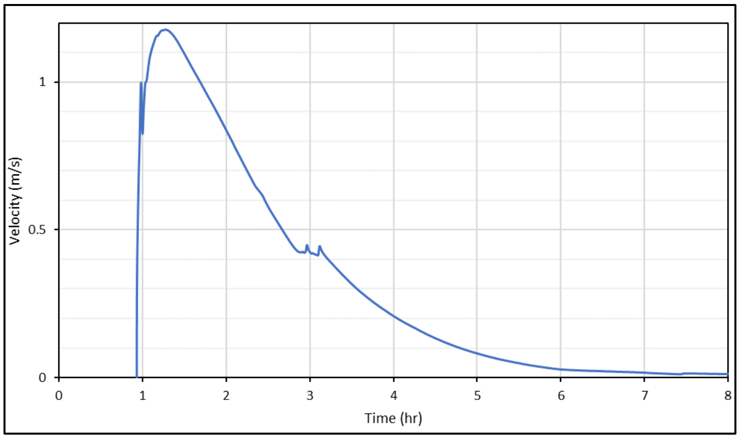

Figure 6-36 Test Point 7 – Velocity versus Time from SRH-2D

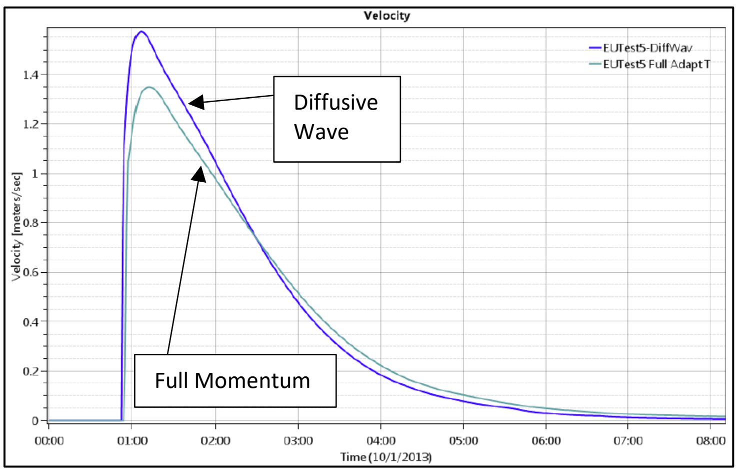

Figure 6-37 Test Point 7 – Velocity versus Time from RD-51 (2018)

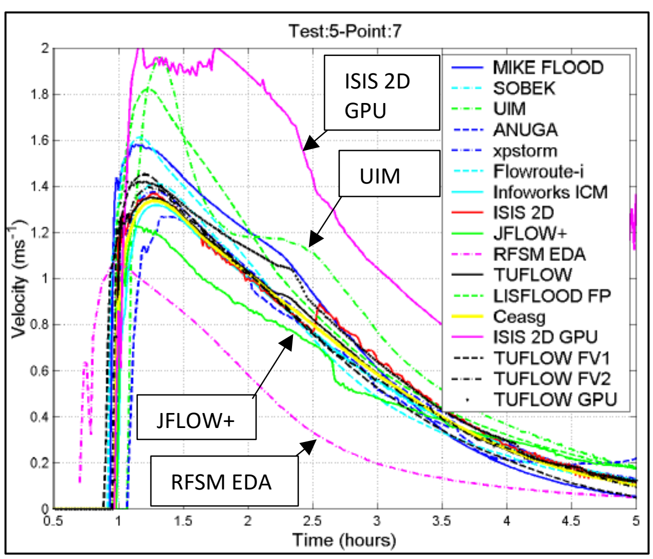

Figure 6-38 Test Point 7 – Velocity versus Time from Report SC120002 (2013)

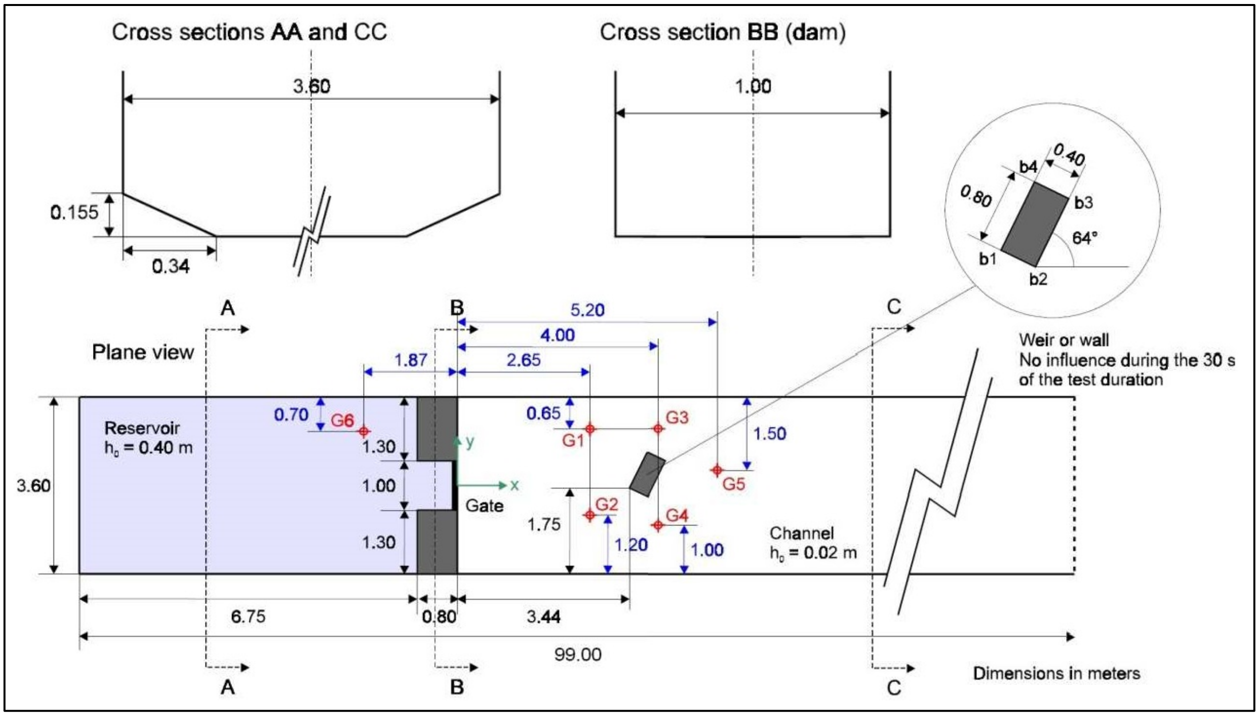

Figure 7-1 Setup for Benchmark Test 6A adapted from Soares-Frazao and Zech (2002).

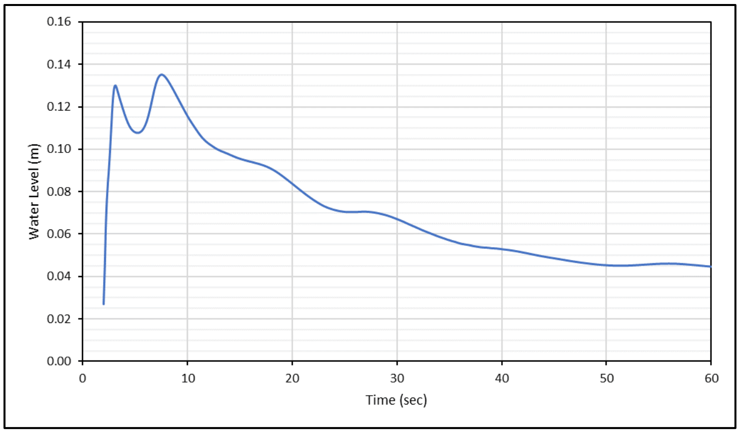

Figure 7-2 Test Point G1 – Water Level versus Time from SRH-2D

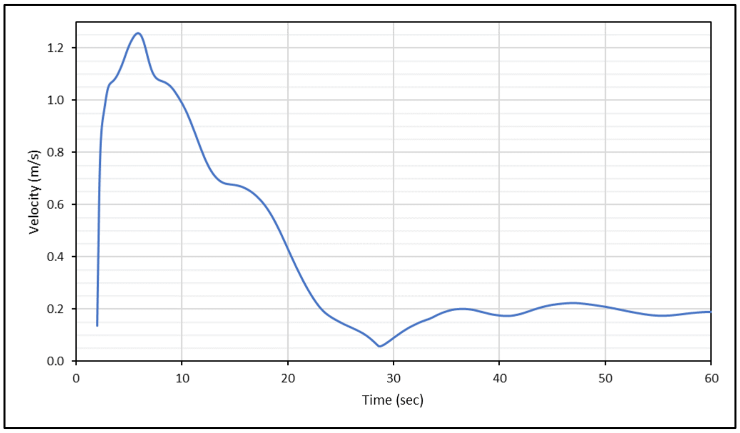

Figure 7-3 Test Point G1 – Velocity versus Time from SRH-2D

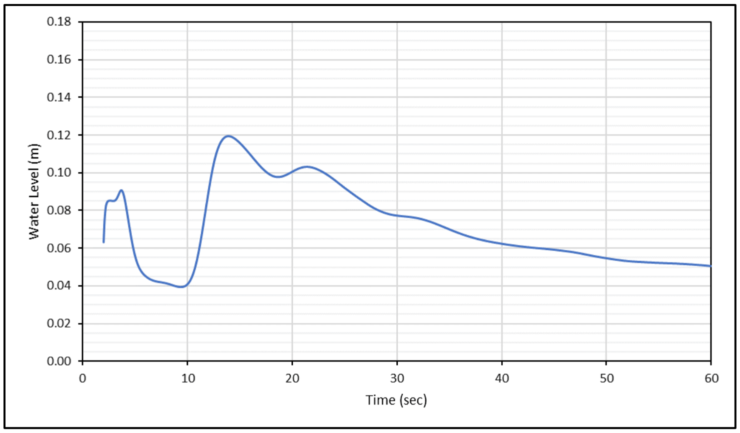

Figure 7-4 Test Point G2 – Water Level versus Time from SRH-2D

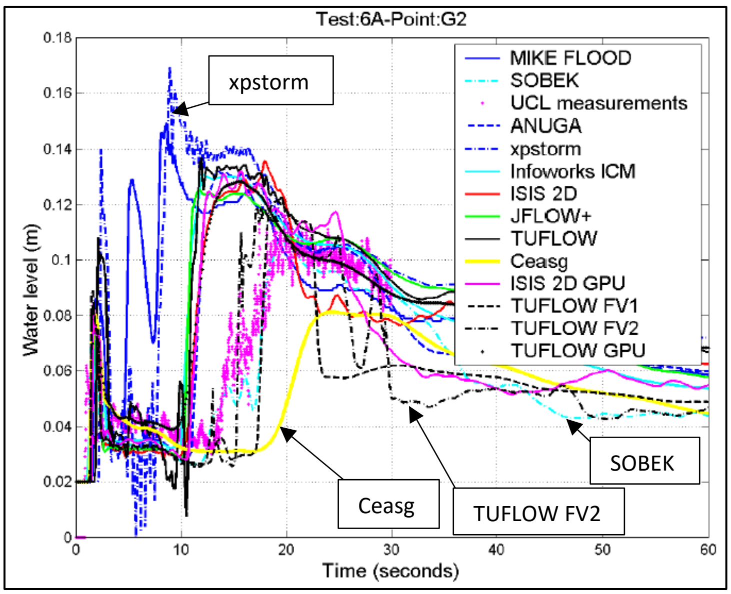

Figure 7-5 Test Point G2 – Water Level versus Time from Report SC120002 (2013)

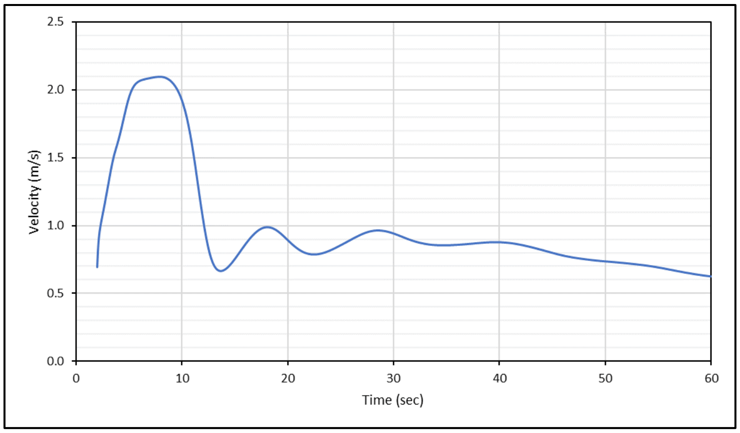

Figure 7-6 Test Point G2 – Velocity versus Time from SRH-2D

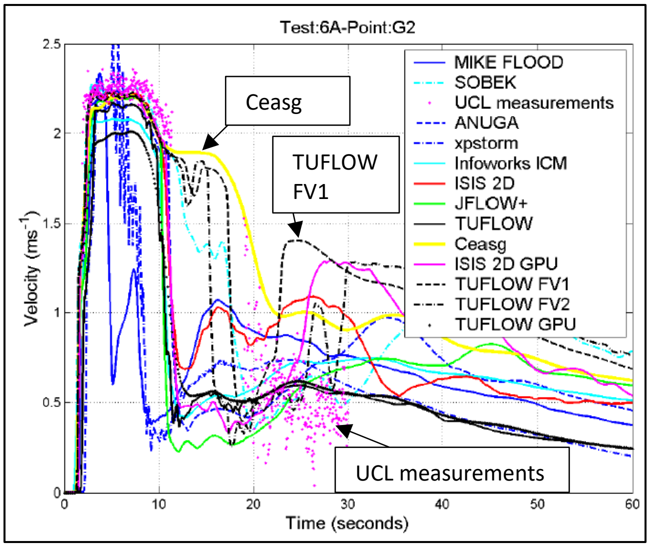

Figure 7-7 Test Point G2 – Velocity versus Time from Report SC120002 (2013)

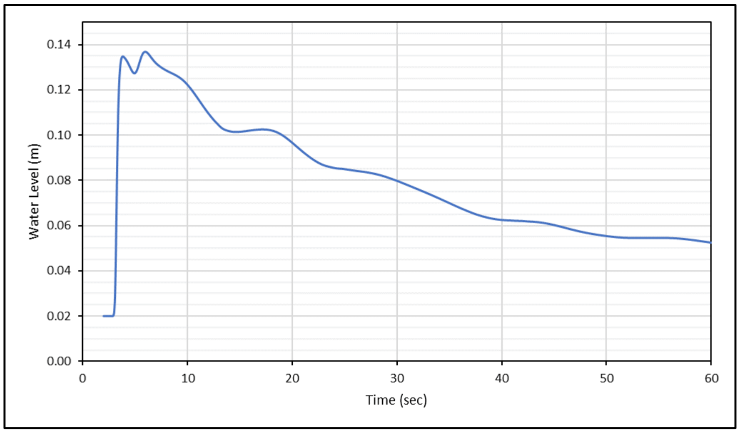

Figure 7-8 Test Point G3 – Water Level versus Time from SRH-2D

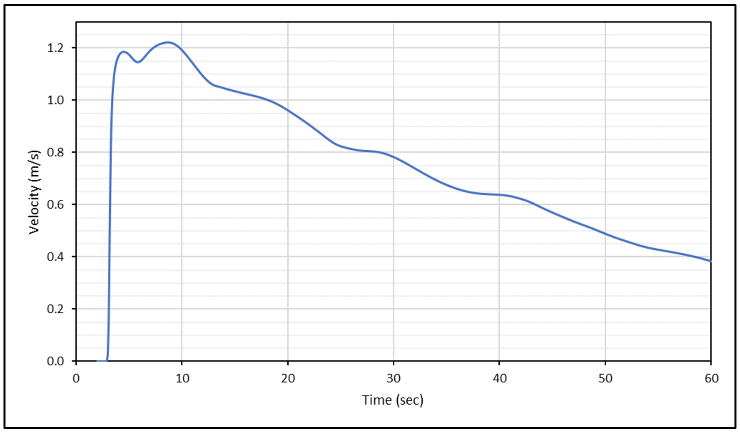

Figure 7-9 Test Point G3 – Velocity versus Time from SRH-2D

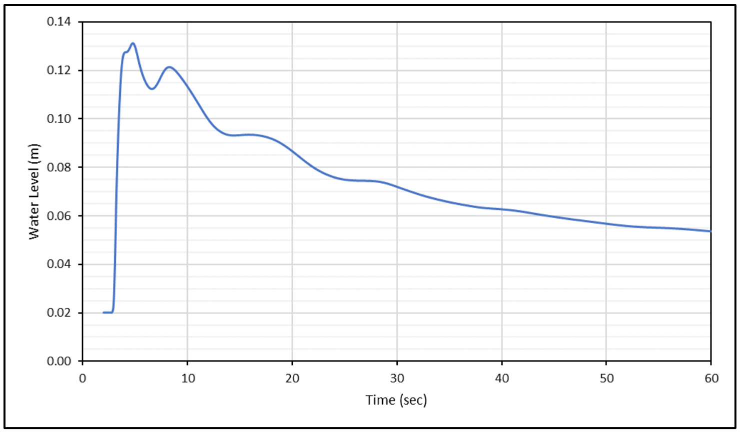

Figure 7-10 Test Point G4 – Water Level versus Time from SRH-2D

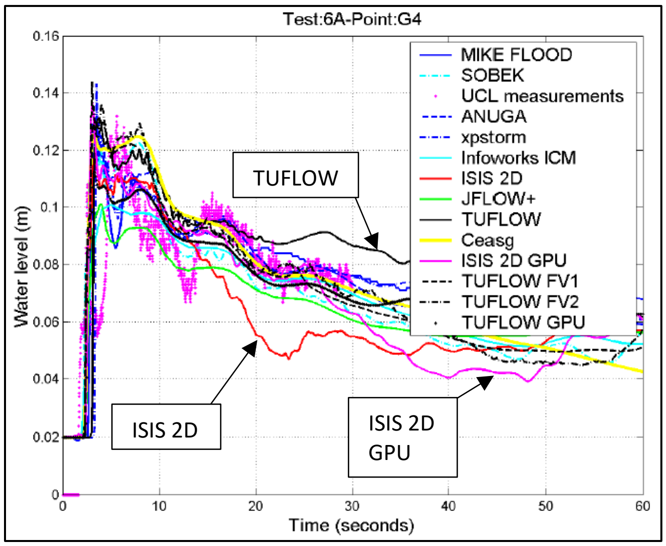

Figure 7-11 Test Point G4 – Water Level versus Time from Report SC120002 (2013)

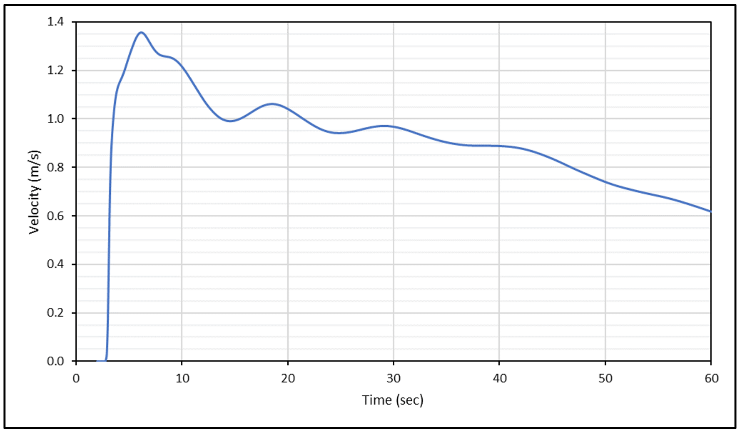

Figure 7-12 Test Point G4 – Velocity versus Time from SRH-2D

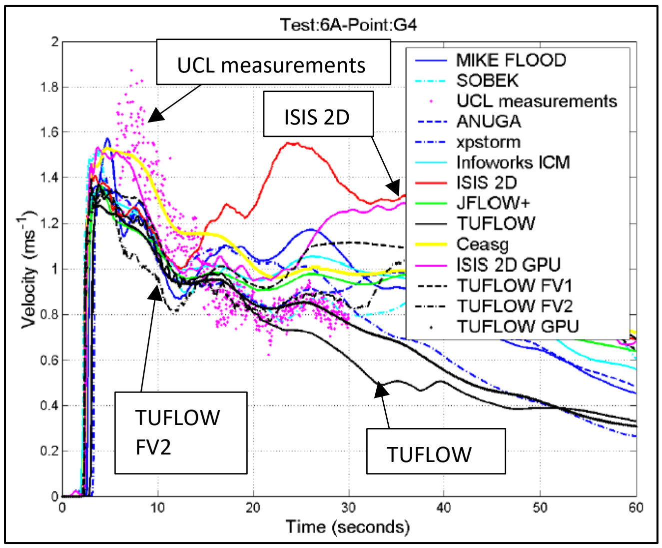

Figure 7-13 Test Point G4 – Velocity versus Time from Report SC120002 (2013)

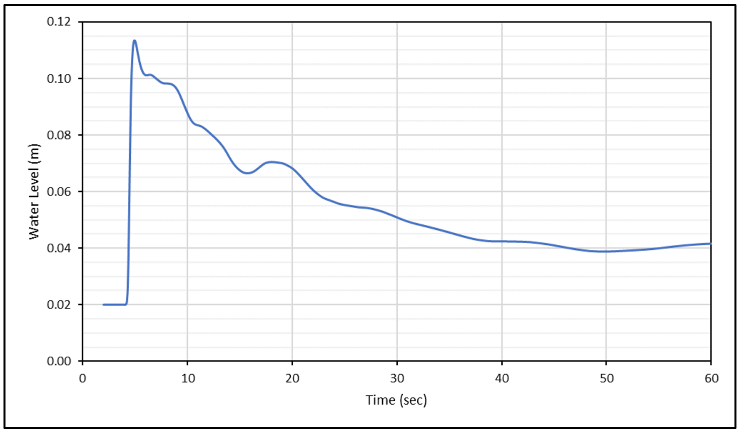

Figure 7-14 Test Point G5 – Water Level versus Time from SRH-2D

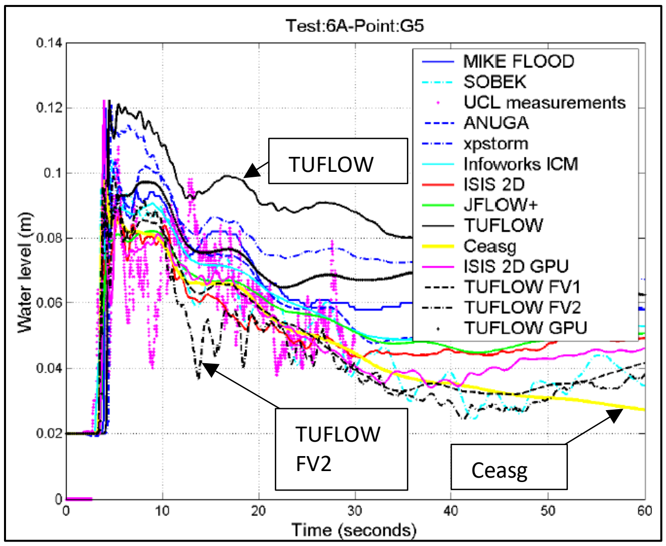

Figure 7-15 Test Point G5 – Water Level versus Time from Report SC120002 (2013)

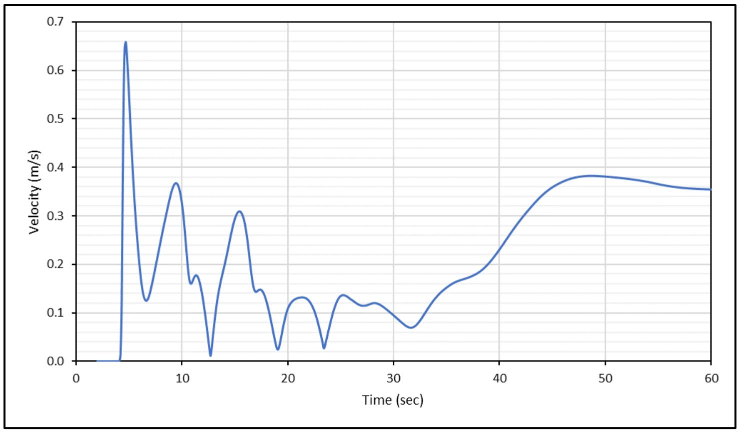

Figure 7-16 Test Point G5 – Velocity versus Time from SRH-2D

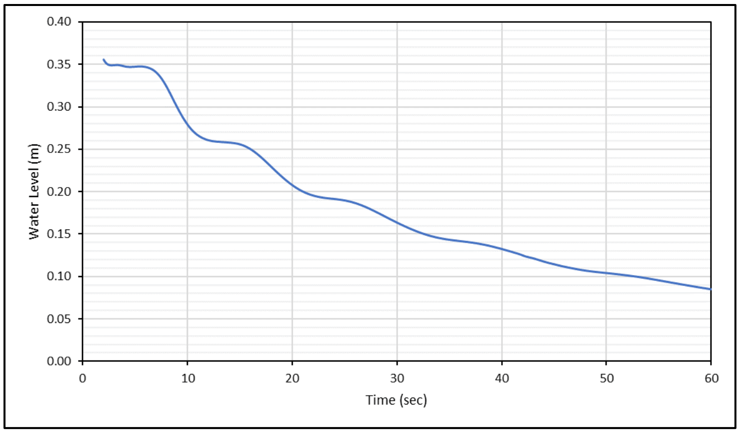

Figure 7-17 Test Point G6 – Water Level versus Time from SRH-2D

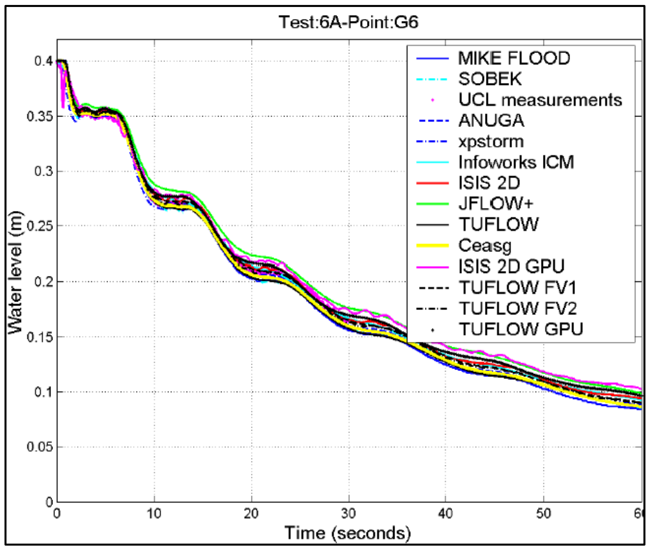

Figure 7-18 Test Point G6 – Water Level versus Time from Report SC120002 (2013)

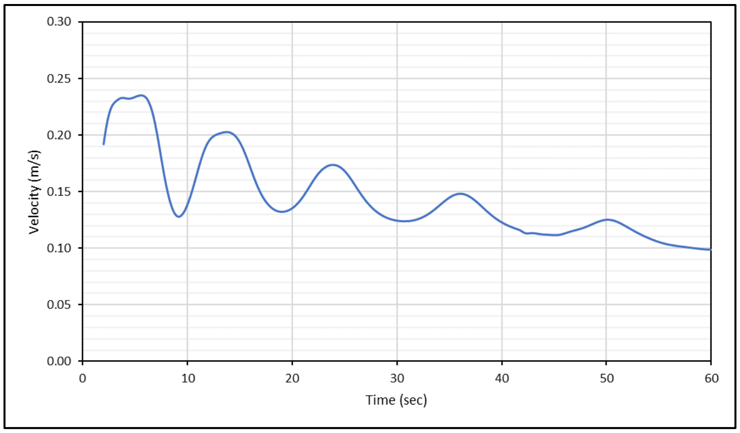

Figure 7-19 Test Point G6 – Velocity versus Time from SRH-2D

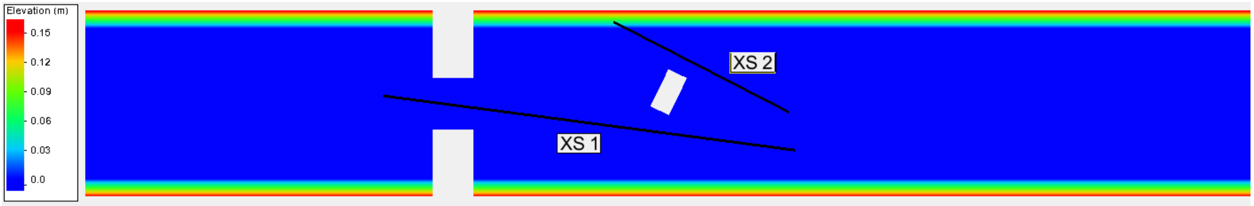

Figure 7-20 Test 6A Elevation Mesh Depicting XS 1 and XS 2

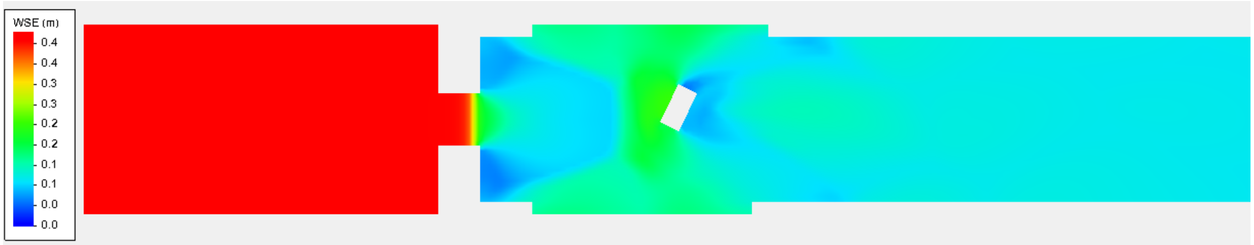

Figure 7-21 Test 6A Maximum Water Surface Elevation (meters)

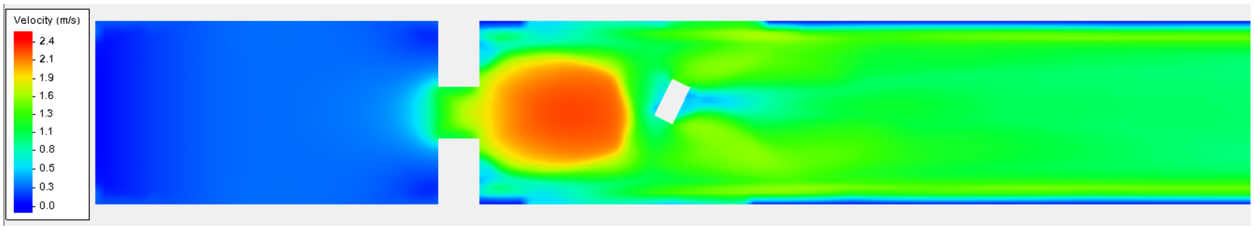

Figure 7-22 Test 6A Maximum Velocity Magnitude (meters per second)

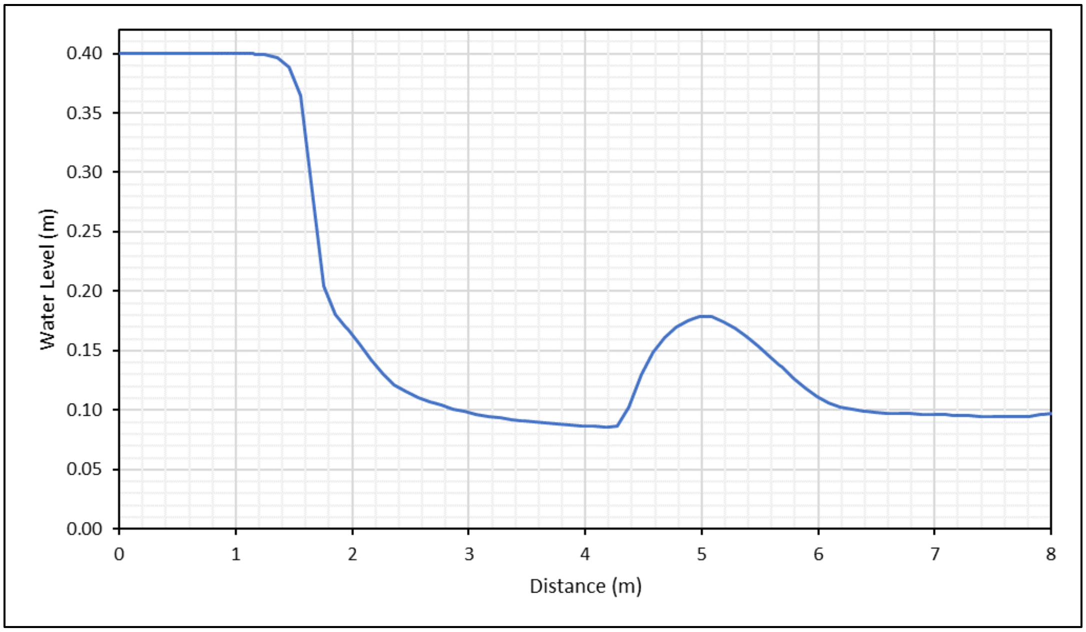

Figure 7-23 Test 6A Maximum Water Surface Elevation Along XS 1

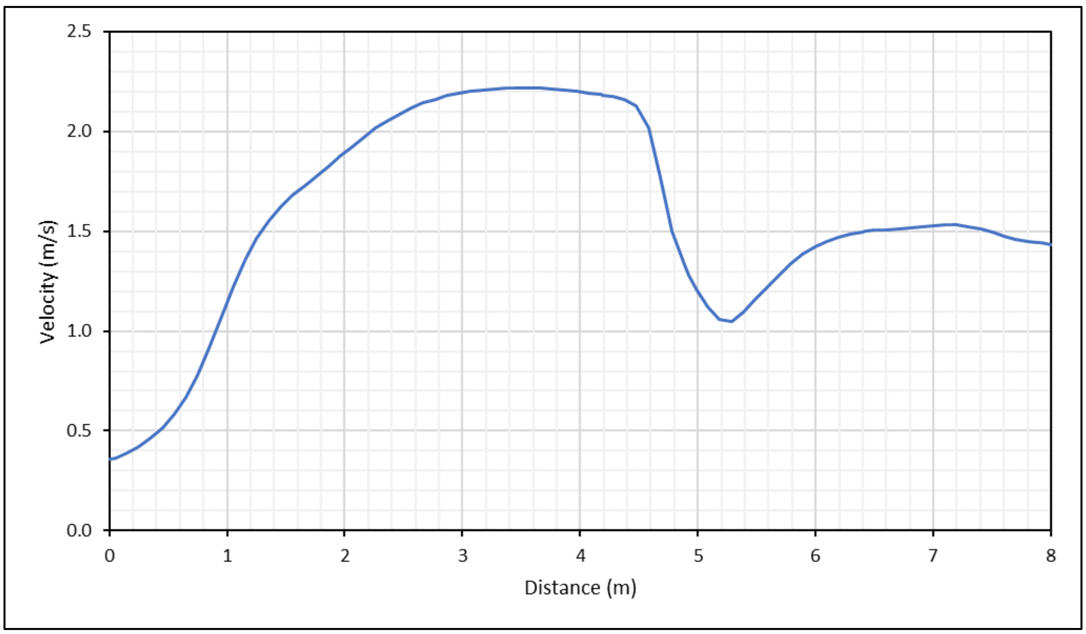

Figure 7-24 Test 6A Maximum Velocity Magnitude Along XS 1

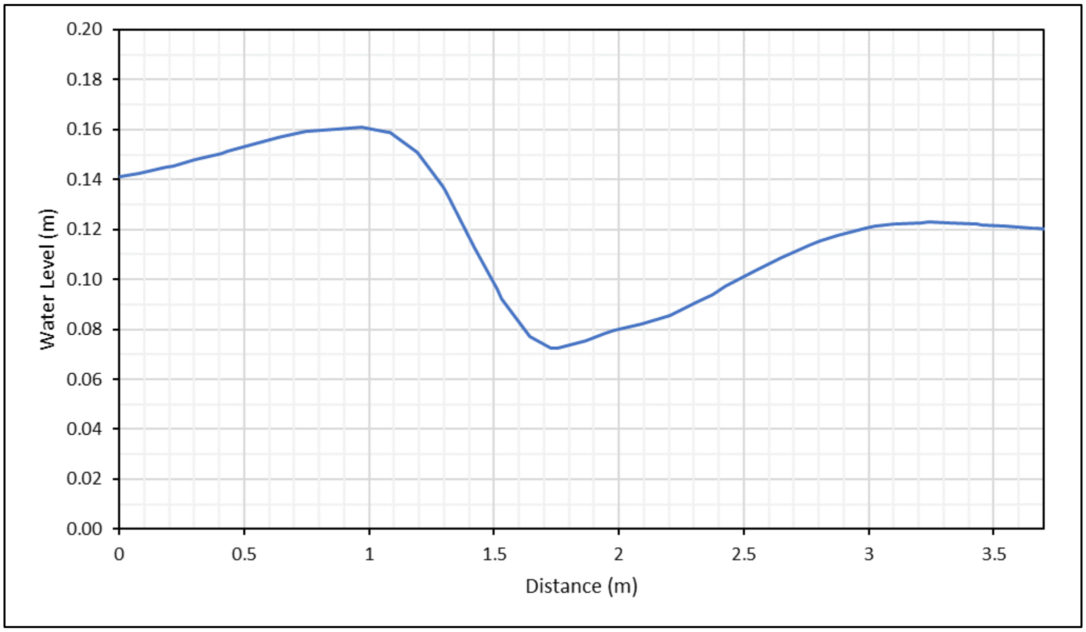

Figure 7-25 Test 6A Maximum Water Surface Elevation Along XS 2

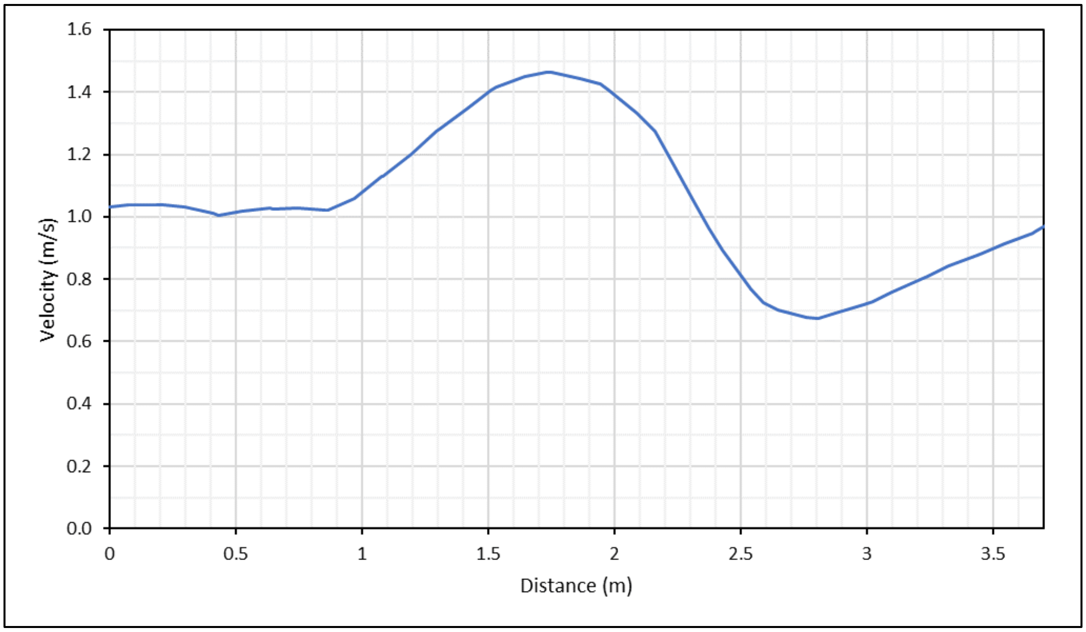

Figure 7-26 Test 6A Maximum Velocity Magnitude Along XS 2

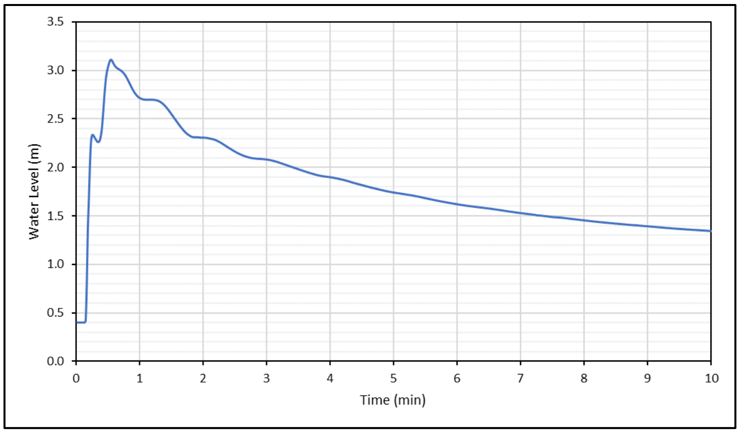

Figure 7-27 Test Point G1 – Water Level versus Time from SRH-2D

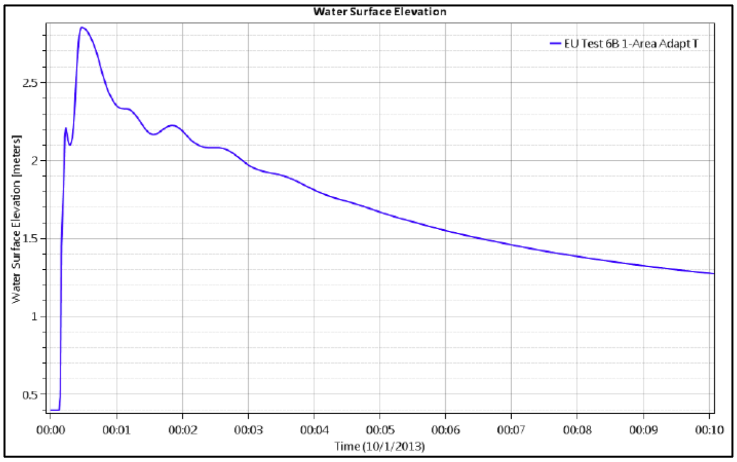

Figure 7-28 Test Point G1 – Water Level versus Time from RD-51 (2018)

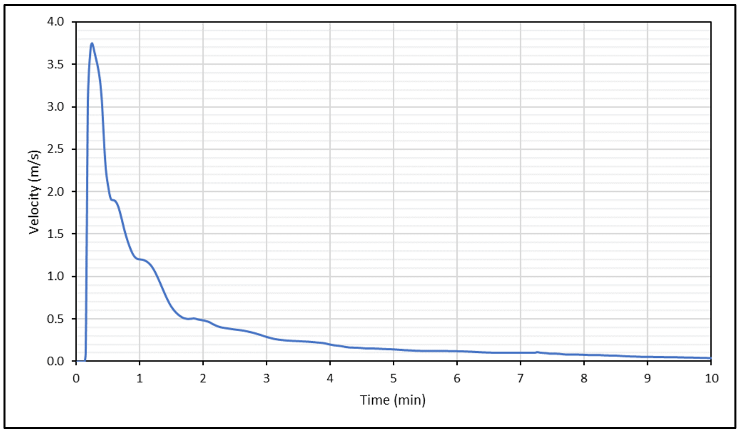

Figure 7-29 Test Point G1 – Velocity versus Time from SRH-2D

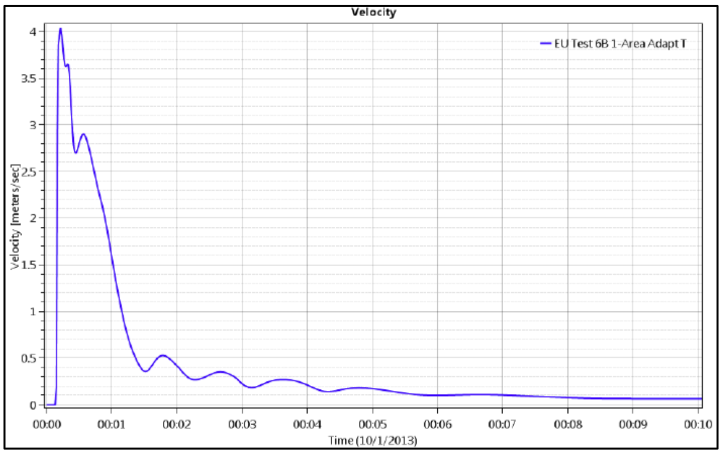

Figure 7-30 Test Point G1 – Velocity versus Time from RD-51 (2018)

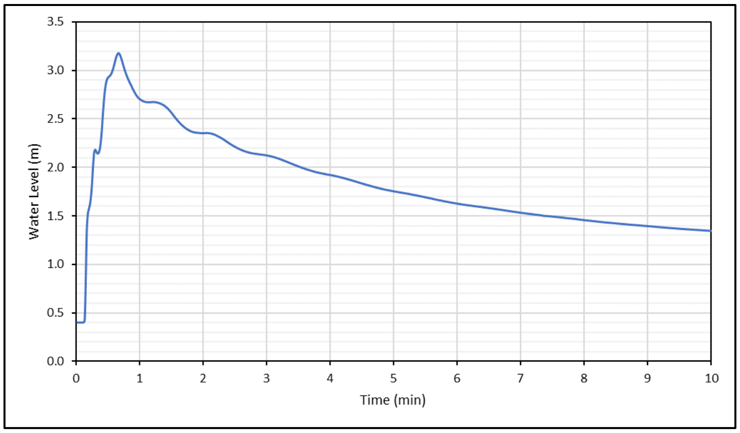

Figure 7-31 Test Point G2 – Water Level versus Time from SRH-2D

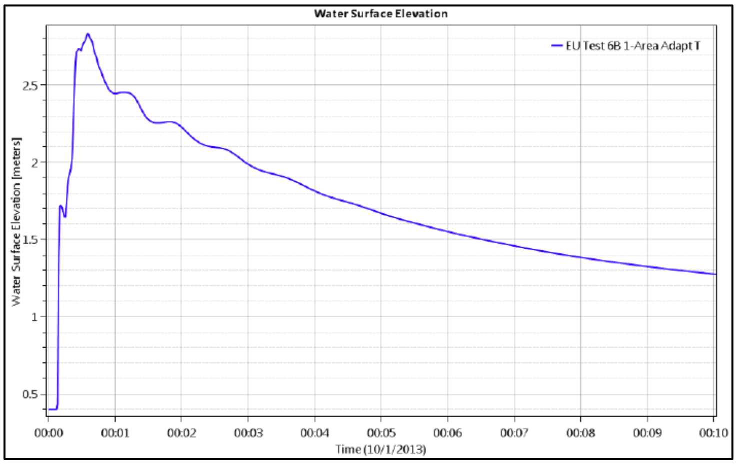

Figure 7-32 Test Point G2 – Water Level versus Time from RD-51 (2018)

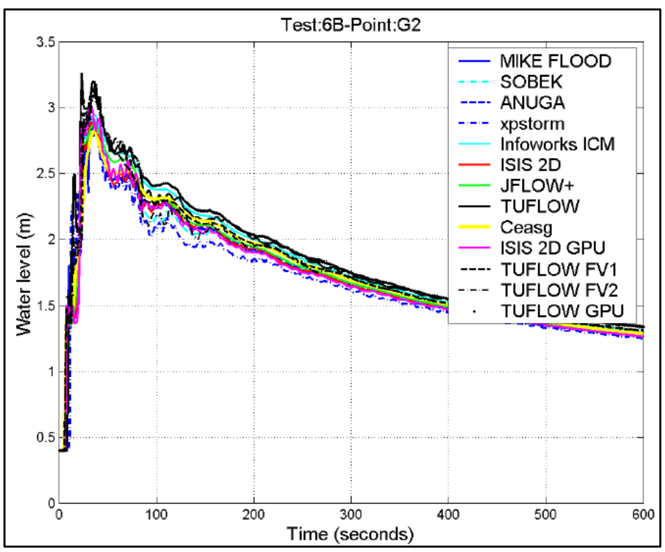

Figure 7-33 Test Point G2 – Water Level versus Time from Report SC120002 (2013)

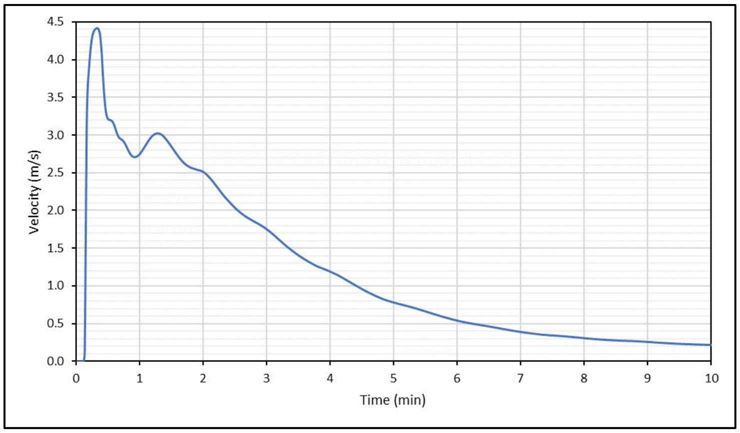

Figure 7-34 Test Point G2 – Velocity versus Time from SRH-2D

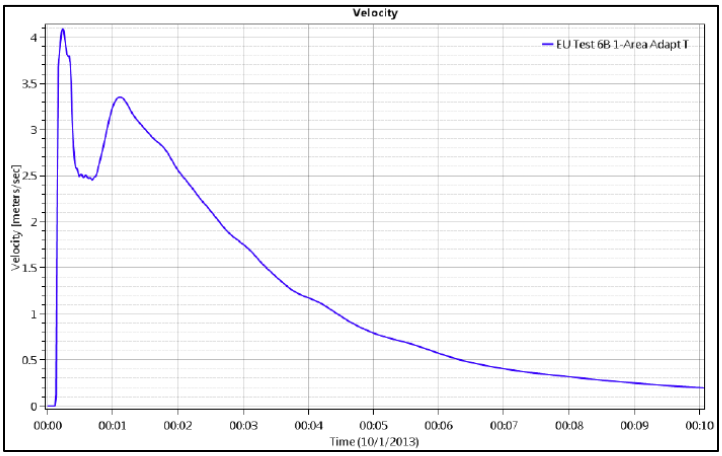

Figure 7-35 Test Point G2 – Velocity versus Time from RD-51 (2018)

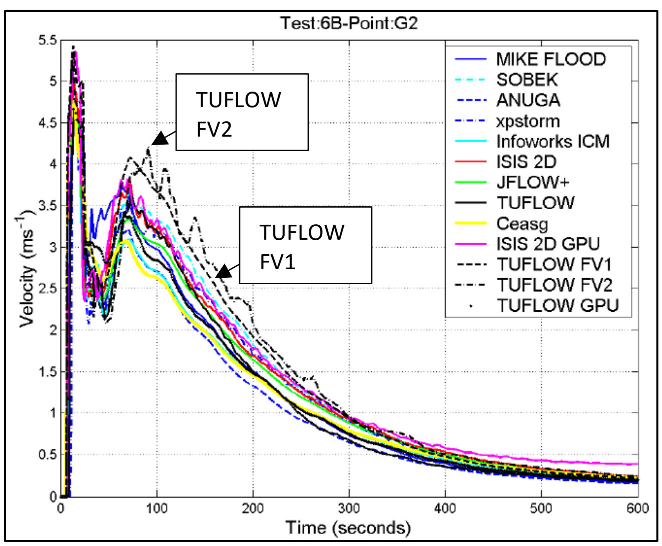

Figure 7-36 Test Point G2 – Velocity versus Time from Report SC120002 (2013)

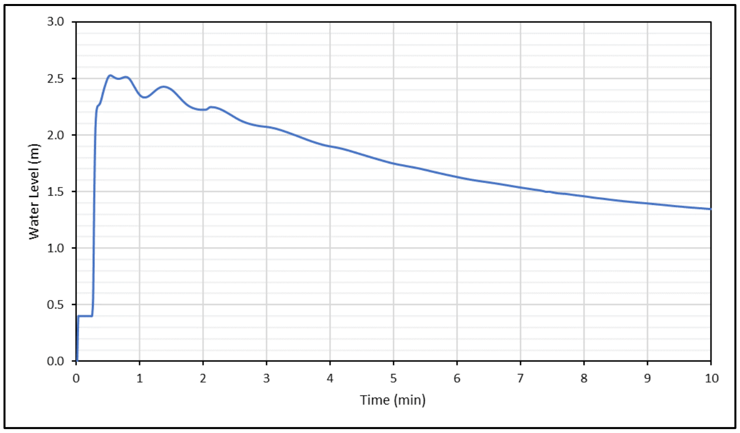

Figure 7-37 Test Point G3 – Water Level versus Time from SRH-2D

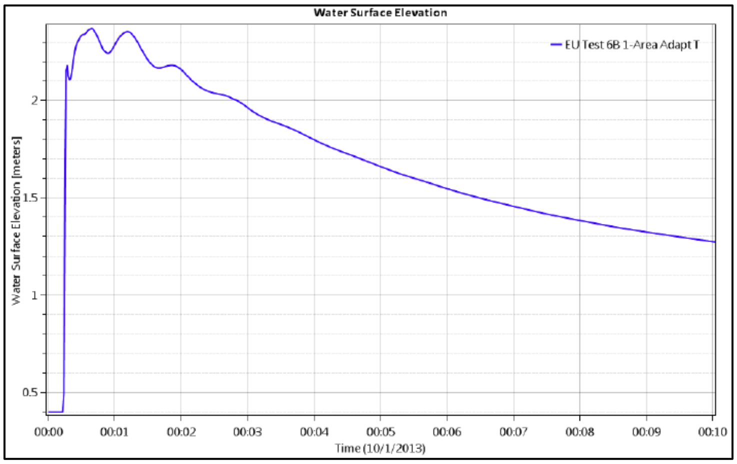

Figure 7-38 Test Point G3 – Water Level versus Time from RD-51 (2018)

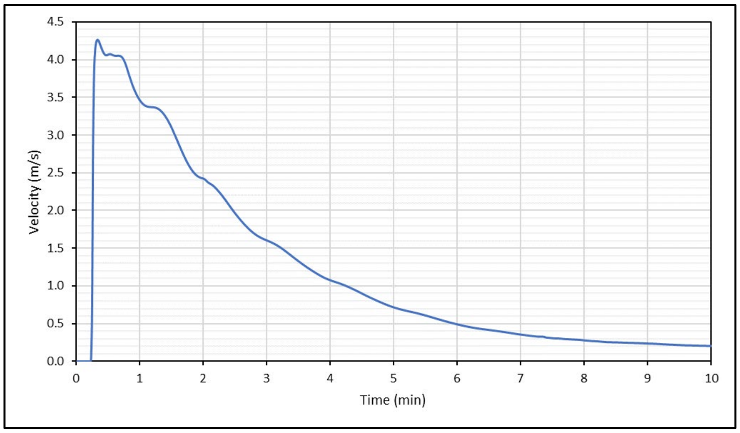

Figure 7-39 Test Point G3 – Velocity versus Time from SRH-2D

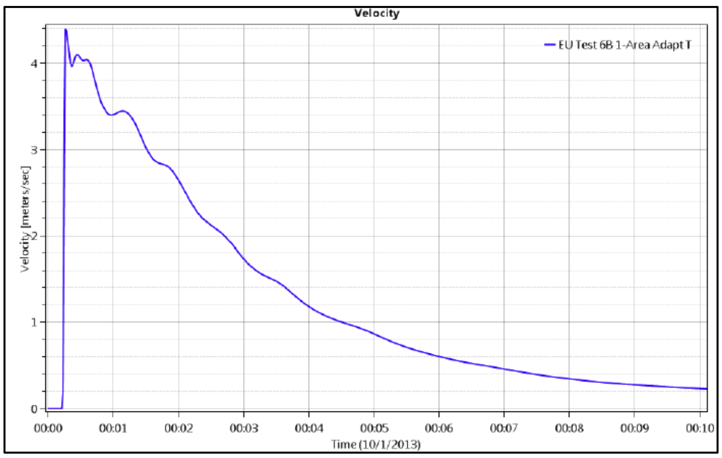

Figure 7-40 Test Point G3 – Velocity versus Time from RD-51 (2018)

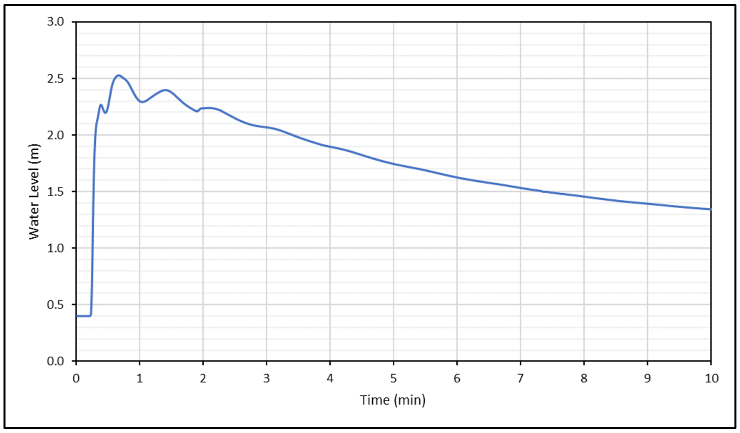

Figure 7-41 Test Point G4 – Water Level versus Time from SRH-2D

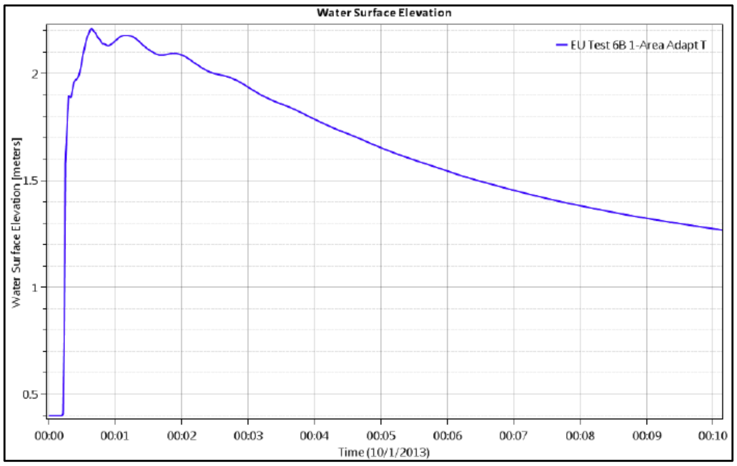

Figure 7-42 Test Point G4 – Water Level versus Time from RD-51 (2018)

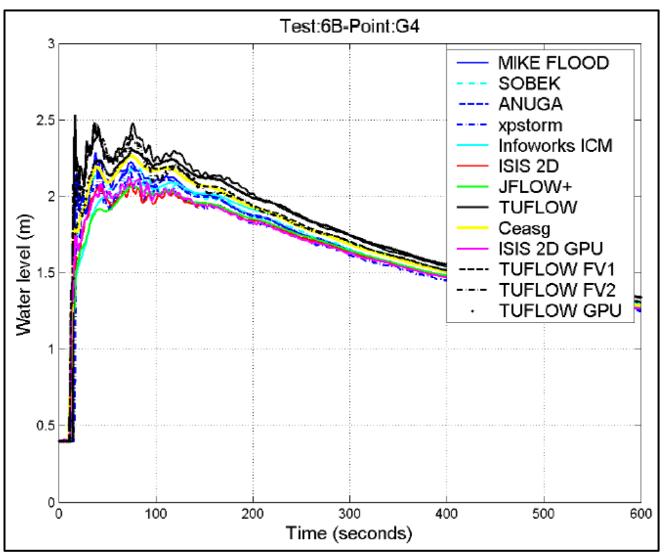

Figure 7-43 Test Point G4 – Water Level versus Time from Report SC120002 (2013)

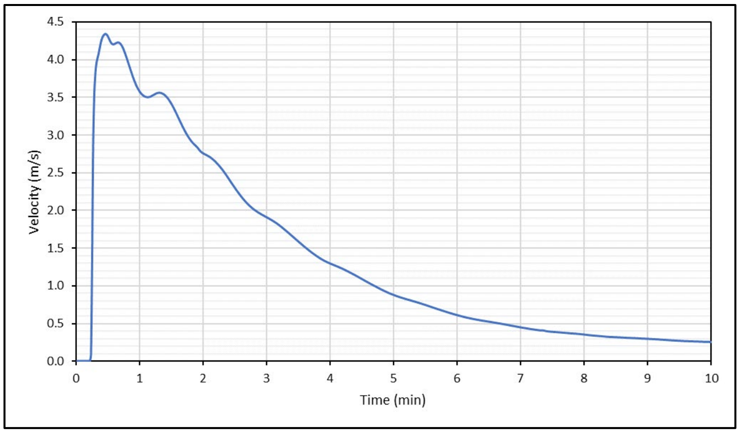

Figure 7-44 Test Point G4 – Velocity versus Time from SRH-2D

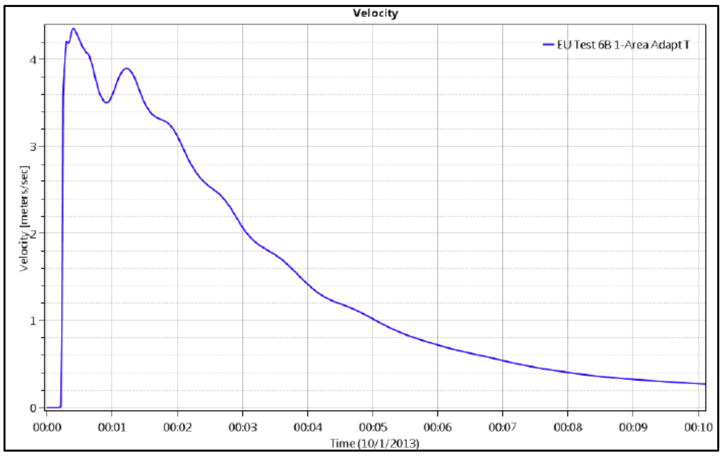

Figure 7-45 Test Point G4 – Velocity versus Time from RD-51 (2018)

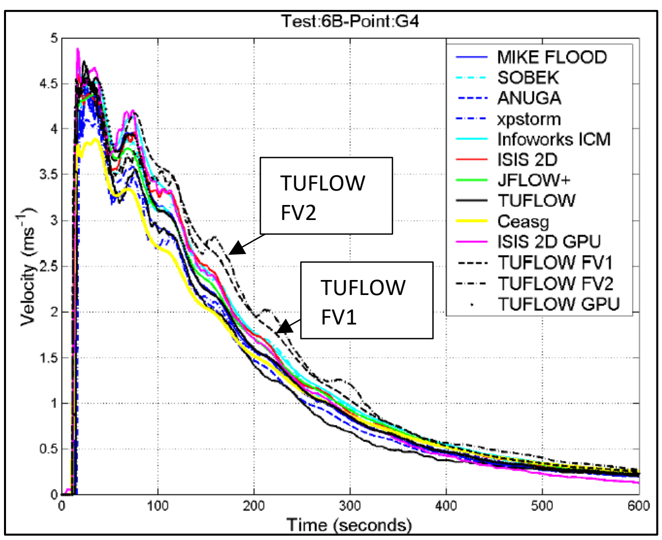

Figure 7-46 Test Point G4 – Velocity versus Time from Report SC120002 (2013)

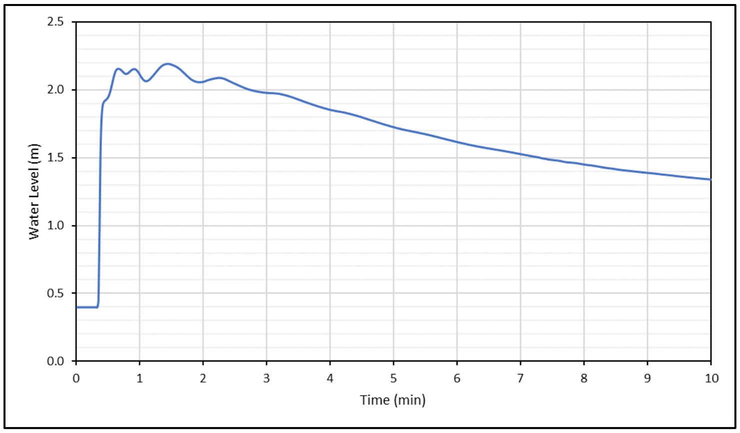

Figure 7-47 Test Point G5 – Water Level versus Time from SRH-2D

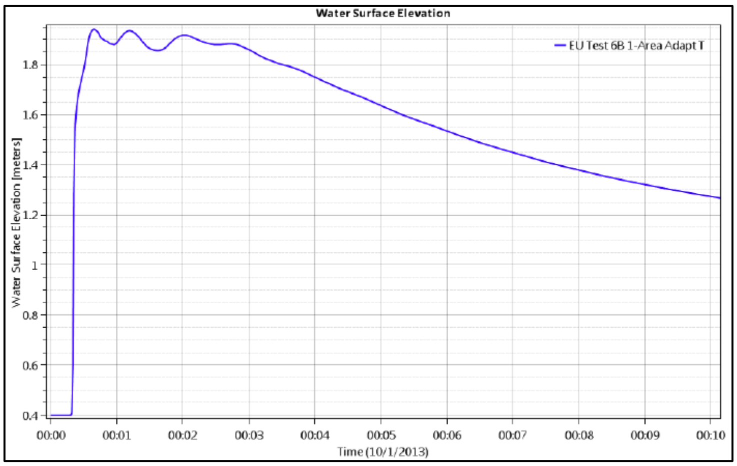

Figure 7-48 Test Point G5 – Water Level versus Time from RD-51 (2018)

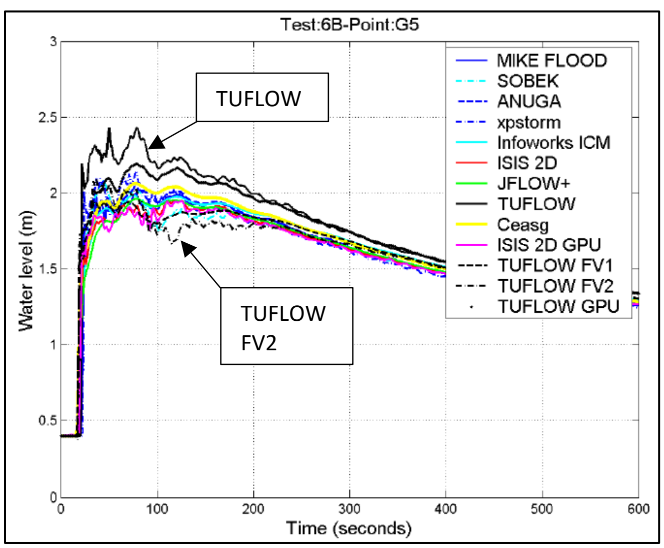

Figure 7-49 Test Point G5 – Water Level versus Time from Report SC120002 (2013)

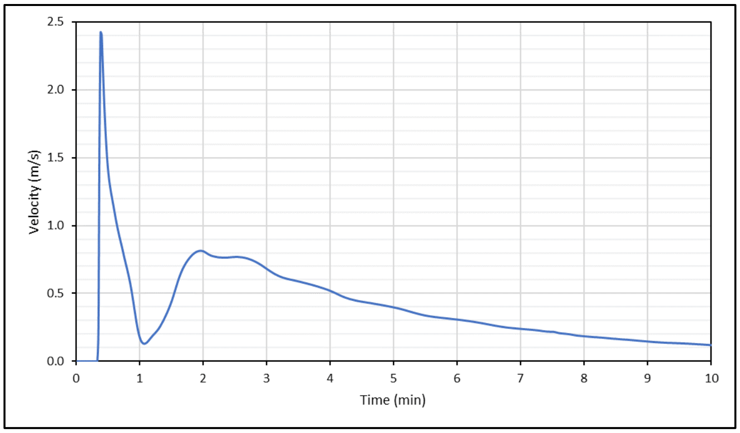

Figure 7-50 Test Point G5 – Velocity versus Time from SRH-2D

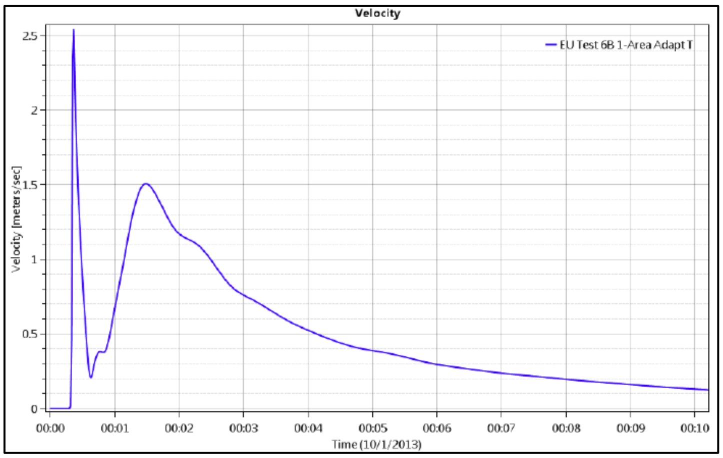

Figure 7-51 Test Point G5 – Velocity versus Time from RD-51 (2018)

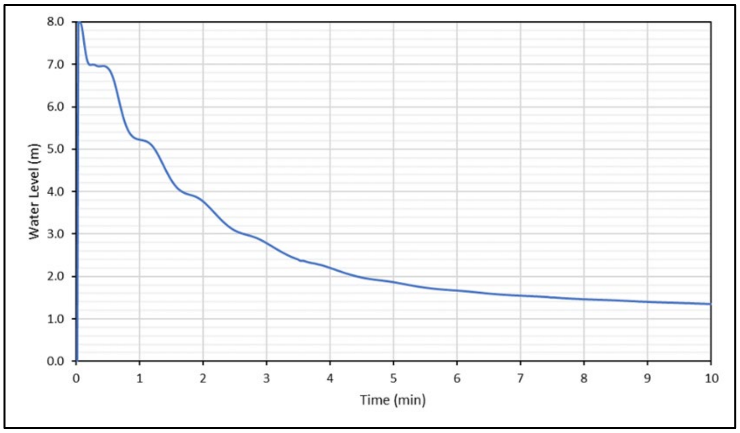

Figure 7-52 Test Point G6 – Water Level versus Time from SRH-2D

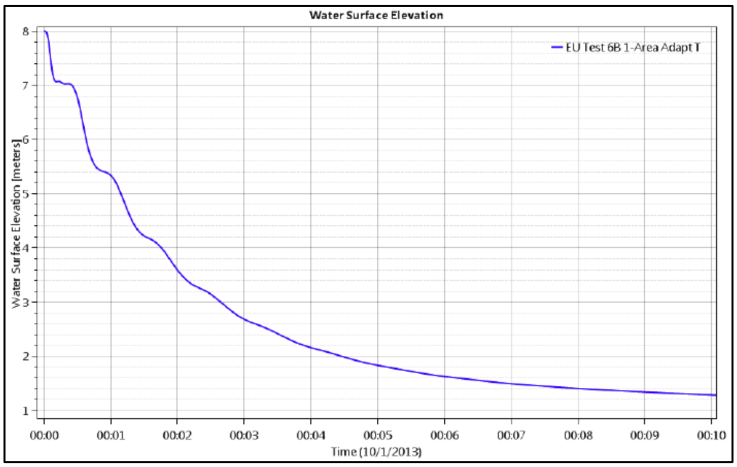

Figure 7-53 Test Point G6 – Water Level versus Time from RD-51 (2018)

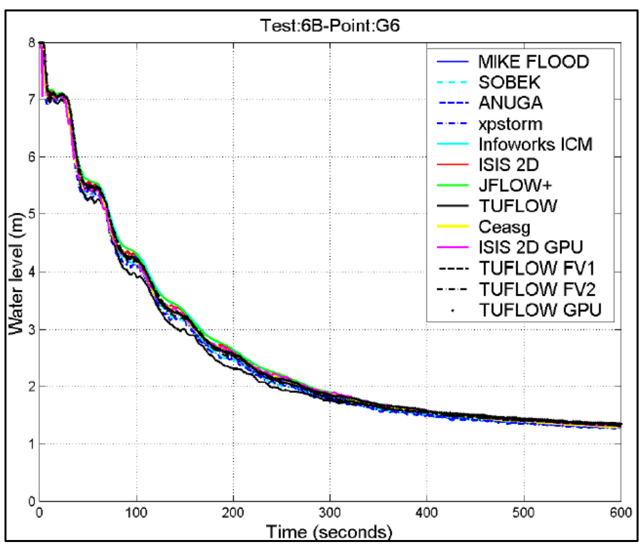

Figure 7-54 Test Point G6 – Water Level versus Time from Report SC120002 (2013)

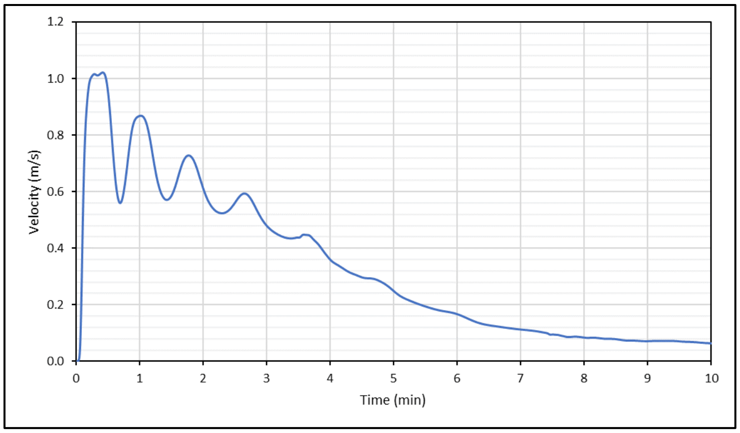

Figure 7-55 Test Point G6 – Velocity versus Time from SRH-2D

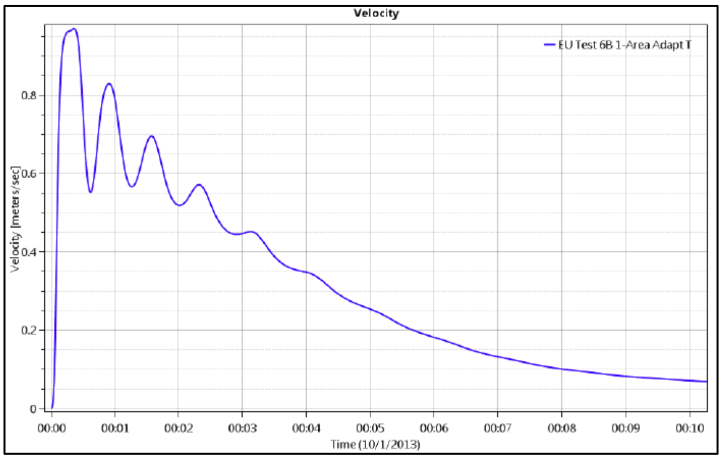

Figure 7-56 Test Point G6 – Velocity versus Time from RD-51 (2018)

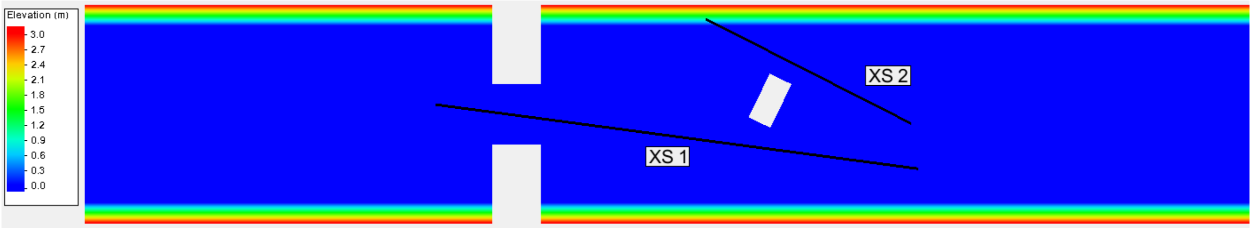

Figure 7-57 Test 6B Elevation Mesh Depicting XS 1 and XS 2

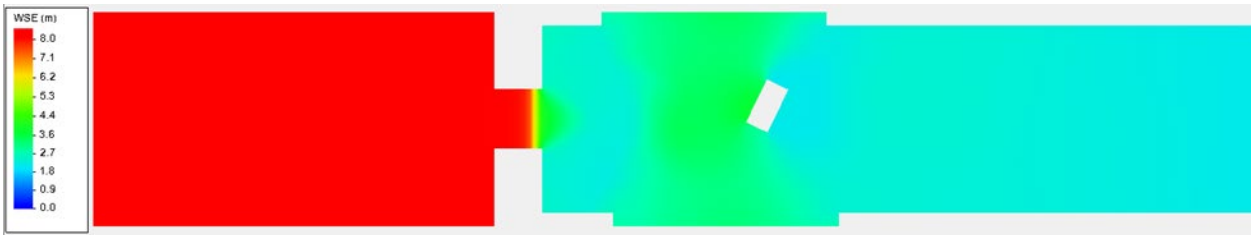

Figure 7-58 Test 6B Maximum Water Surface Elevation (meters) from SRH-2D

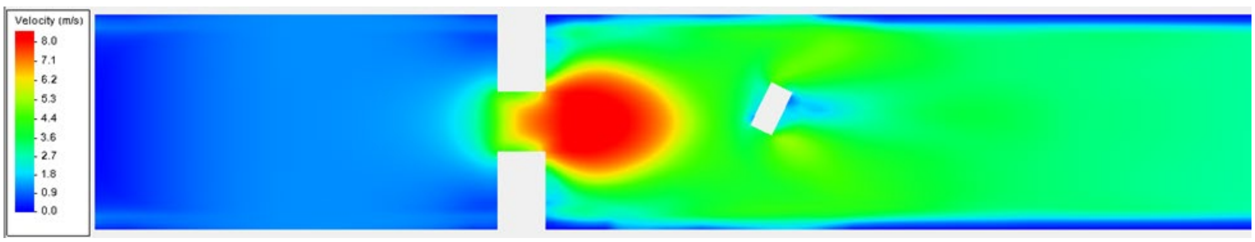

Figure 7-59 Test 6B Maximum Velocity Magnitude (meters per second) from SRH-2D

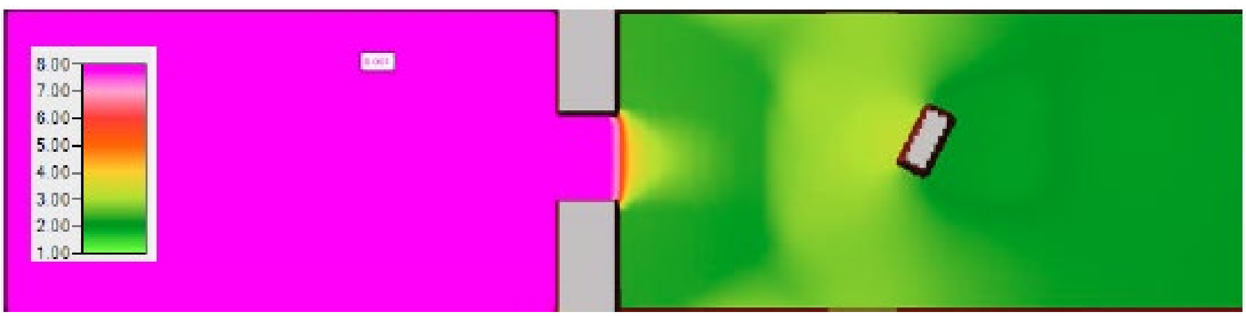

Figure 7-60 Test 6B Maximum Water Surface Elevation (meters) from RD-51 (2018)

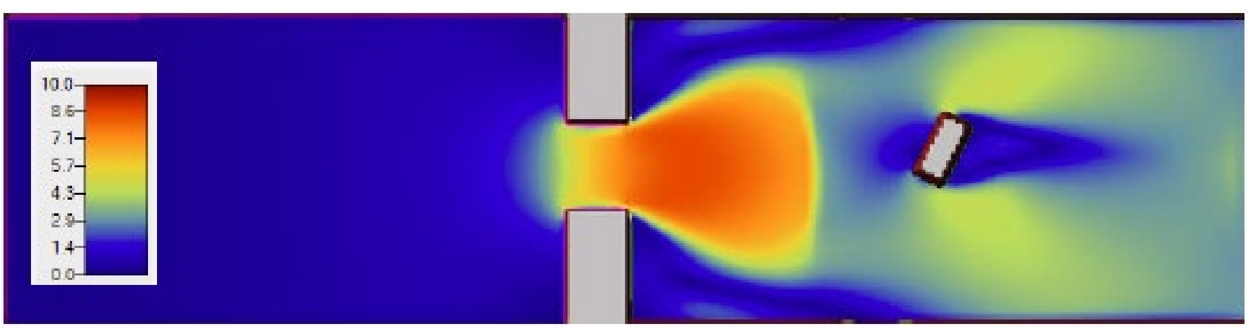

Figure 7-61 Test 6B Maximum Velocity Magnitude (meters per second) from RD-51 (2018)

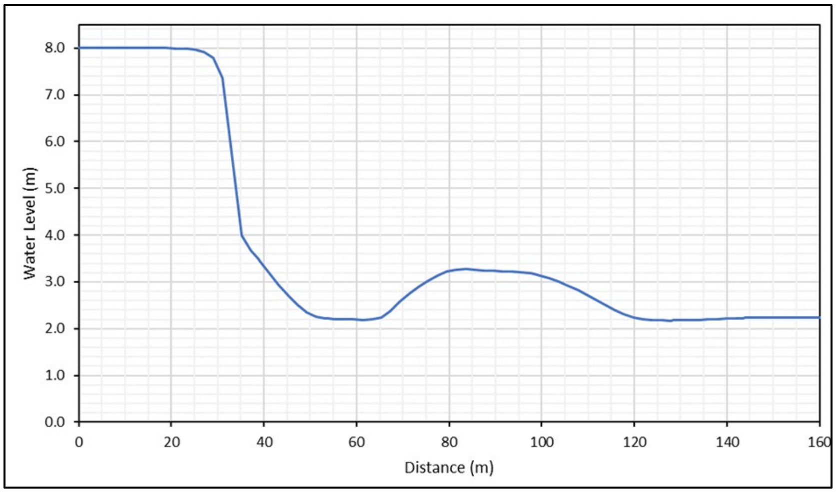

Figure 7-62 Test 6B Maximum Water Surface Elevation Along XS 1 from SRH-2D

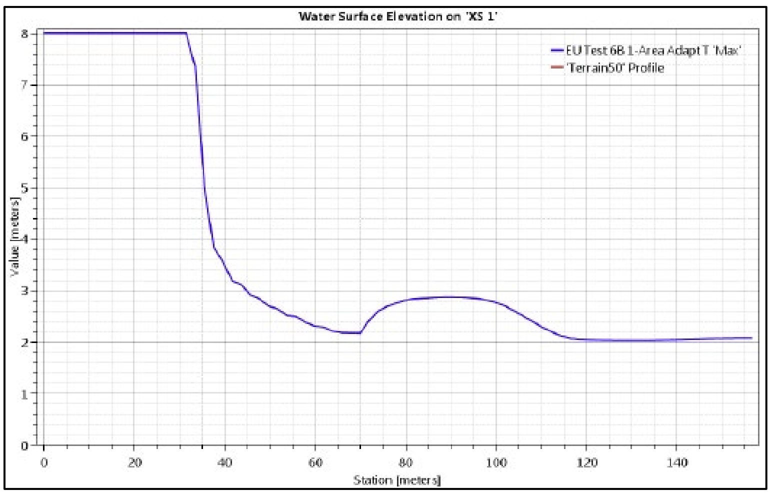

Figure 7-63 Test 6B Maximum Water Surface Elevation Along XS 1 from RD-51 (2018)

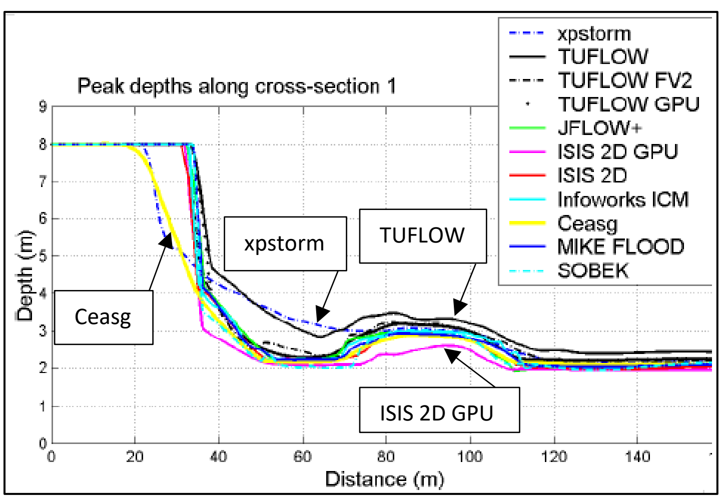

Figure 7-64 Test 6B Maximum Water Surface Elevation Along XS 1 from Report SC120002 (2013)

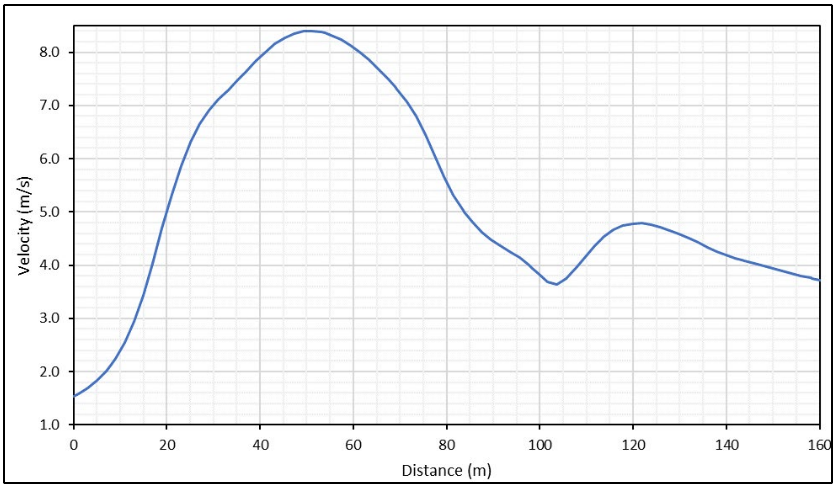

Figure 7-65 Test 6B Maximum Velocity Magnitude Along XS 1 from SRH-2D

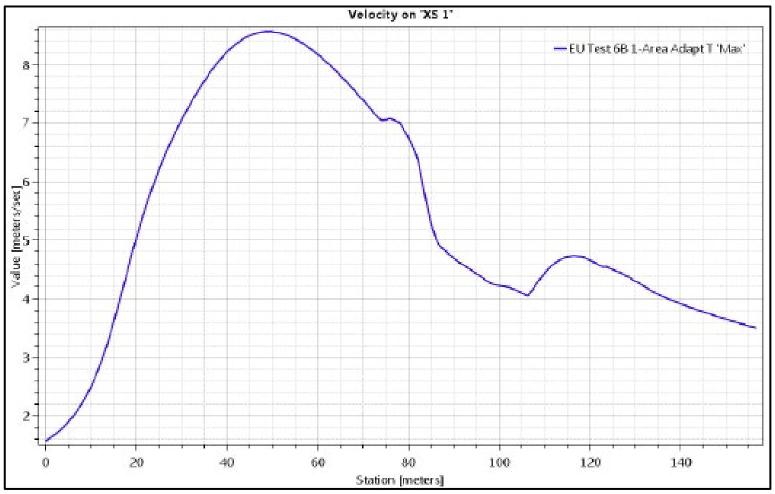

Figure 7-66 Test 6B Maximum Velocity Magnitude Along XS 1 from RD-51 (2018)

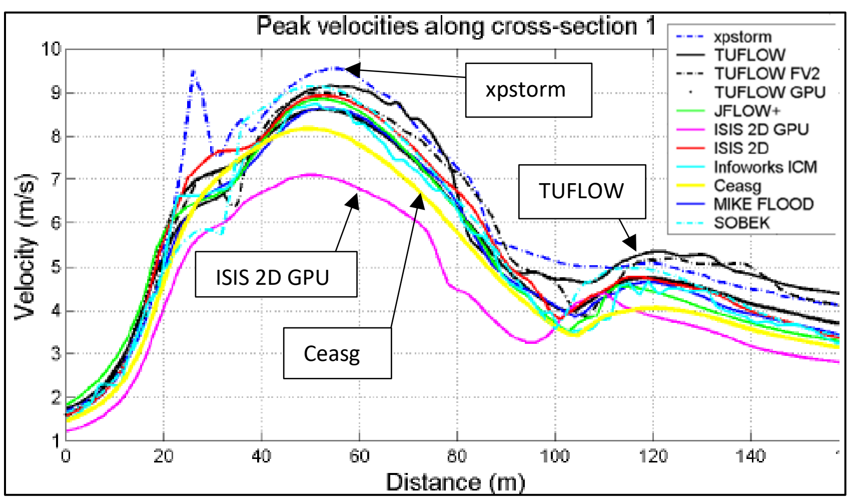

Figure 7-67 Test 6B Maximum Velocity Magnitude Along XS 1 from Report SC120002 (2013)

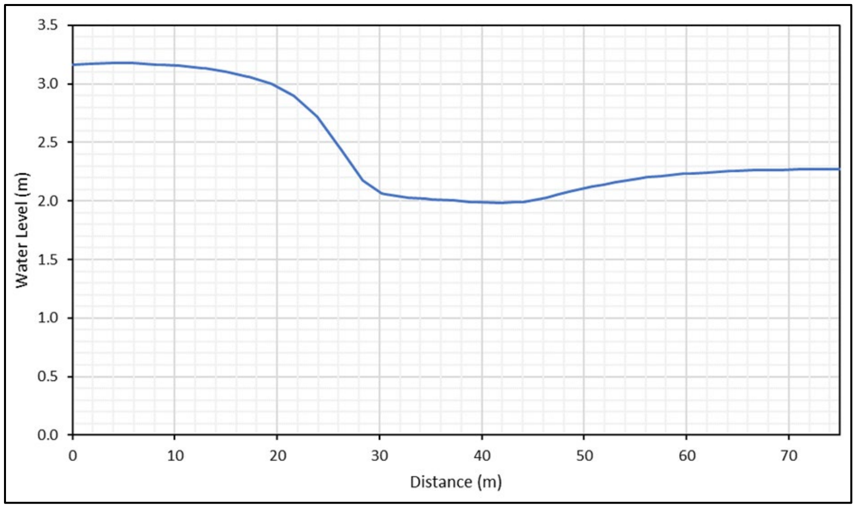

Figure 7-68 Test 6B Maximum Water Surface Elevation Along XS 2 from SRH-2D

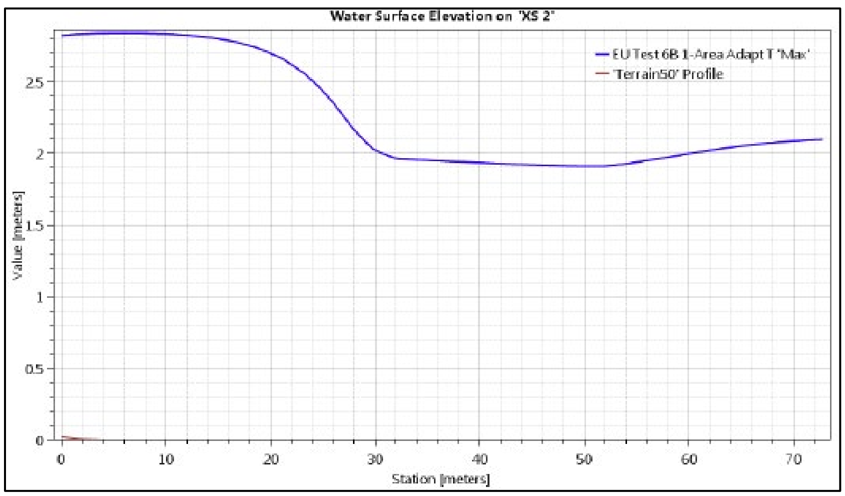

Figure 7-69 Test 6B Maximum Water Surface Elevation Along XS 2 from RD-51 (2018)

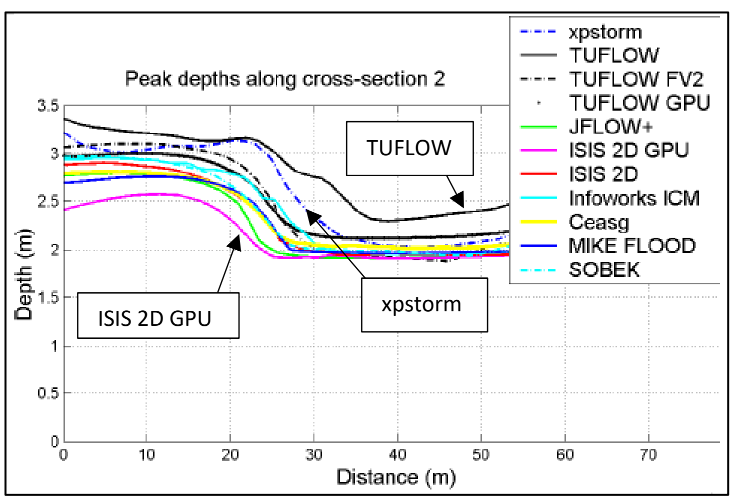

Figure 7-70 Test 6B Maximum Water Surface Elevation Along XS 2 from Report SC120002 (2013)

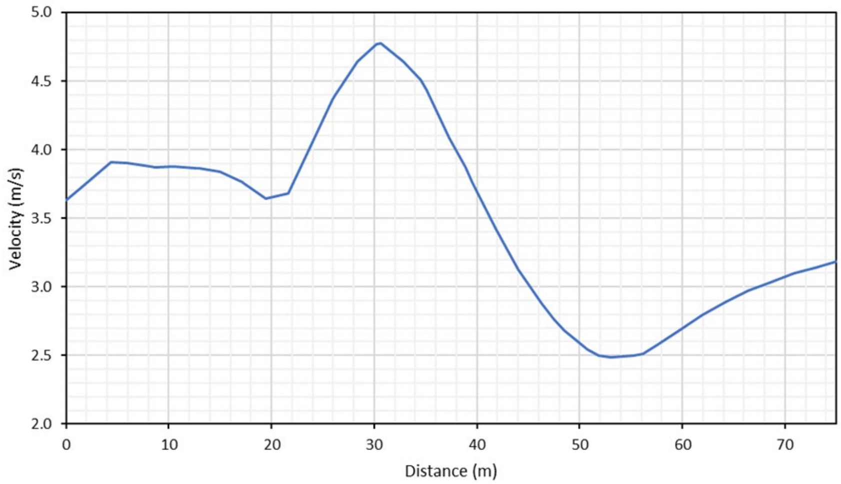

Figure 7-71 Test 6B Maximum Velocity Magnitude Along XS 2 from SRH-2D

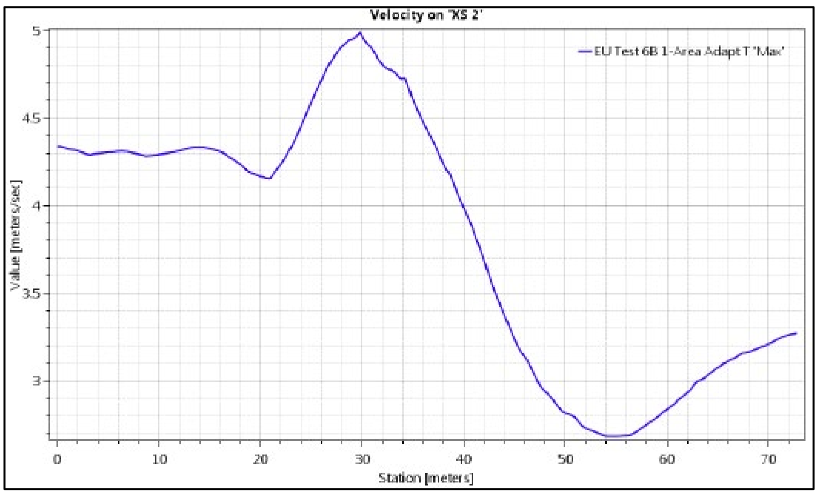

Figure 7-72 Test 6B Maximum Velocity Magnitude Along XS 2 from RD-51 (2018)

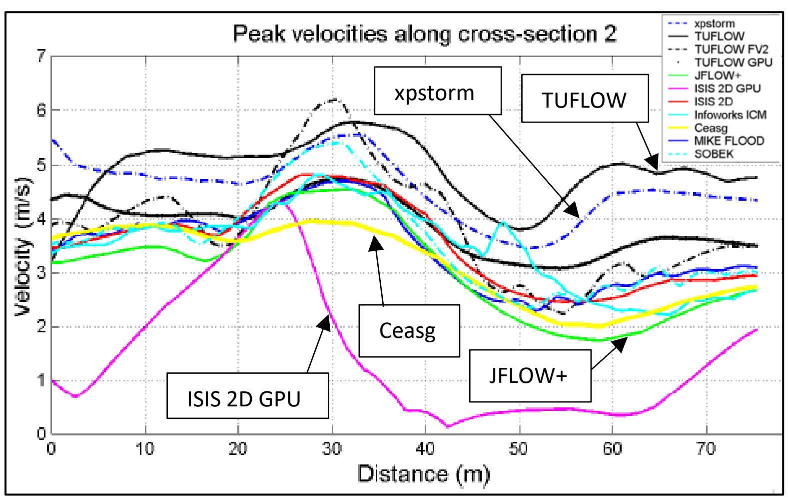

Figure 7-73 Test 6B Maximum Velocity Magnitude Along XS 2 from Report SC120002 (2013)