3Di passing 2D hydraulic modelling UK benchmark tests

3Di waterbeheer

Nelen & Schuurmans

8-1-2018

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Based on SC120002 ‘Benchmarking the latest generation 2D hydraulic modelling packages' from the Environment Agency

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1 Introduction

The Environment Agency executed a benchmark test in 2013 in order to assess the latest tools for 2D hydraulic modelling (Néelz & Pender, 2013). Since then the new hydraulic modelling package 3Di has been developed. After passing the Dutch national benchmark test for inundation models as one of the most accurate (Henckens & Engel, 2017), the 3Di-team has recreated the benchmark test of the Environment Agency. In this memo the results of 3Di are compared to that of other modelling packages.

As shown in the following sections, 3Di performs very well against other industry standard packages that solve the full shallow water equations. There are some slight differences in some of the point velocity results. These differences can be explained by the use of the subgrid technique which does not simply average the digital elevation model within the calculation grid, but preserves more detail. Since flow velocity is very sensitive to localised variations in shallow water, the averaging method has a significant influence on the velocity results. Water level results are very good in all tests, which is the most important measure. This demonstrates that 3Di is a package suitable for all types of modelling in the benchmark tests. This is also in agreement with the conclusions from the Dutch national benchmark tests.

More on the background of the 3Di modelling package and the subgrid technique can be found in Appendix I.

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2 Benchmark tests

The numbering of the tests below corresponds to the tests executed in the benchmark of the Environmental Agency. For each test several graphs are overlaid by a plot of the 3Di results, indicated by the thick red lines. It is important to note that whenever a cell is considered 'dry' in a 3Di model, the water level is *Null*. This is the reason why the plotted time series don't always start at t=0. Furthermore, 3Di uses the subgrid technique which enables the model to incorporate detail from the Digital Elevation Model on a higher level than the calculation grid. More on the subgrid technique can be read in the appendix.

2.1 Test 1: Flooding a disconnect water body

This test describes the 2D domain as described in the figures below, with a time series water level boundary on X = 0, ranging from 9.7 to 10.35 m.

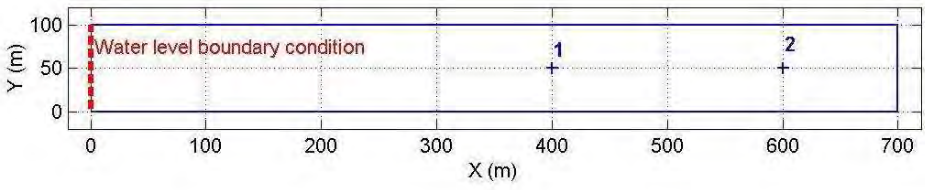

Figure 1 – Test1: Top view of the modelling domain (delineated by the blue border).

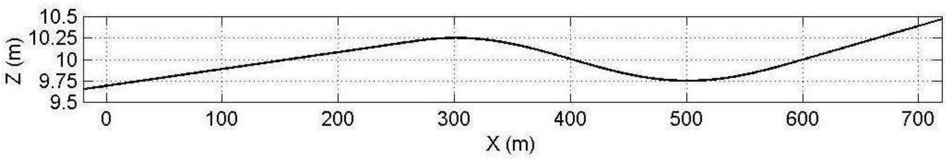

Figure 2 - Test 1: Side view of the modelling domain.

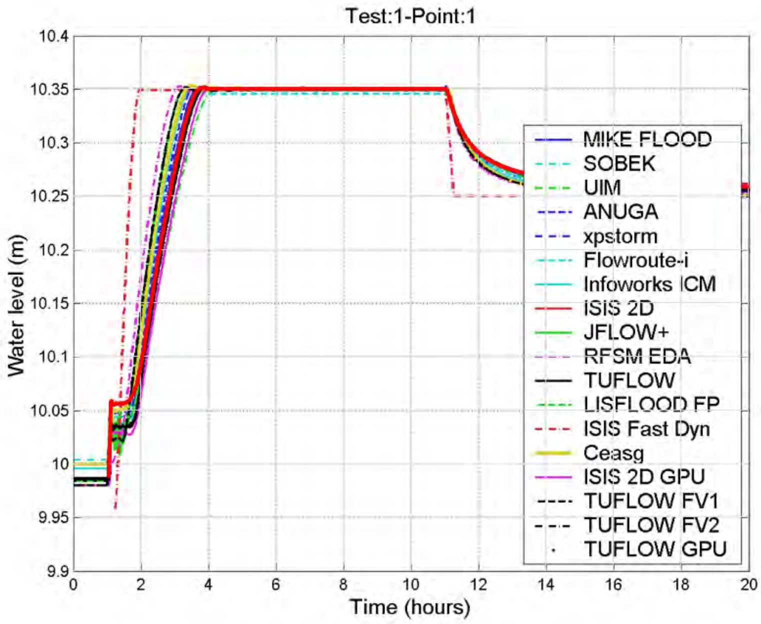

Figure 3 - Test 1: Water level in point 1. The thick red line indicates the 3Di result.

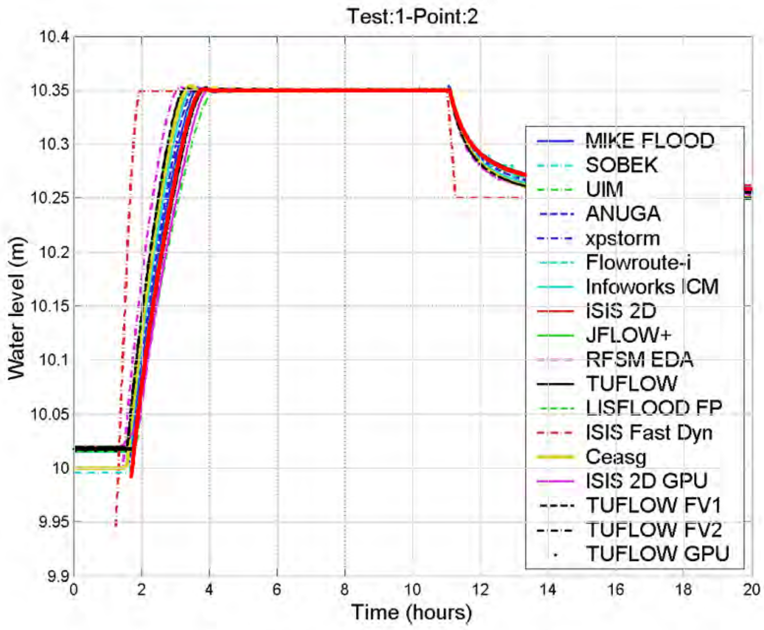

Figure 4 - Test 1: Water level in point 2. The thick red line indicates the 3Di result.

2.2 Test 2: Filling of floodplain depressions

A square modelling domain, tilted in both x and y direction, contains 16 depressions. At the highest point an inflow discharge time series is applied on the boundary of the model.

The aim of this model is to test the predictive capabilities for low momentum flows.

The water level in each depressions is compared with other modelling packages, as well as the final inundation extend.

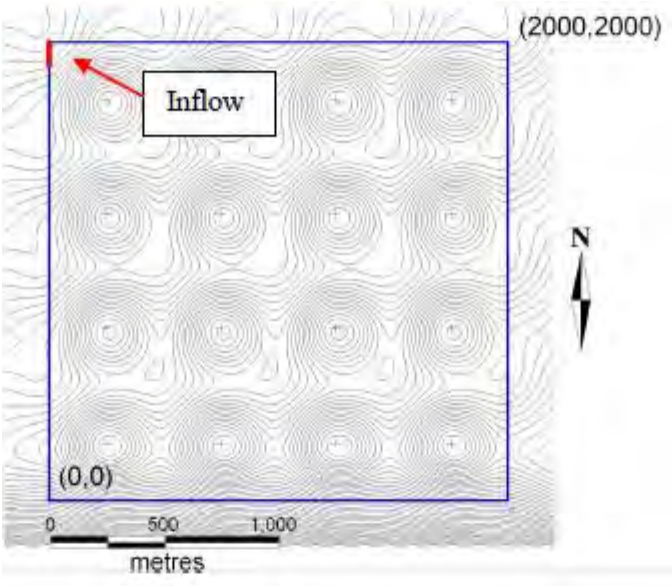

Figure 5 - Test 2: Modelling domain with elevation contour lines

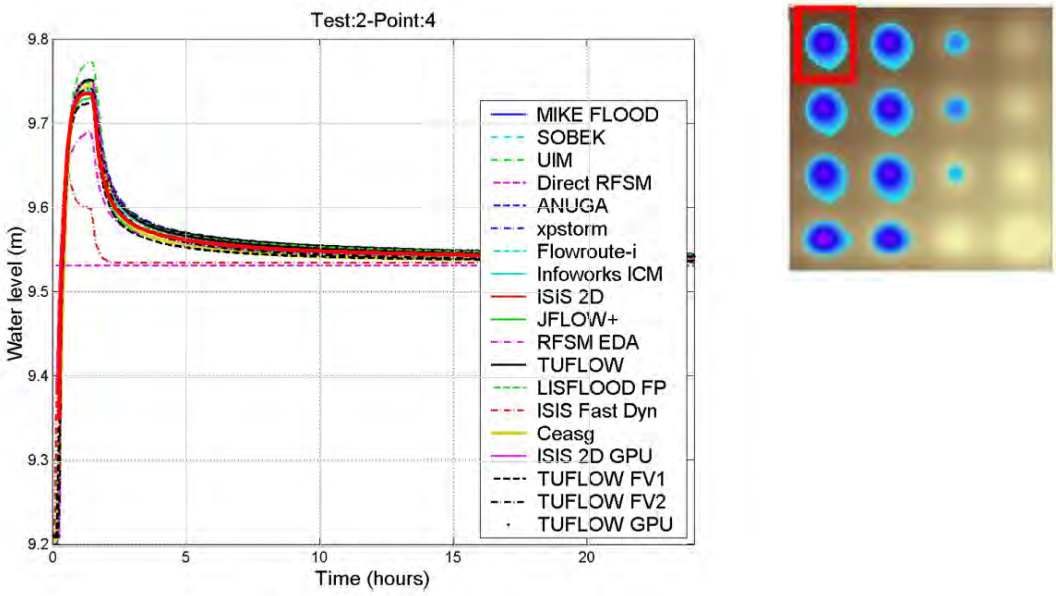

Figure 6 – Test 2: Water level in point 4. The thick red line indicates the 3Di result.

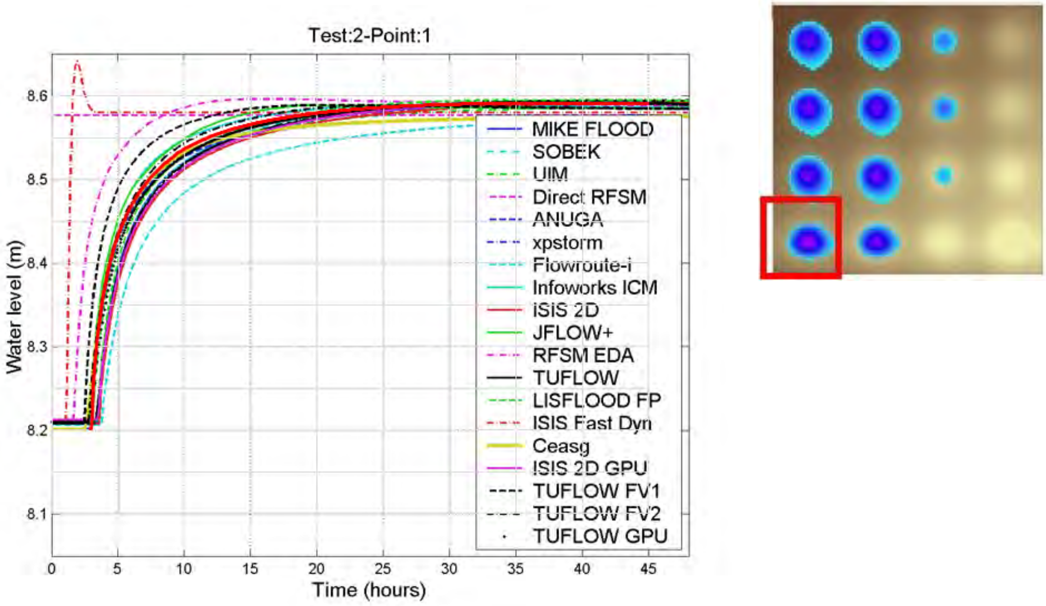

Figure 7 - Test 2: Water level in point 1. The thick red line indicates the 3Di result.

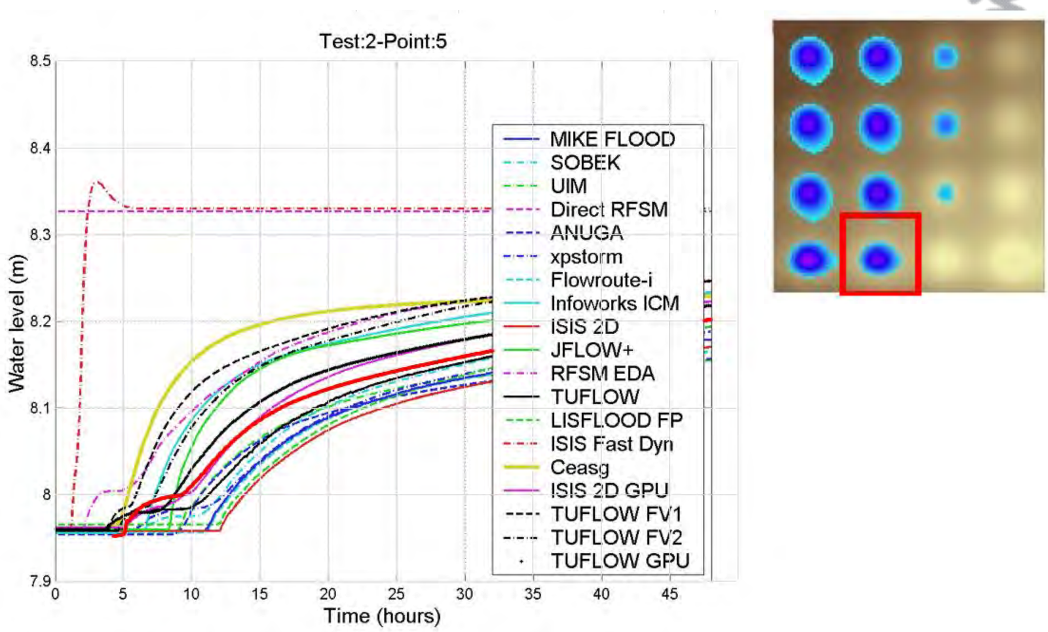

Figure 8 - Test 2: Water level in point 5. The thick red line indicates the 3Di result.

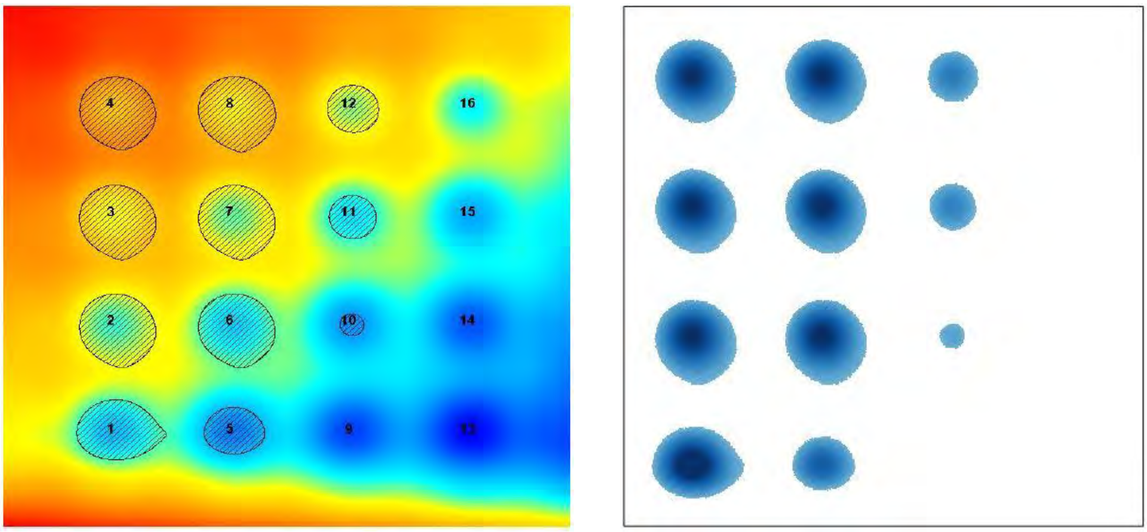

Figure 9 - Test 2: On the left the final flood extent (shaded) calculated by most benchmark modelling packages, plotted on top of the Digital Elevation Model. On the right the final flood extent as calculated by 3Di.

2.3 **Test 3:** Momentum conservation over a small obstruction

The concept of momentum conservation is tested by simulating an inflow at the top of a slope. The water accelerates towards the first valley (point 1). The total volume of water should fit completely in the first valley but due to its momentum, some of the water will overtop the hill towards point 2.

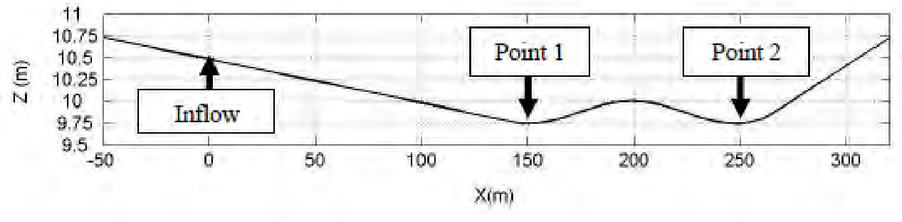

Figure 10 - Test 3: A side view of the Digital Elevation Model. The elevation in y direction is uniform

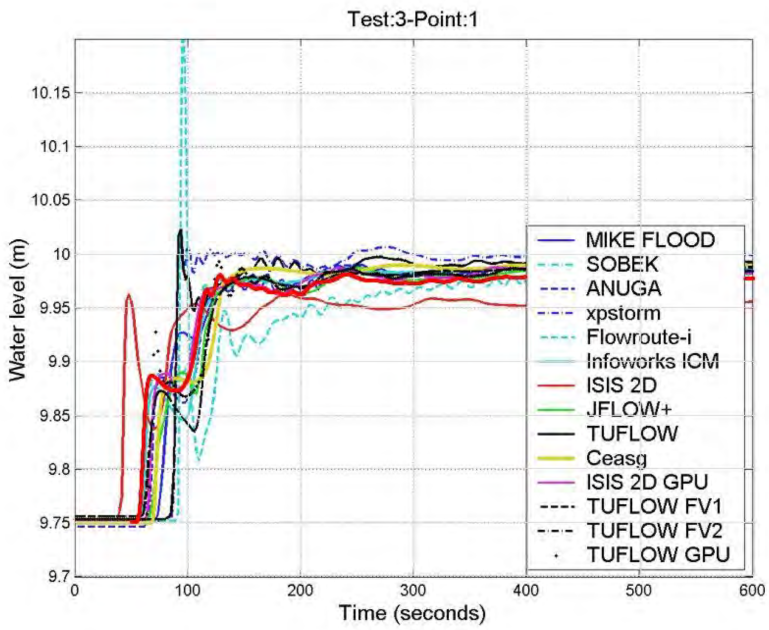

Figure 11 - Test 3: Water level in point 1. The thick red line indicates the 3Di result.

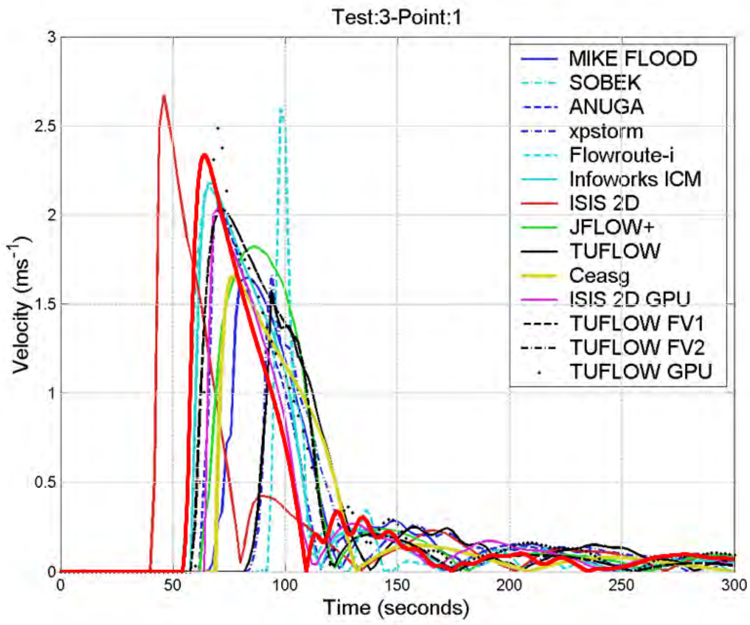

Figure 12 - Test 3: Flow velocity in point 1. The thick red line indicates the 3Di result.

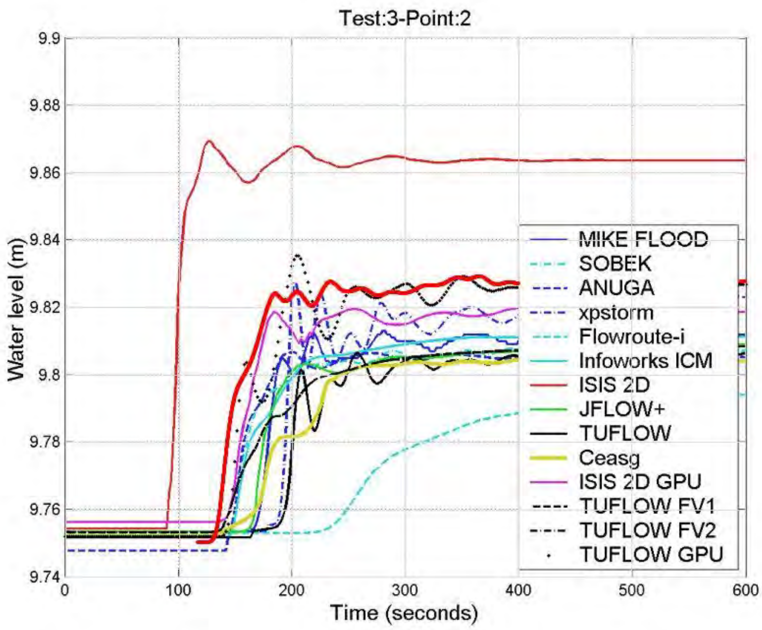

Figure 13 - Test 3: Water level in point 2. The thick red line indicates the 3Di result.

2.4 Test 4: Speed of flood propagation over an extended floodplain

This model describes the flooding of a floodplain from a point source at the edge of the modelling domain (left of point 1). The elevation and friction of the floodplain is uniform and the model boundaries are closed (no flow allowed).

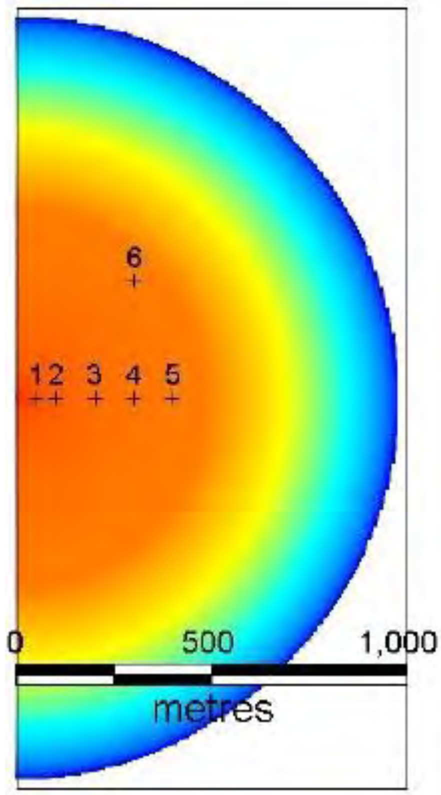

Figure 14 - Test 4: A typical flooding extent after 3 hours

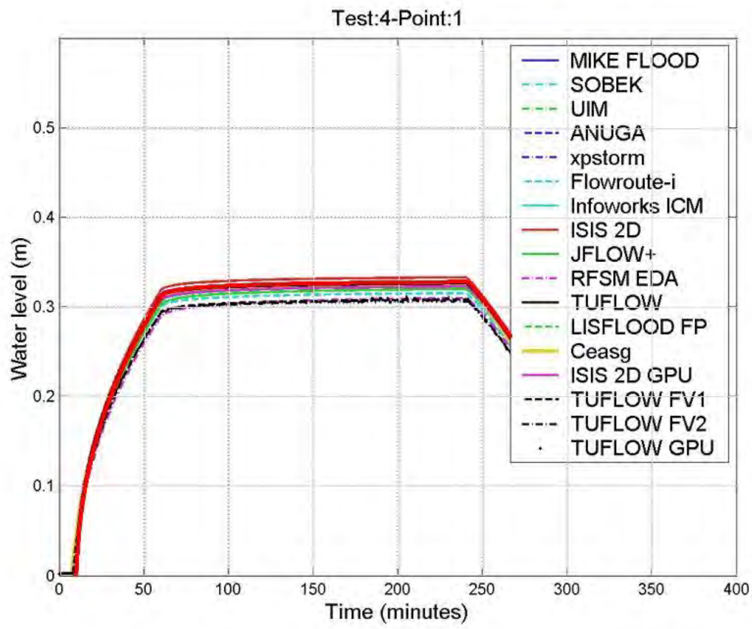

Figure 15 - Test 4: Water level in point 1. The thick red line indicates the 3Di result.

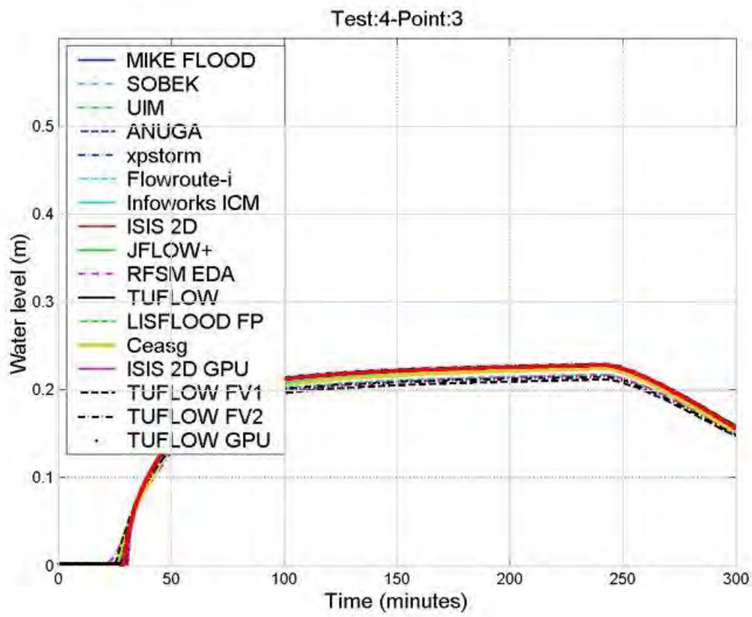

Figure 16 - Test 4: Water level in point 3. The thick red line indicates the 3Di result.

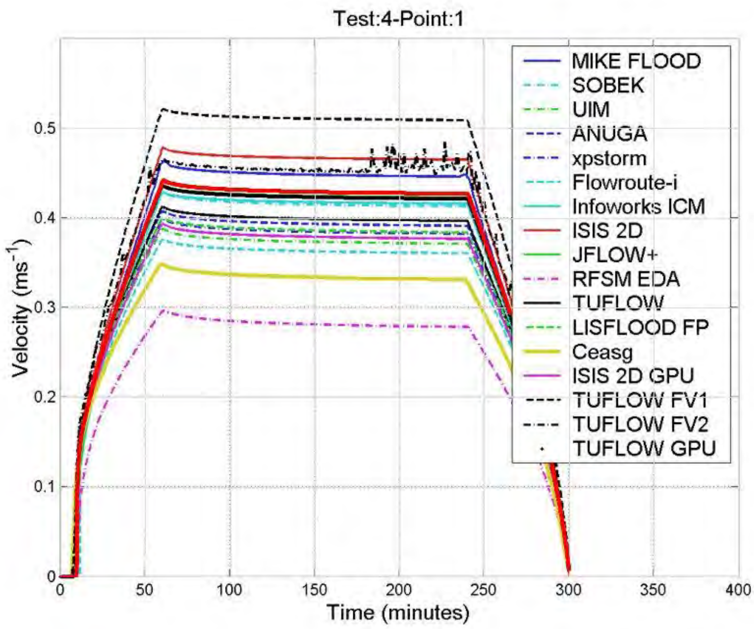

Figure 17 - Test 4: Flow velocity in point 3. The thick red line indicates the 3Di result.

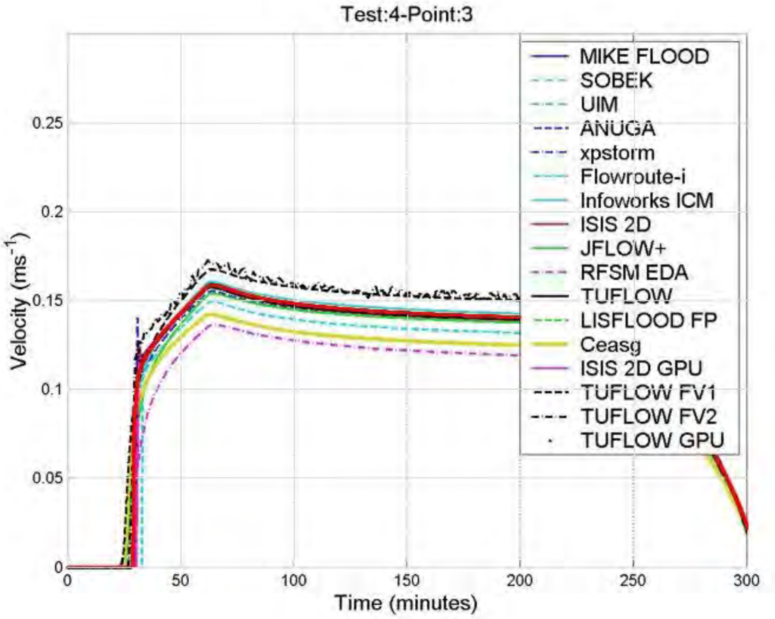

Figure 18 - Test 4: Flow velocity in point 3. The thick red line indicates the 3Di result.

2.5 Test 5: Valley flooding

This test describes a valley flooding caused by a dam break. A discharge time series is applied on the boundary condition (red line). Water flows downstream over the initially dry bed.

The water level and flow velocity at several points is used to compare different model packages.

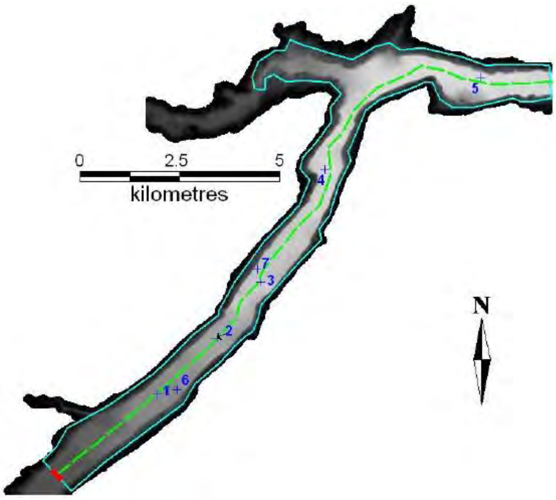

Figure 19 - Test 5: Overview of the DEM, model extent (blue line) and discharge boundary condition (red line)

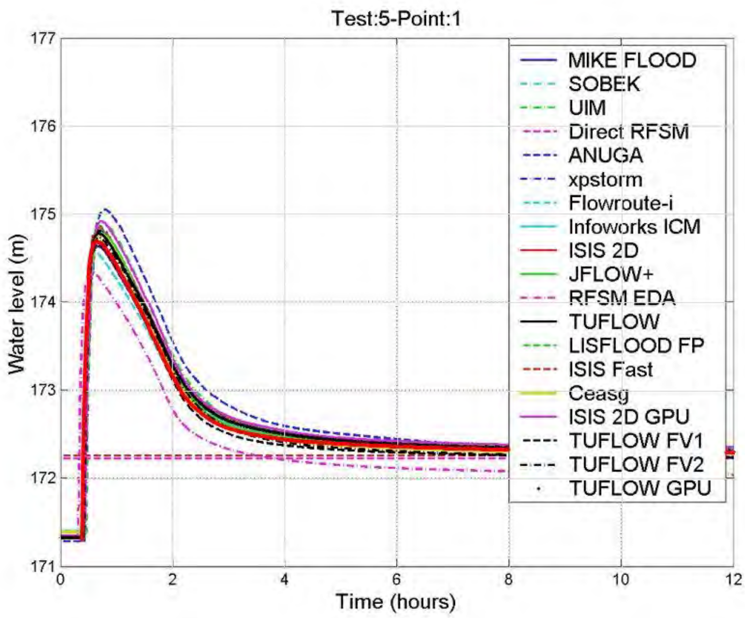

Figure 20 - Test 5: Water level in point 1. The thick red line indicates the 3Di result.

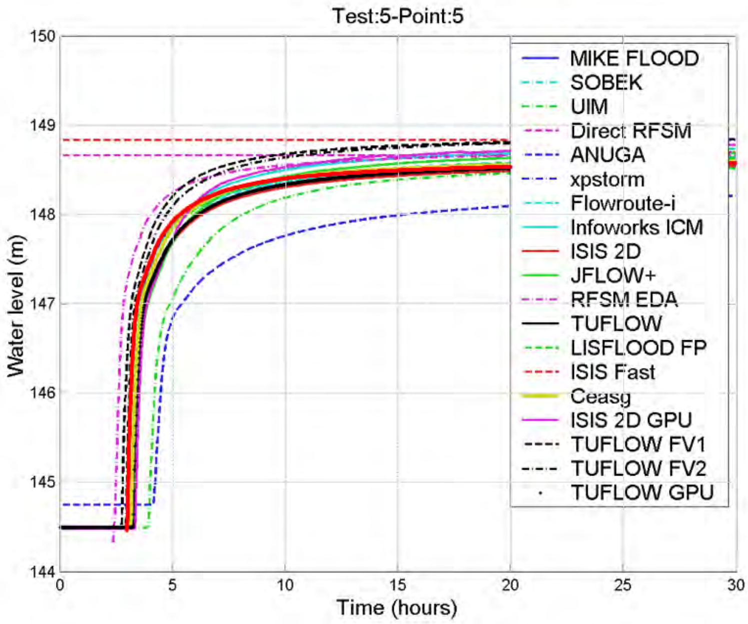

Figure 21 - Test 5: Water level in point 5. The thick red line indicates the 3Di result.

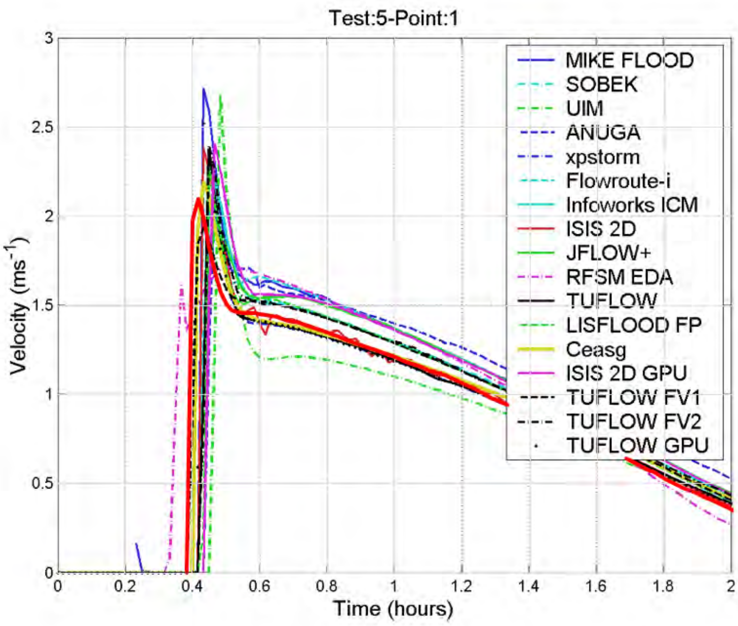

Figure 22 - Test 5: Flow velocity in point 1. The thick red line indicates the 3Di result.

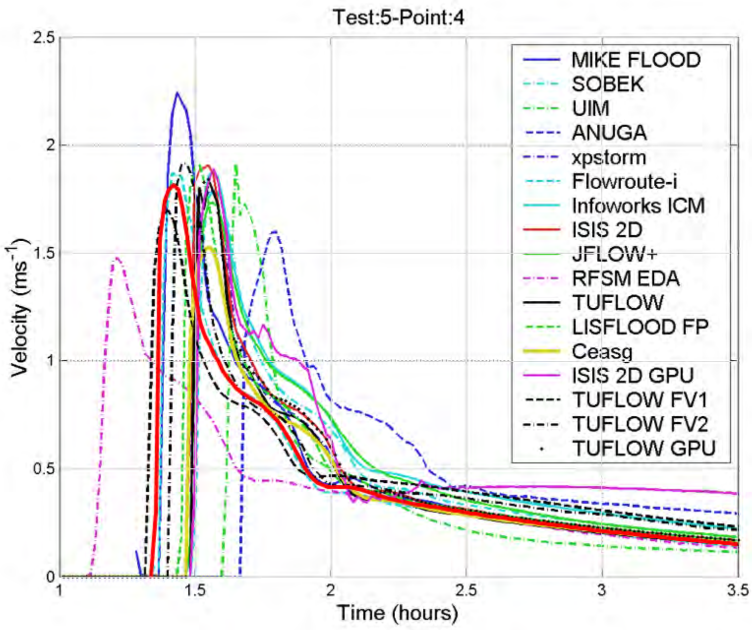

Figure 23 - Test 5: Flow velocity in point 4. The thick red line indicates the 3Di result.

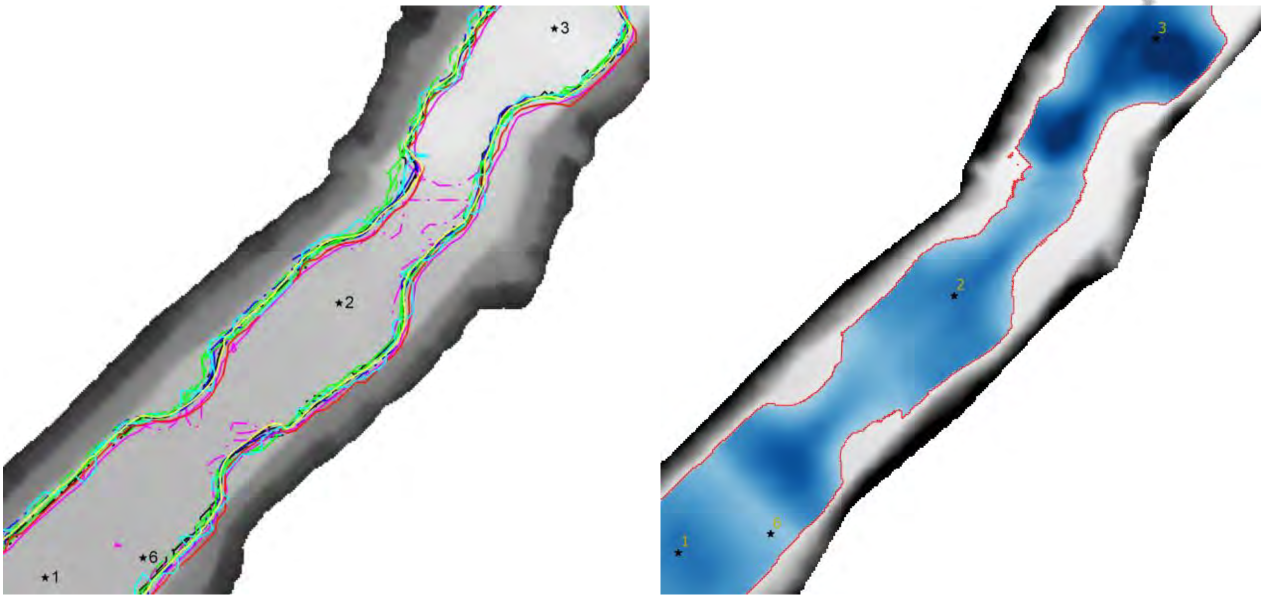

Figure 24 - Test 5: 0.5m contour lines from the benchmark report (left) and the 3Di results (right)

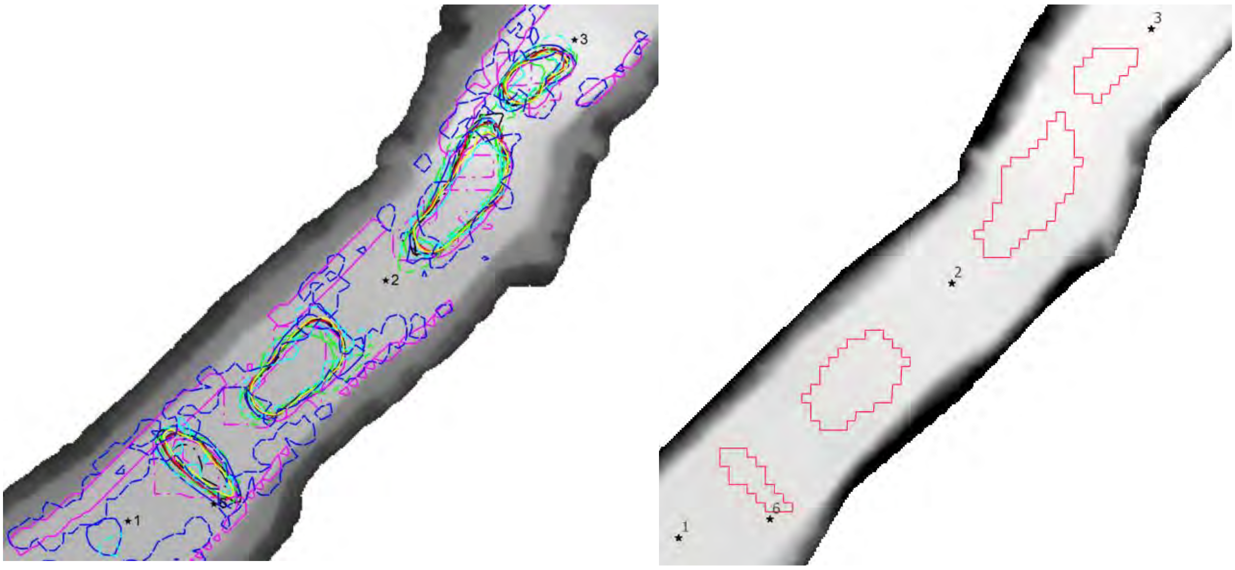

Figure 25 - Test 5: 3 m/s flow velocity contour lines from the benchmark report (left) and the 3Di results (right)

2.6 Test 6: Dam break

2.6.1 *Test 6A: Laboratory scale*

This laboratory scale dam break test case has been developed within the IMPACT project (Soares-Frazão & Zech, 2002). It describes a reservoir which empties through a breached dam onto a floodplain with a single building. The model was not optimized for the small scale size, other than lowering the time step.

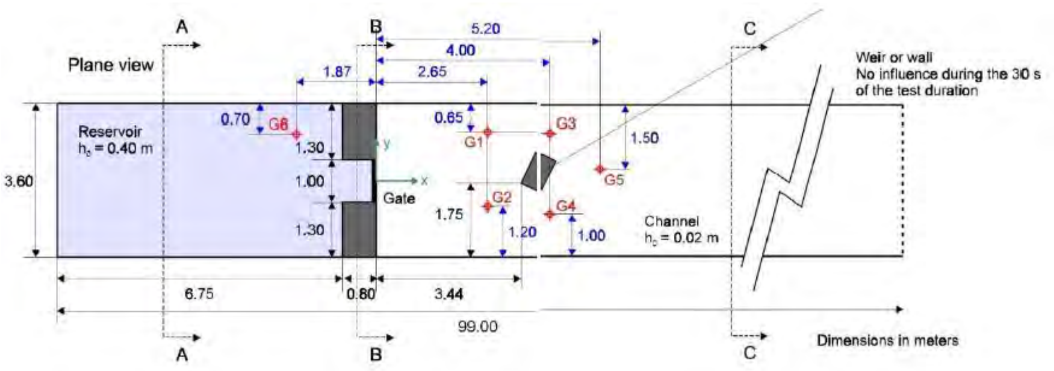

Figure 26 - Test 6A: Technical description from the IMPACT benchmark technical report. Source: (Soares-Frazão & Zech, 2002)

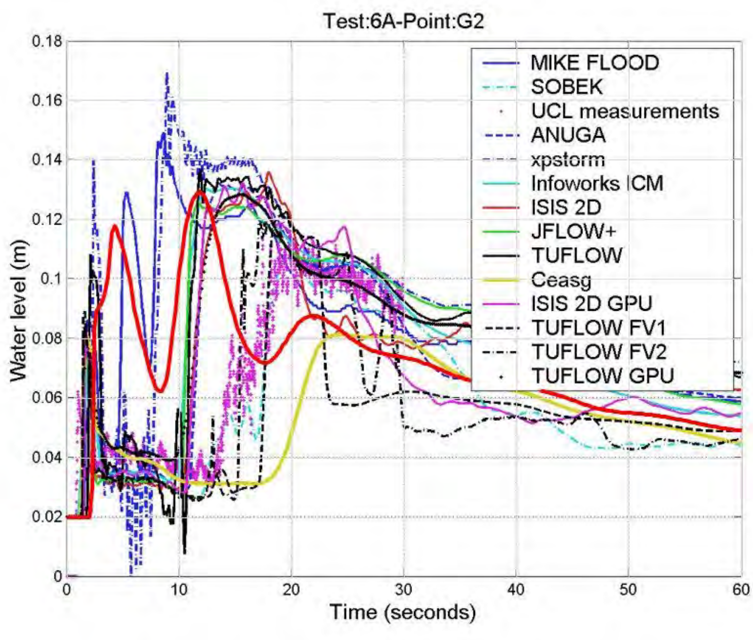

Figure 27 - Test 6A: Water level in point G2. The thick red line indicates the 3Di result.

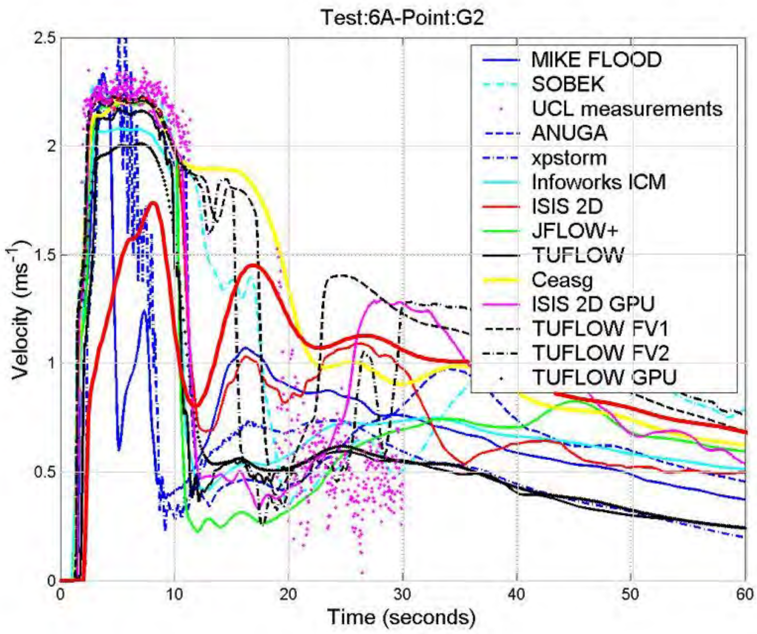

Figure 28 - Test 6A: Flow velocity in point G2. The thick red line indicates the 3Di result.

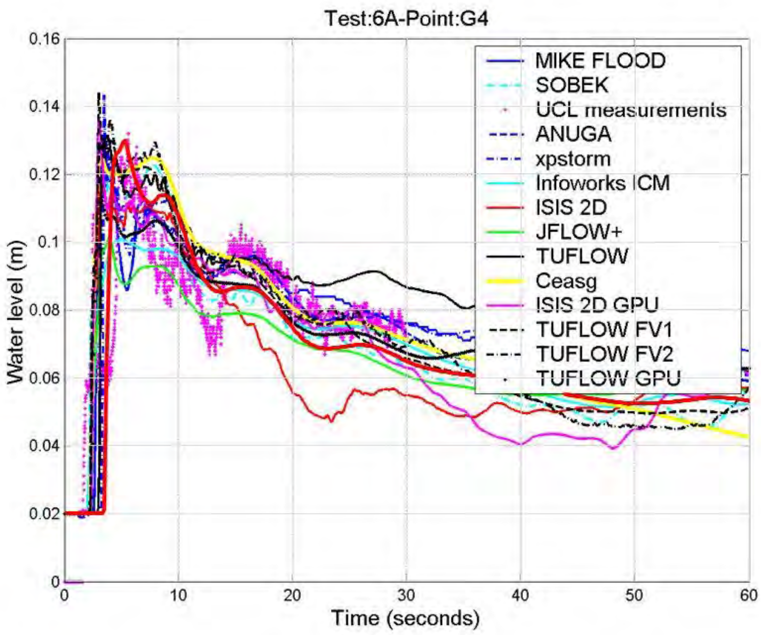

Figure 29 - Test 6A: Water level in point G4. The thick red line indicates the 3Di result.

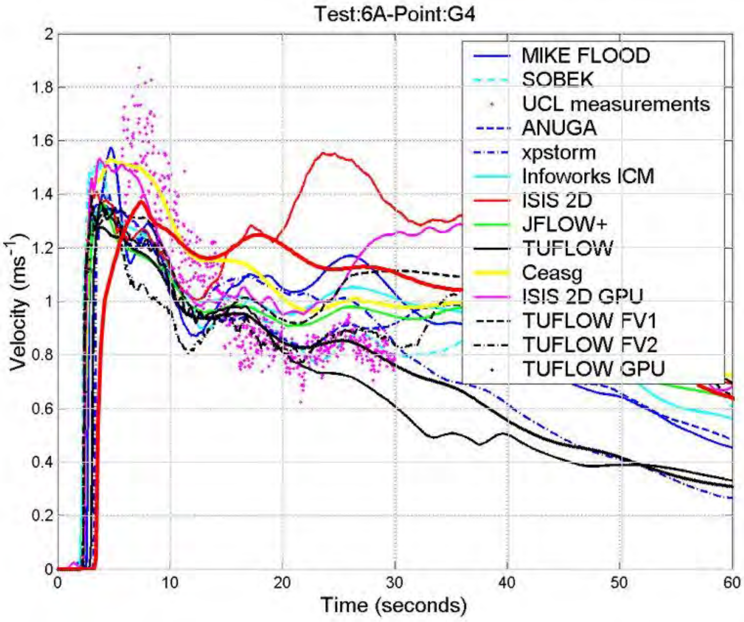

Figure 30 - Test 6A: Flow velocity in point G4. The thick red line indicates the 3Di result.

2.6.2 Test 6B: Full scale

The full scale test is similar to the laboratory test, with all dimensions multiplied by a factor 20 in order to resemble a real-life scenario.

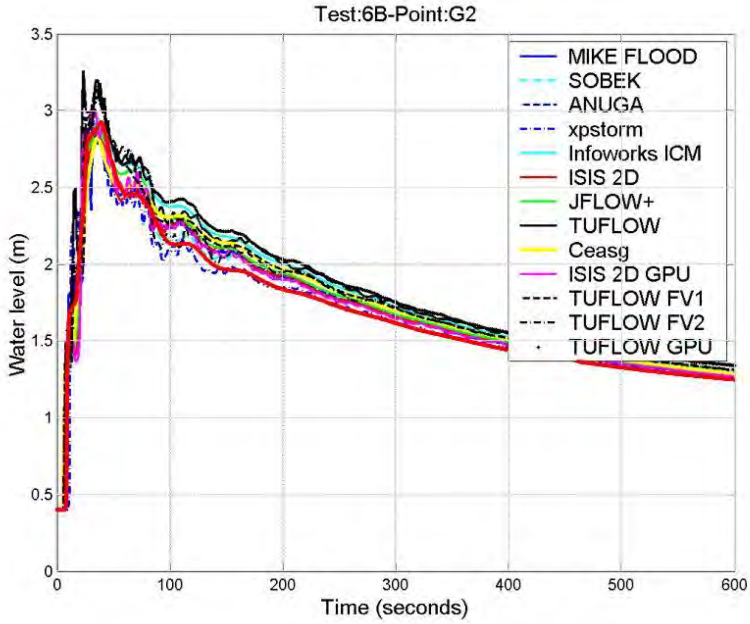

Figure 31 - Test 6B: Water level in point G2. The thick red line indicates the 3Di result.

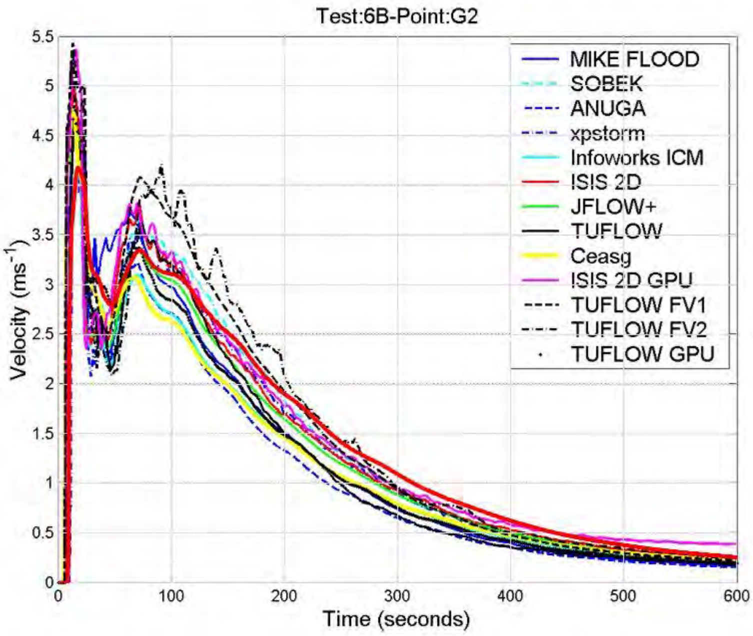

Figure 32 - Test 6B: Flow velocity in point G2. The thick red line indicates the 3Di result.

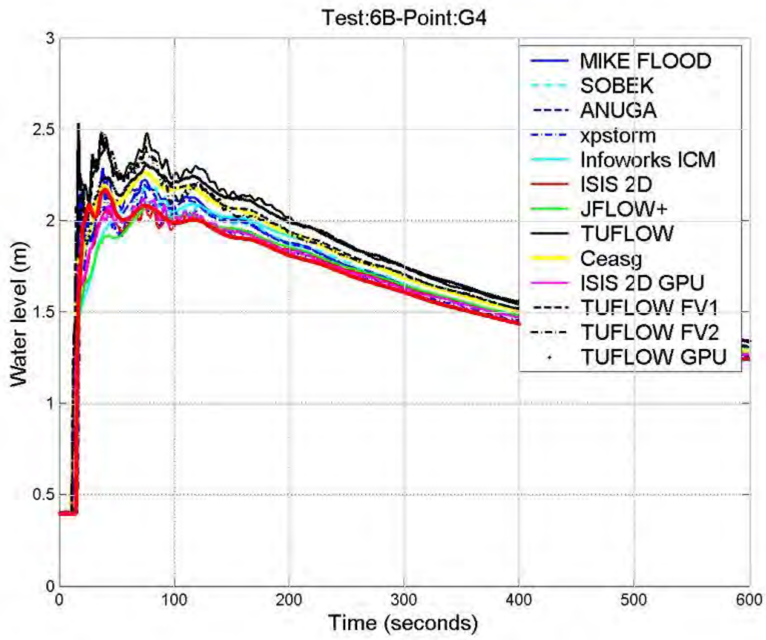

Figure 33 - Test 6B: Water level in point G4. The thick red line indicates the 3Di result.

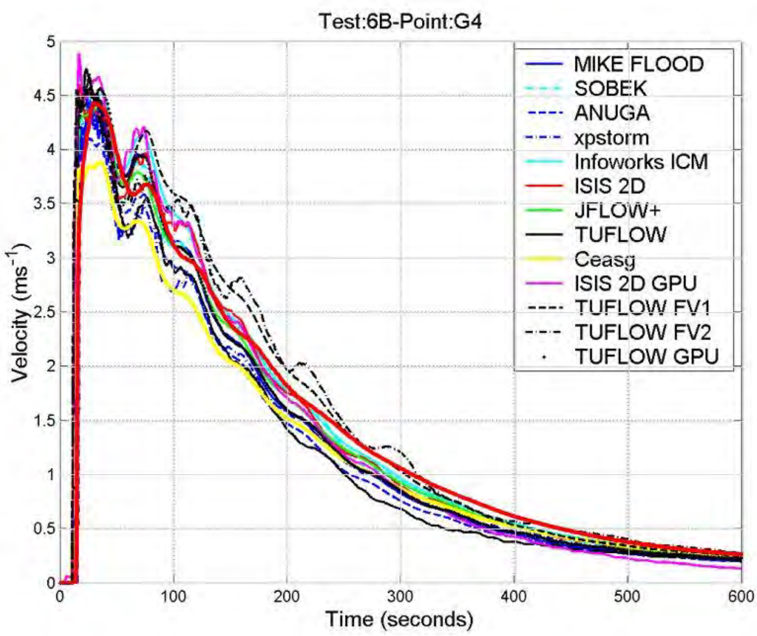

Figure 34 - Test 6B: Flow velocity in point G4. The thick red line indicates the 3Di result.

2.7 Test 7: River and floodplain linking

This test describes a 1D river and a 2D floodplain, which are linked using provided riverbanks. Several 1D elements like levees and culverts are added to the floodplains.

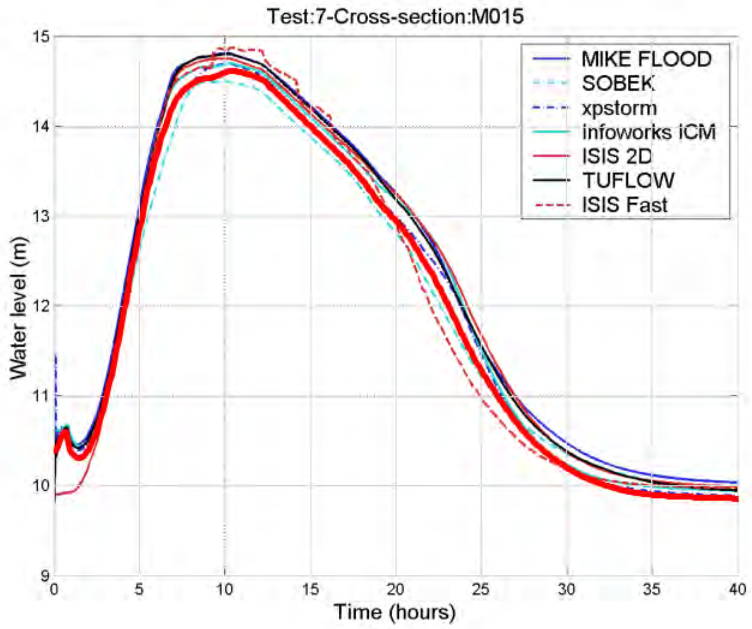

Figure 35 - Test 7: Water level in cross-section M015. The thick red line indicates the 3Di result.

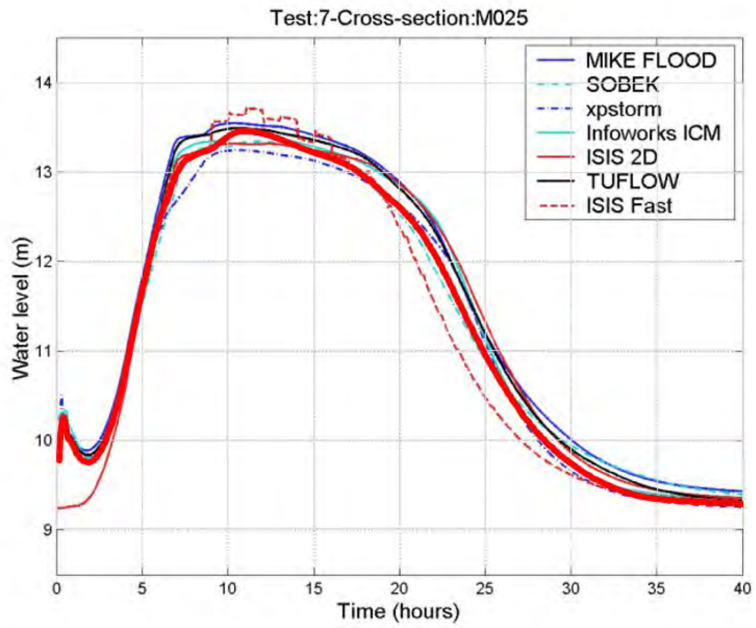

Figure 36 - Test 7: Water level in cross-section M025. The thick red line indicates the 3Di result.

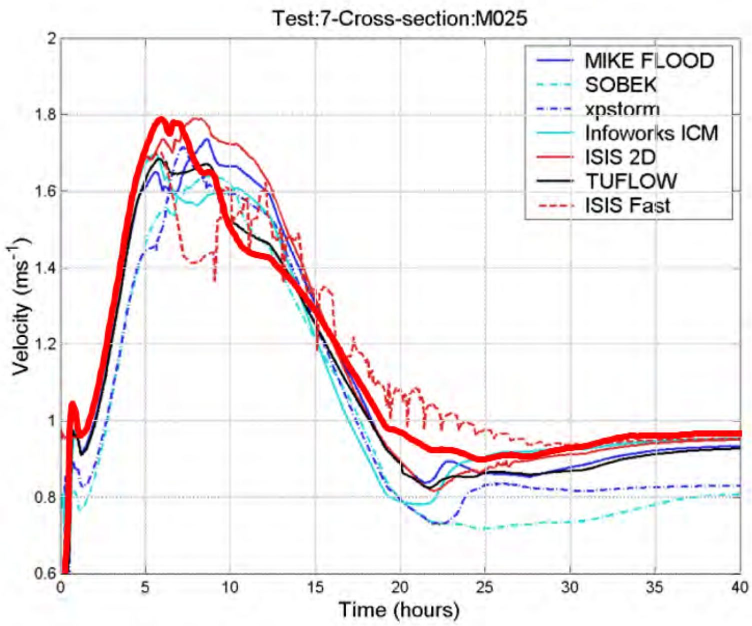

Figure 37 - Test 7: Flow velocity in cross-section M025. The thick red line indicates the 3Di result.

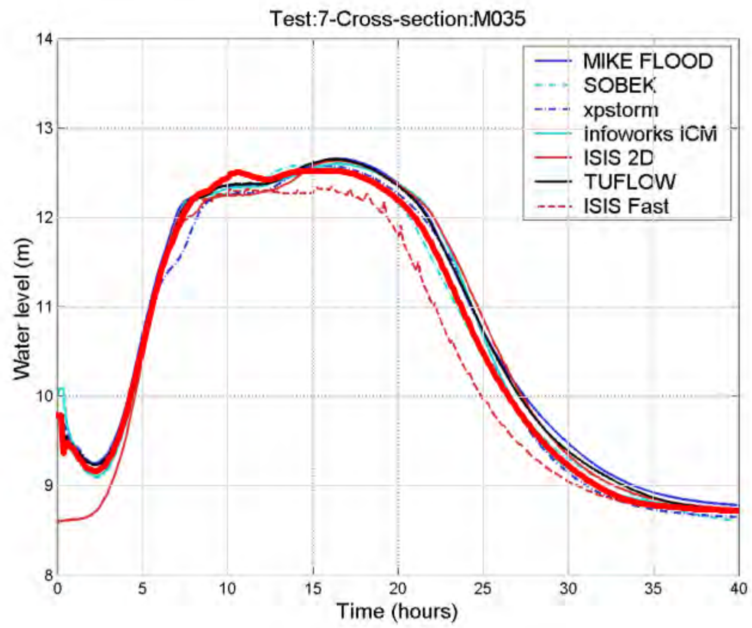

Figure 38 - Test 7: Water level in cross-section M035. The thick red line indicates the 3Di result.

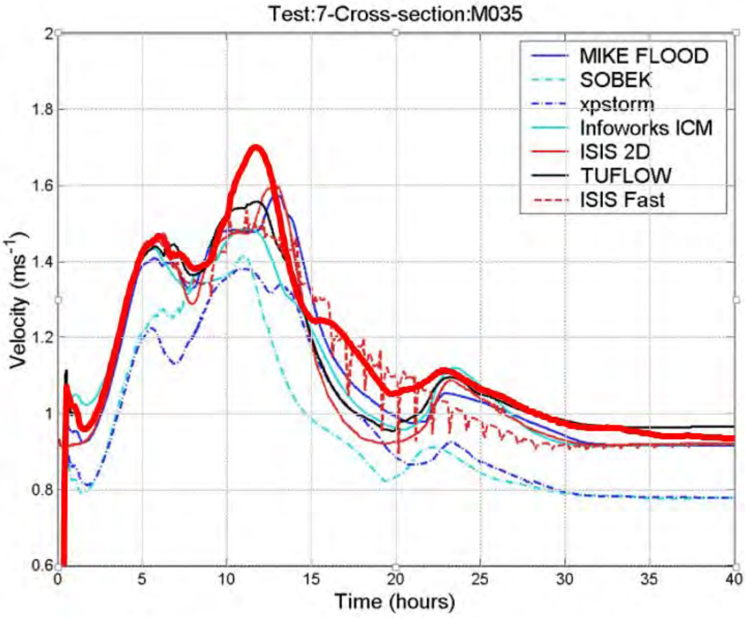

Figure 39 - Test 7: Flow velocity in cross-section M035. The thick red line indicates the 3Di result.

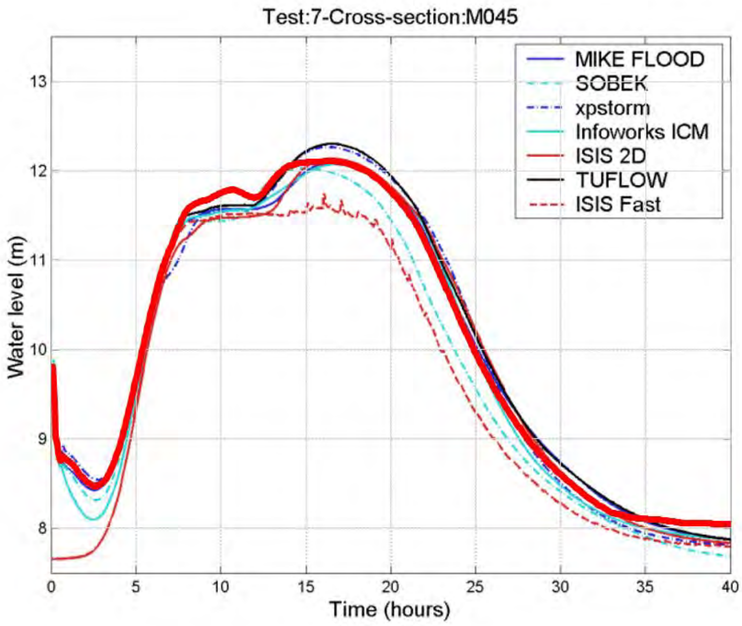

Figure 40 - Test 7: Water level in cross-section M045. The thick red line indicates the 3Di result.

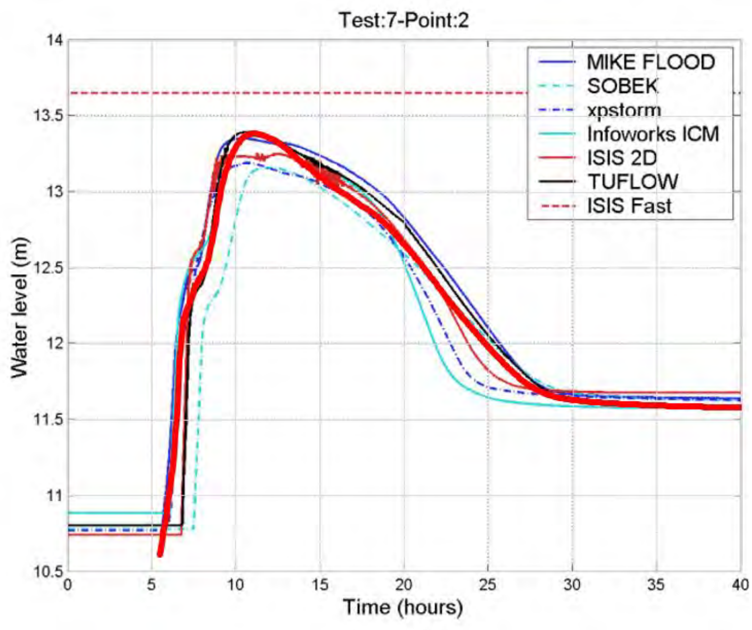

Figure 41 - Test 7: Water level in point 2. The thick red line indicates the 3Di result.

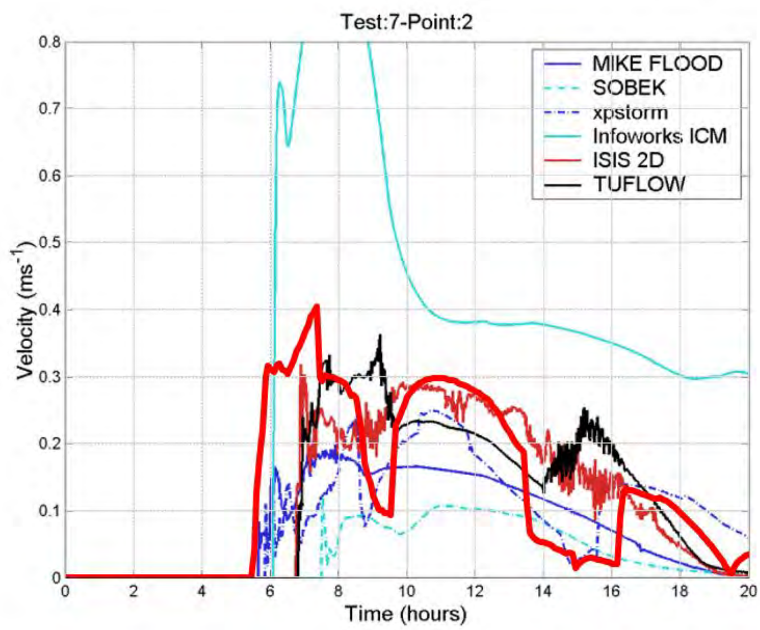

Figure 42 - Test 7: Flow velocity in point 2. The thick red line indicates the 3Di result.

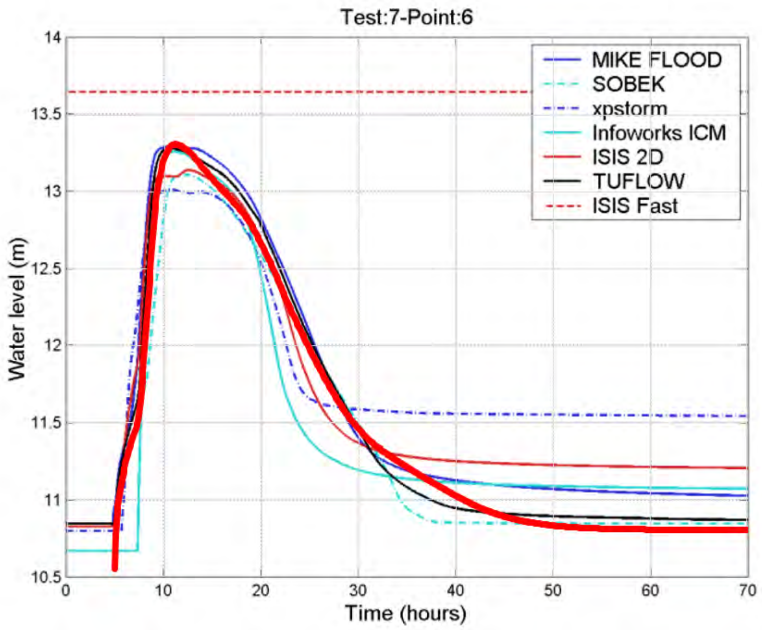

Figure 43 - Test 7: Water level in point 6. The thick red line indicates the 3Di result.

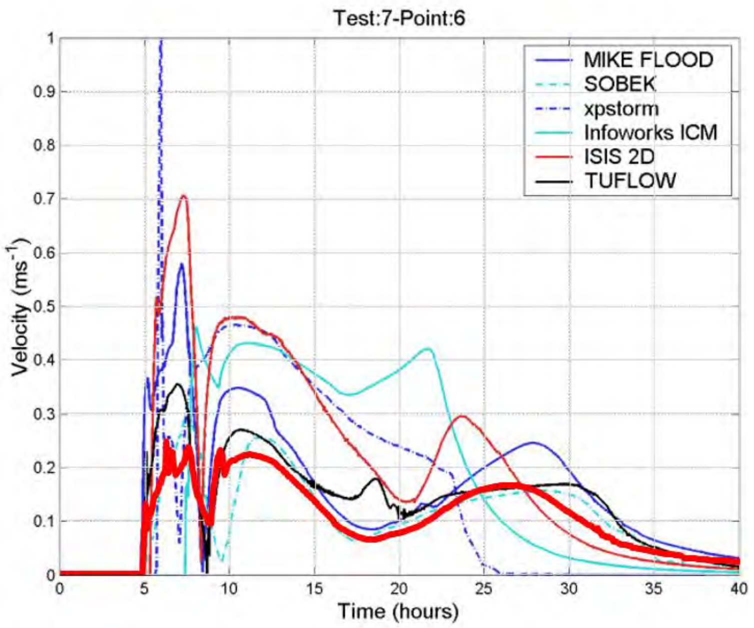

Figure 44 - Test 7: Flow velocity in point 6. The thick red line indicates the 3Di result.

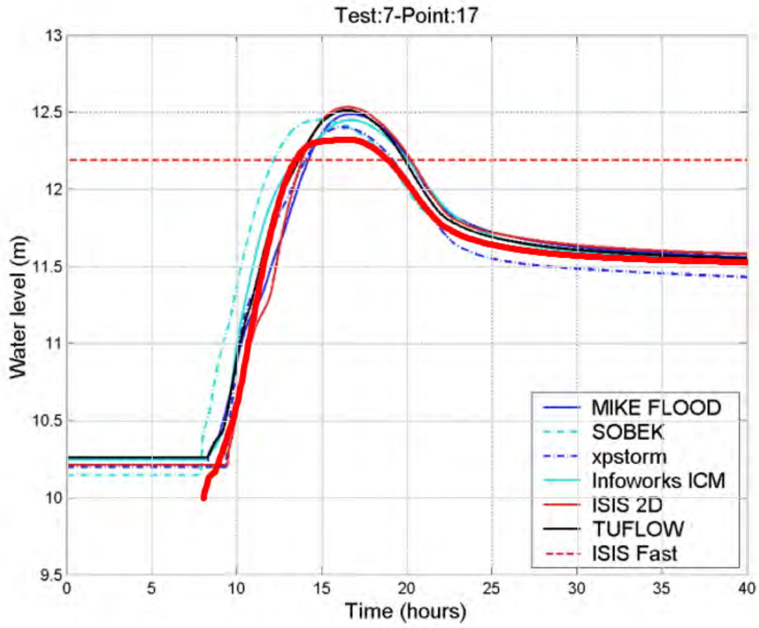

Figure 45 - Test 7: Water level in point 17. The thick red line indicates the 3Di result.

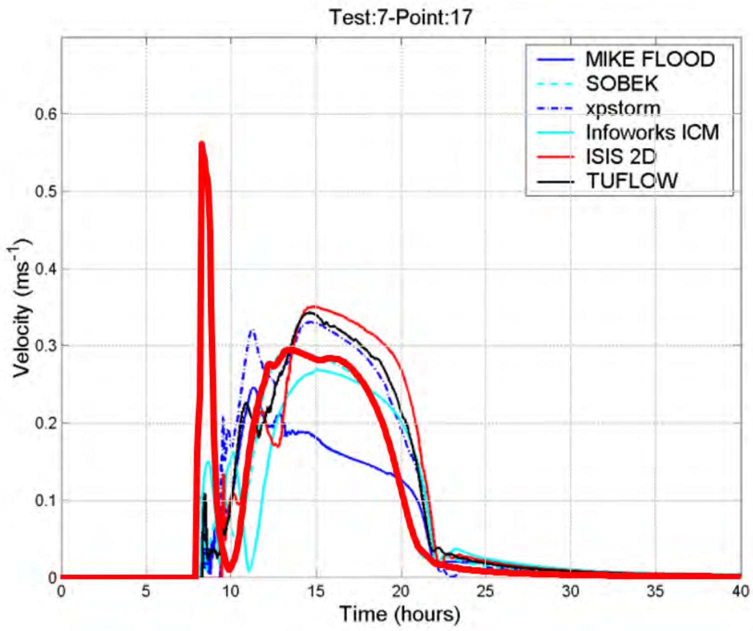

Figure 46 - Test 7: Flow velocity in point 17. The thick red line indicates the 3Di result.

2.8 Test 8: Surface flow in urban areas

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

A Digital Elevation Model of an urban area is used in order to model rainfall (400 mm/h for 3 minutes) and point source (15 minute time series, peaking at 5 m³/s) runoff.

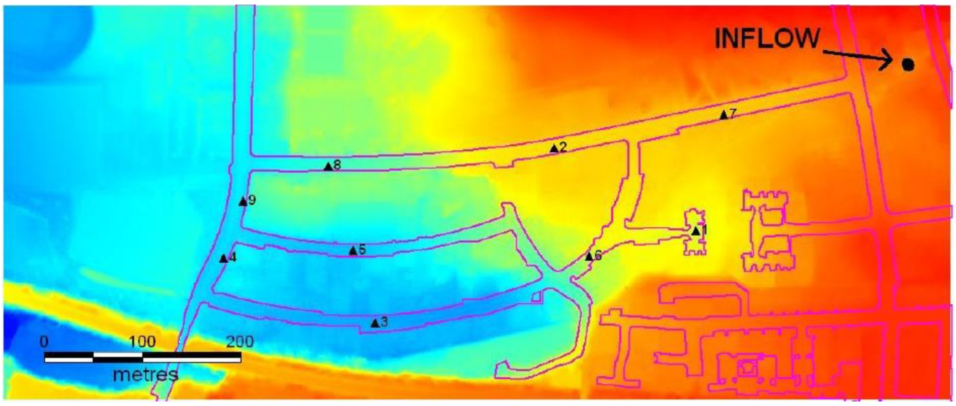

Figure 47 - Test 8A: Digital Elevation Model of the modelled area. The outline of roads – where the friction is lowered – is plotted over the DEM.

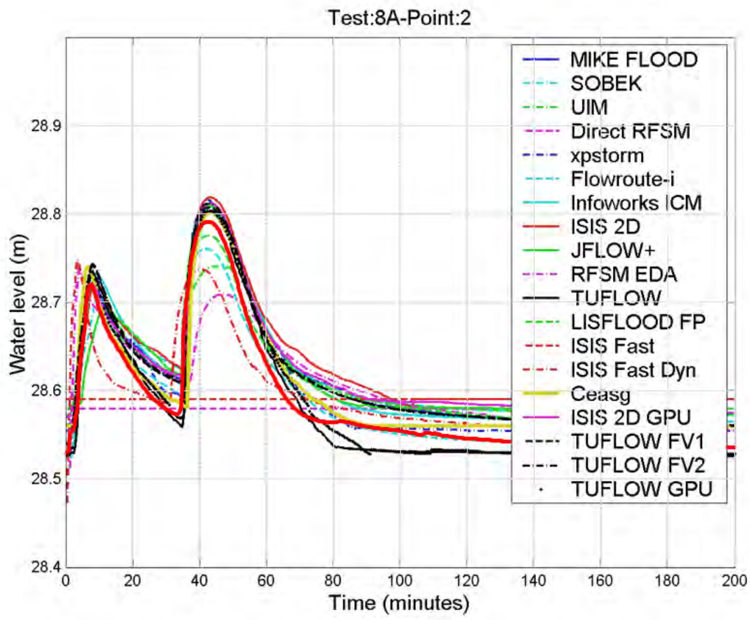

Figure 48 - Test 8A: Water level in point 2. The thick red line indicates the 3Di result.

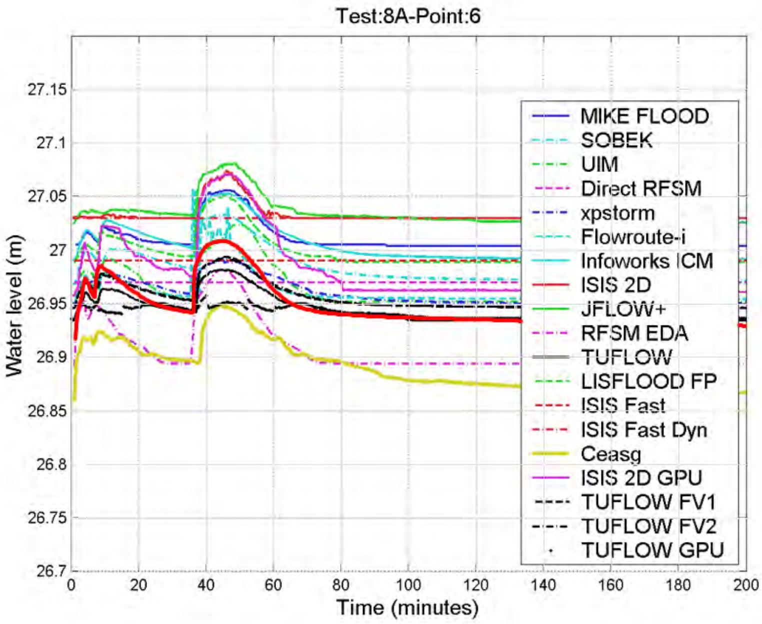

Figure 49 - Test 8A: Water level in point 6. The thick red line indicates the 3Di result.

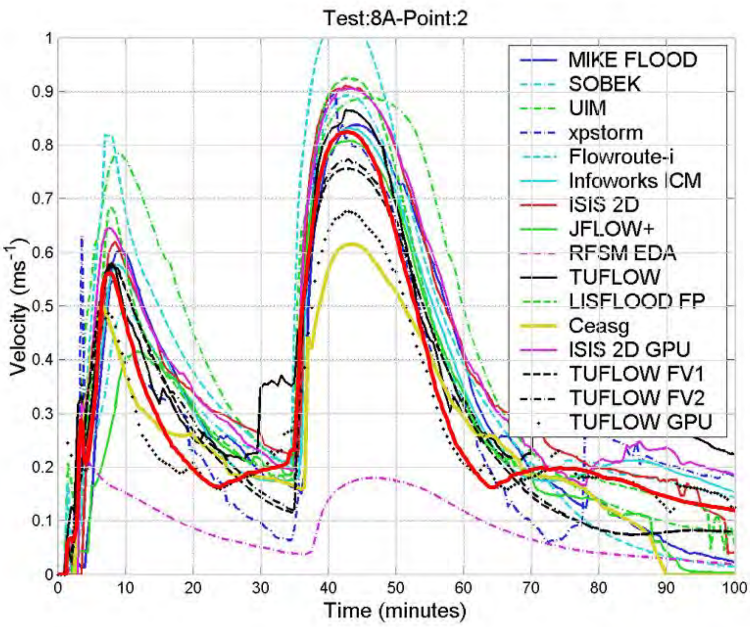

Figure 50 - Test 8A: Flow velocity in point 2. The thick red line indicates the 3Di result.

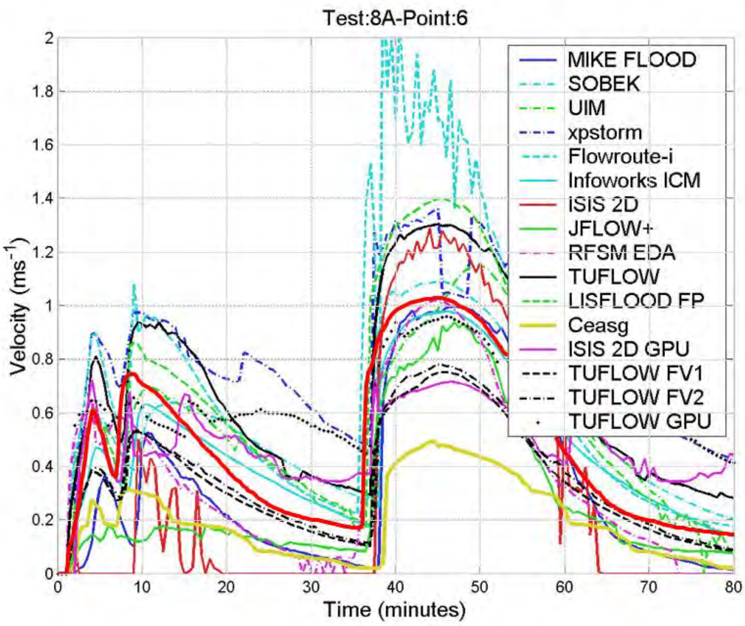

Figure 51 - Test 8A: Flow velocity in point 6. The thick red line indicates the 3Di result.

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

In this test the point inflow of test 8A has been replaced by a manhole above a pipe with a boundary condition upstream and free outflow conditions downstream. There will be a surcharge from the 1D sewer to the 2D domain. Buildings are taken into account, which is done by elevating the DEM based on a building shapefile.

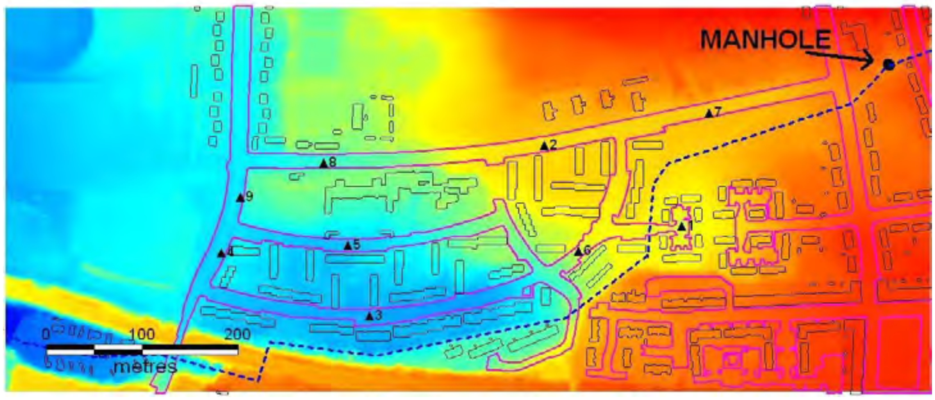

Figure 52 - Test 8B: Figure 31-Digital Elevation Model of the modelled area, including the outline of roads (where friction is lower) and buildings (where the elevation is raised) is plotted. Also the location of the manhole and the comparison points is indicated.

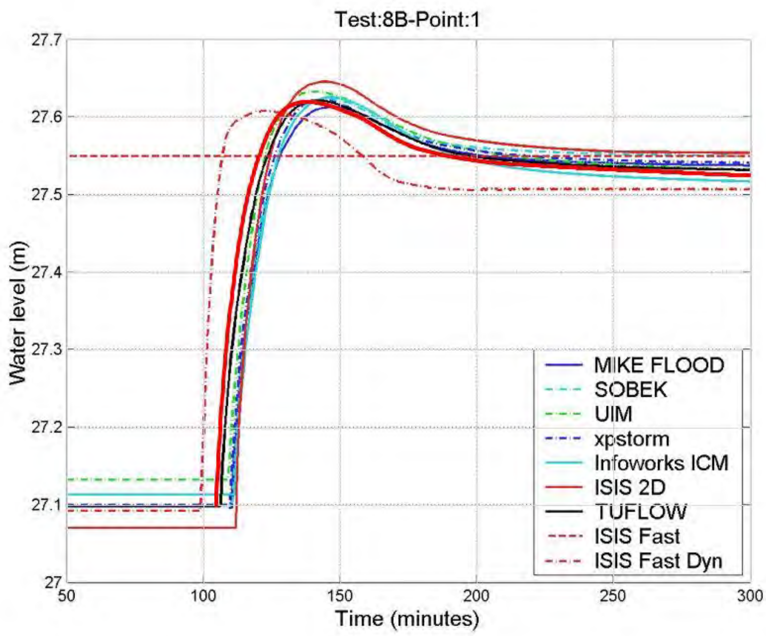

Figure 53 - Test 8B: Water level in point 1. The thick red line indicates the 3Di result.

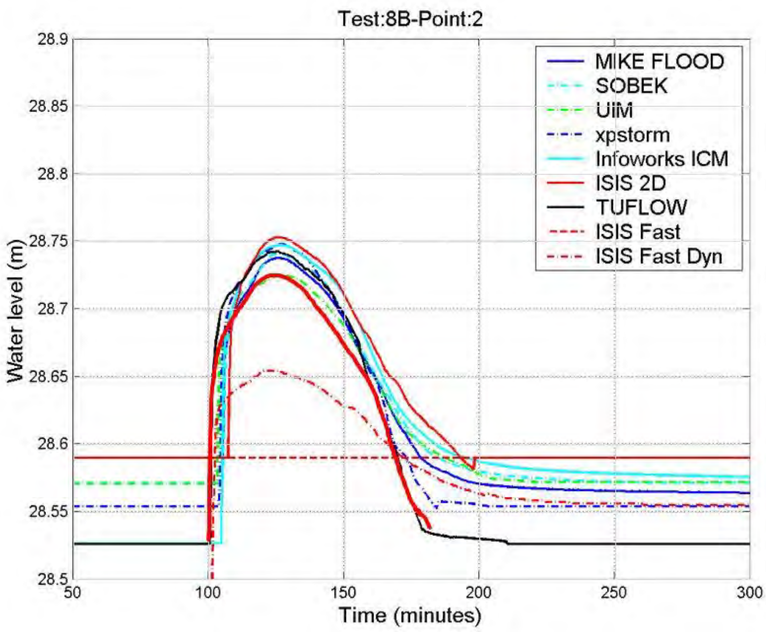

Figure 54 - Test 8B: Water level in point 2. The thick red line indicates the 3Di result.

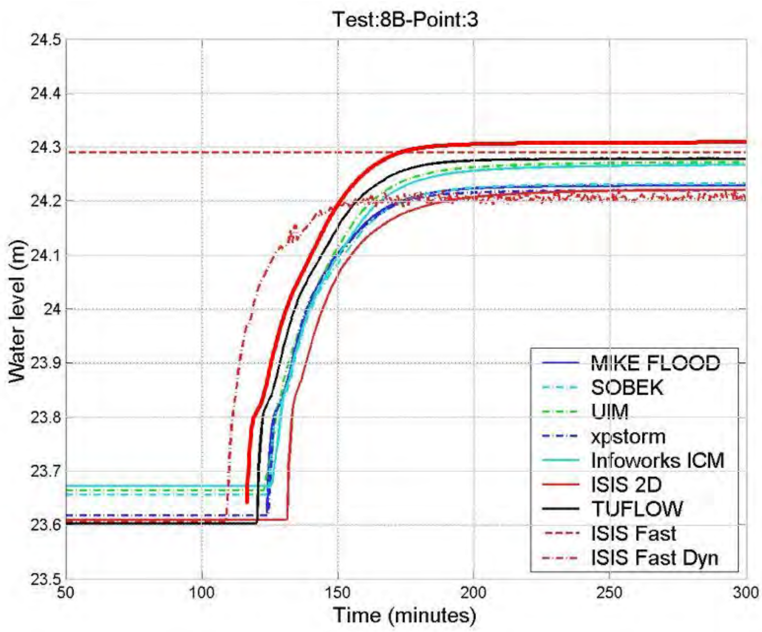

Figure 55 - Test 8B: Water level in point 3. The thick red line indicates the 3Di result.

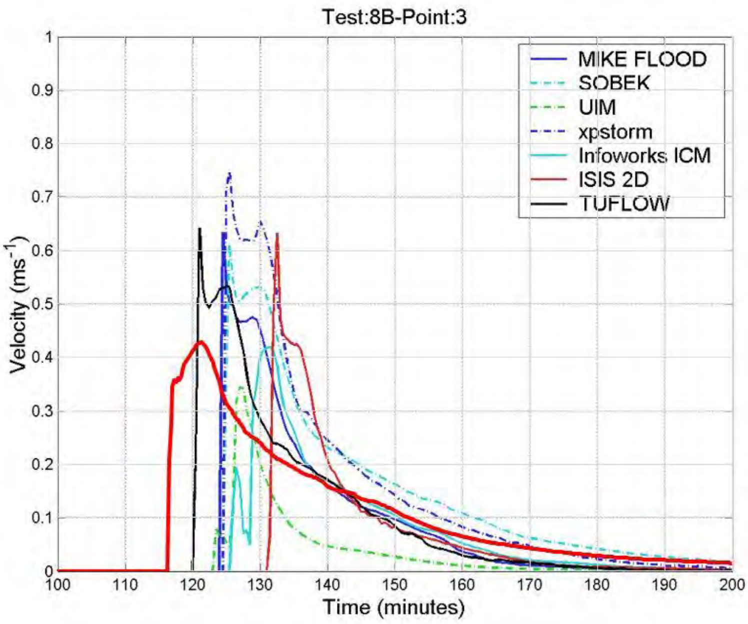

Figure 56 - Test 8B: Flow velocity in point 3. The thick red line indicates the 3Di result.

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I. Appendix

3Di: A new Dutch hydrological model

Wytze Schuurmans[1] and Elgard van Leeuwen[2]

There are already numerous water simulation models, so it may be surprising that a new simulation model has been developed in the Netherlands again. 3Di distinguishes itself with two features: it uses a new numerical computing technique and it is not only a computing tool, but also a communication tool. The new subgrid computing technique allows for higher-resolution, faster and more accurate computations. 3Di integrates 0D, 1D and 2D model components into one single computation core. As a communication tool, 3Di has an interface that works well in interactive workshops. After seven years of development, 3Di has become a mature product, which supports professionals to work on the challenge of designing climate-resilient urban and rural areas.

The 3Di software is now fully operational and suitable for us consultants, water boards and municipalities. This article explains some features and background of 3Di.

3Di, what's in a name?

We started the development of a new instrument under the name of 3Di seven years ago. The 3Di software has been developed especially for professional use in complex urban environments. The name '3D' was given because of the 3D stereo visualization. But its name also refers to the three model components 0D, 1D and 2D. Finally, the 'i' stands for its integral concept and interactive use.

A Dutch product

The new computational core was developed in the period 2010 to 2014 by a consortium consisting of Deltares, Delft University of Technology and Nelen & Schuurmans. The seven-million-euro development costs were covered by various Dutch funds, water boards, municipalities and a private company. During recent years, the software has evolved from research software into a user-friendly modelling package that has been applied by numerous cities and water authorities worldwide. 3Di stands in the Dutch tradition of integrated water management, in which spatial planning and multi-stakeholder processes play an important role (Bruges et al., 2005).

The subgrid technique

3Di's computational core is based on the subgrid technique (Stelling 2012). The subgrid technique is a new numerical calculation technique for time-efficient description of 2D flow at a high spatial resolution.

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[2] Deltares, Delft, Elgard.vanLeeuwen@deltares.nl

The technique enables simulation of a river basin or city at a spatial resolution of less than 1 m2 (Figure 1) in a time period of minutes to hours.

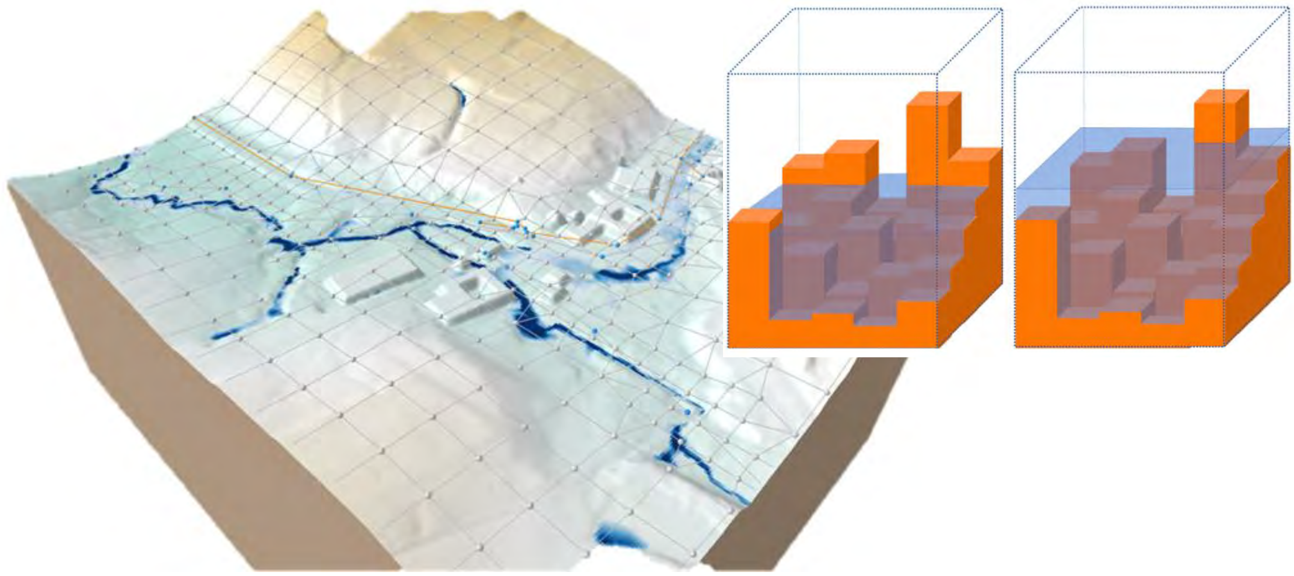

Figure 1: *A high resolution Digital Elevation Map underlying a 3Di model. The water depths are computed on each subgrid, whereas the water levels are computed per quadtree cell*

Casulli and Stelling, an intriguing duo

The subgrid technique was initially developed by professor Casulli (Casulli, 2011) with the purpose of calculating the process of 'wetting and drying' in estuaries. Professor Stelling has expanded the subgrid technology for rapidly varying flow in time and space, such as floods (Stelling, 2012). He made the subgrid technique applicable for the complete "Saint-Venant" flow equations (Chow, 1959). The user can set the trade-off between speed and accuracy by editing the parameter settings of each model, but indifferent of the settings, a strict conservation of momentum and volume is always guaranteed. 3Di was the first commercial modelling package that uses subgrid technology. Recently the hydrological model of the US Army Corps of Engineers, HEC-Ras 5.0, also adopted the subgrid technology. In recent years wind effects, rainfall-runoff with thin water layers and ground water flow has been incorporated in the subgrid technology. Volp (Volp, 2016) has applied the subgrid technology for morphology in rivers and estuaries.

2D flow

The subgrid technology works with two types of grids: a high-resolution data grid and a coarser computational grid. The high-resolution data grid contains spatial information, such as elevation levels, infiltration capacity and hydraulic resistance. This computational grid has a quadtree structure, an orthogonal structure that can be refined locally. Refinement is useful, to accurately track levees, canals or roads (Esse, 2017). The quadtree grid has been chosen because this is the most accurate for complex flow conditions, which will occur on steep slopes, dam breaches, or river flow along structures.

Figure 2: Example of a Quadtree grid (white lines) in combination with obstacles (red line)

The important assumption underlying the subgrid methodology is that in space, the water level varies much less than the water depths. This assumption makes it possible to compute water levels on the quadtree grid and water depths and the local flow rates at each subgrid cell. A typical 3Di model thus consists of a hundred million to a billion subgrid cells, but only a hundred thousand quadtree computational cells. It is possible to refine the calculation grid around obstacles. However, the downside of grid refinement is an increase of the computational time, due to the increase of the number of computing cells. Therefore, a second solution has been built in, “obstacles”. These obstacle lines provide watertight separation up to a specified level (Figure 2). For levees, this obstacle concept is further refined. 'Obstacle levees' are used to unambiguously define the left and right bank (Figure 3), and make it possible to simulate both overtopping and the dynamic growth of a dike breach.

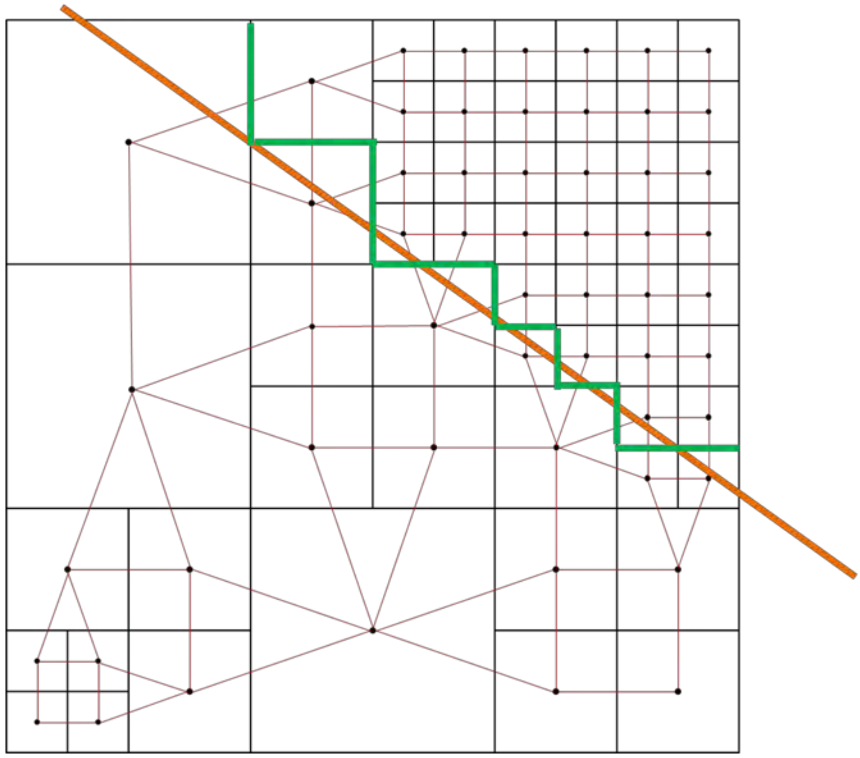

Figure 3: A 2D computing grid with a levee (brown line) and the resulting sealed edges (green) of related quadtrees

1D Flow

The flow in channels, sewers and pressure lines typically shows 1D flow patterns and these flow patterns are usually modelled with 1D methods. In 3Di a complete 1D flow model has been developed, which can be used stand-alone, or fully integrated with 2D flow. The special feature of this 1D model in 3Di is that sewage flow and open water flow can be combined because 3Di is solving one and the same flow matrix (Figure 4). All types of structures, such as pumps, weirs, sluices and bridges can be included in the 1D model. Moreover, real-time control of these structures can be simulated in various ways. In addition to the set of standard structures, the user can add user defined structures with any cross section. The calculation code detects by itself the applicable flow conditions: free flow or drowned flow. The 1D model code is extremely fast because of the implicit numerical scheme. It also uses another feature that limits time step reduction for dry areas: for unconditional convergence of complex volumes, such as wells and pipes, 3Di uses the Nested Newton iteration method. For the model user, this means full mass conservation and momentum conservation under all conditions, without numerical disturbances.

In urban areas with extreme rainfall conditions or river floods, it is impossible to make a distinction between sewer flow, open channel flow and street flow. For these types of problems 3Di shows its full capabilities using the 1D/2D integration.

Figure 4: 1D model with surface water (dark blue), mixed (yellow), domestic sewage (red) and rainwater sewage (light blue)

1D/2D flow integration

For a quick assessment of flash floods and pluvial flooding a high resolution 2D model is sufficient. But in a 2D model, the flow through ditches, channels and sewers is not taken into account very precisely. The urban drainage system and the open channel and ditches can often be better described in a 1D model (Luijtelaar et al., 2014). 3Di can work with a combined 1D/2D flow model (Figure 5). The interaction between 2D surface flow and 1D flow can be defined by three types of 1D flow sections: isolated, embedded, or connected. In the 'isolated' sections, there is no interaction between 1D and 2D. For embedded sections, the 1D cross-sectional profile is included in the 2D subgrid elevation and resistance grid. For connected sections, a relationship is defined between the 2D water level and the 1D water level. These three types of 1D flow sections apply to 1D open water flow and 1D sewage flow alike. In 3Di, the 1D and 2D calculations are fully integrated and solved simultaneously in one matrix. The implicit scheme allows for using large time steps without numerical oscillations.

The accuracy of the various modelling tools, including 3Di, was recently investigated in a Benchmark study (STOWA, 2017). From this Benchmark, 3Di appears to be the most accurate model code (Figure 6).

Figure 5: A 2D computing grid (white), coupled via 1D/2D with 1D (open water (blue), combined sewers (green) and dry flow sewage (red)

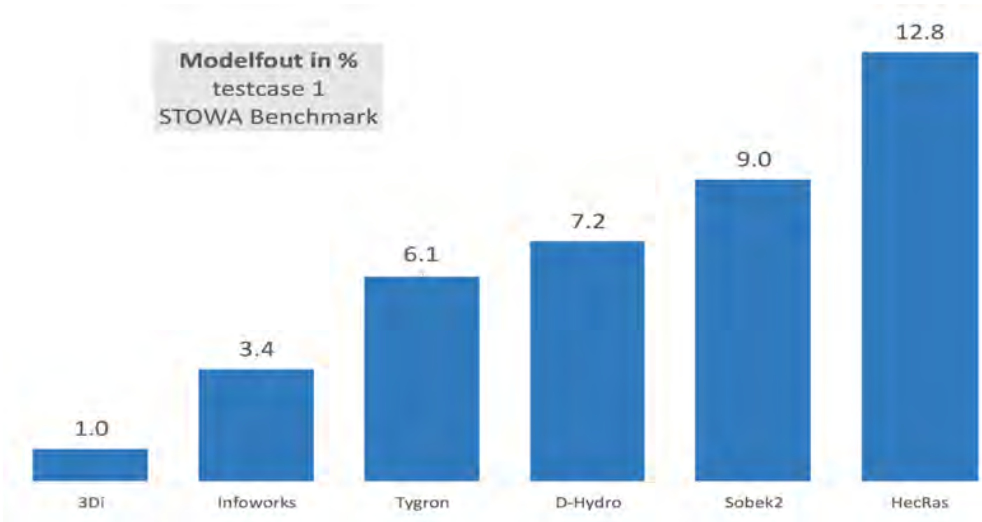

Figure 6: Accuracy of various model codes relative to the exact analytical solution from the STOWA Benchmark study, Source (STOWA, 2017)

0D-rainfall runoff

For rainfall-runoff modelling, 0D nodes or reservoir models are widely used. Well-known examples are Sacramento, HBV, Rainfall Runoff (RR) nodes of Sobek and the Wageningen Lowland Runoff Simulator (WALRUS, 2014). In 3Di, rainfall runoff nodes are strictly not necessary because the rainfall runoff is computed in 2D. However, the possibility of 0D nodes has been added as it computes faster and fits better with existing models. The user can define six parameters for each 0D node. When using the rain radar, the geographic location of the 0D nodes are taken into account. In a 3Di model, an unlimited amount of 0D nodes can be used, virtually without loss of computing time. In hybrid models, 0D is used in conjunction with 2D. By removing specific areas from the 2D grid, marking these areas as 'no data', a strict water balance is maintained. For example, in urban areas, the roof of each building can be modelled as a 0D node connected to the sewer network. The rainfall runoff of gardens and streets is modelled in 2D (Figure 7). In river basins 0D nodes can be used to optimize computing performance.

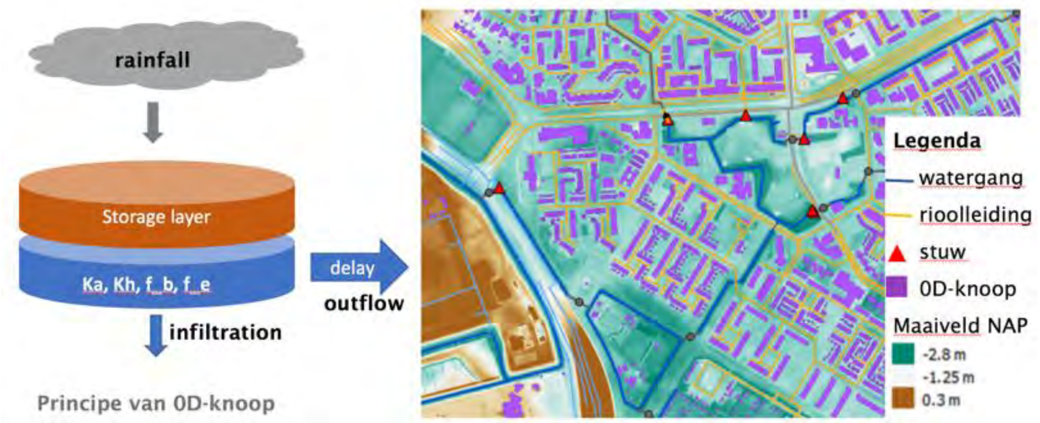

Figure 7: *Left, principle of 0D node with 6 adjustable parameters per node. Right, detail of a 0D / 1D / 2D model schematic of Rotterdam city*

Cloud computing

A 3Di model runs 'in the cloud', on dedicated servers, which are hosted in two mirrored data centers for optimal security. The user creates a model schematic on a laptop and then uploads their model to the cloud to perform the computation. All models are stored in the cloud, and model changes are tracked automatically to keep an overview even if multiple users are involved. The simulation can be followed live during the computation. At the end of the simulation the results can be stored and various post processing tools are available. All results can be downloaded for detailed analysis in a GIS environment (Figure 8). Cloud computing was selected to prevent problems with installation, memory and disk space. Another advantage is that users can work with rainfall radar images directly without storing all rainfall events locally. Finally, the 3Di code used is always up-to-date with the latest version. Existing model schematizations will keep working after each update.

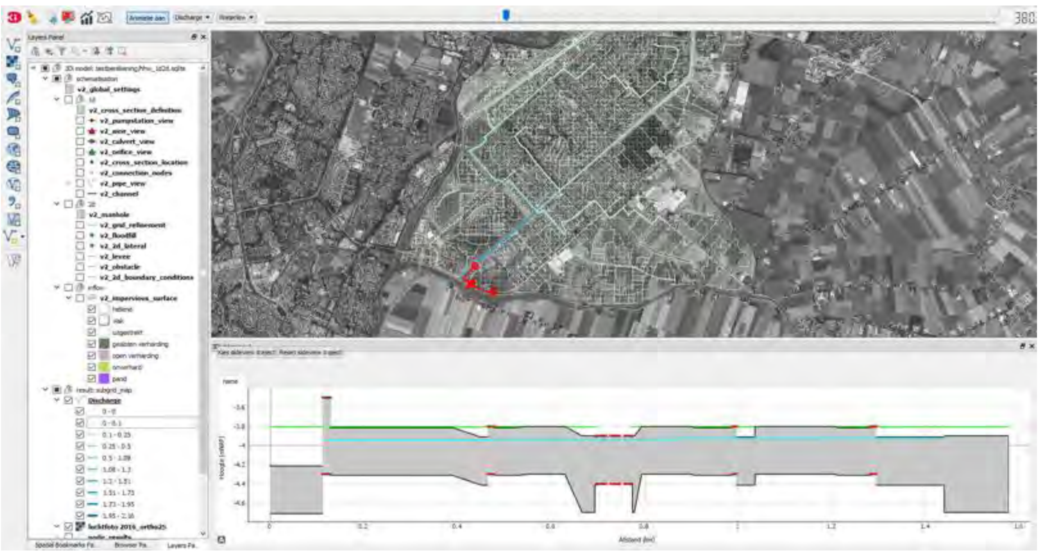

Figure 8: *GIS interface for detailed analyses by the 3Di model user*

The licence model is based on the cloud computing concept. The user buys a runtime bundle similar to a mobile phone bundle. Some users only need a small amount of computation time, whereas large consumers can use virtually unlimited resources.

Communication and interaction

Perhaps the biggest challenge in the development of 3Di was to develop not only a computational model but also a communication tool. In daily practice, model studies are the foundation of many decisions, but the decision makers have no or only little insight into the nuances of the calculations made (Figure 9). The results of most model studies are summarized in a single chart or map. But today's high resolution models offer so much more dynamic information that is highly relevant for informed decision making (Leskens, 2014). In addition, the critical eye of the local expert is of upmost importance for improving models.

Figure 9: *3D visualization of the effects of a levee break*

For a model acting as a communication tool, a special interactive user interface was developed, in addition to the model interface for the specialist. To make results informative to a broad audience, the 1D flow is for example visualized by moving dots, and if a pump starts pumping this is visualized on the map by a spinning pump symbol. Water on land or street also appears as such on the map (Figure 10).

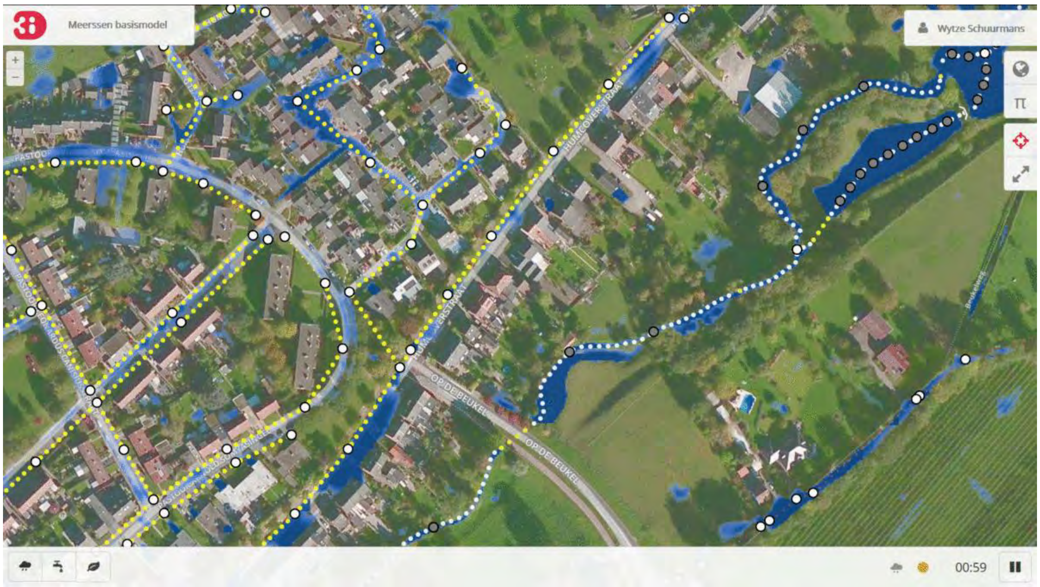

Figure 10: Visualisation of a running calculation presented in the interactive interface. Moving dots reflect the flow velocity and discharge (white = open water, yellow = mixed sewage flow, blue = water on the street)

The visualization is generated live during the actual computation. Advanced ICT-techniques are required to visualize that rapidly and at that level of detail. One of the ‘tricks’ applied is that different zoom levels are incorporated. The resolution of the visualization is adjusted to the resolution of the screen or touch table. The user can breach a levee, place emergency pumps on any location, dig extra water storage or change the rainfall event. And all these interventions can be implemented during the actual computation. These advanced interactive possibilities make it possible to use the model as a ‘serious game’, allowing decision makers to see the impact of disasters and the impact of proposed measures. Making adjustments during a computation is an IT challenge, because all model adjustments must be redirected directly to the computer's memory instead of the input files. Adjustment of the input files will not work in an interactive setting, because the input files are not read again once a simulation is ongoing.

Latest ongoing developments

A model instrument is never finished. A team of software developers is working continuously on the development of 3Di, including improving the documentation and testing. But developments also take place in real time control of structures, an integrated groundwater module, 'thin layer runoff flow', faster post-processing, and many minor improvements of the computational core.

In addition to developments of the computing core, in collaboration with Royal HaskoningDHV, 3Di has been made applicable for use in real time prediction systems. In cooperation with the Dutch Ministry of Public Affairs and Deltares, 3Di has been used for detailed river studies and for climate impact analyses of highways. Deltares has developed a new climate impact “stress test” based on the detailed models that are currently possible (Deltares, 2017). All these innovative and practical applications provide valuable feedback to the developers to make 3Di a better product.

Conclusions

There are already numerous water simulation models, so why develop a new simulation model? 3Di distinguishes itself on two major aspects: it uses a new numerical computing technique; and it can be used as a new way of communication between specialist and end-user (Figure 10). The new computing technology is based on subgrids and allows high-resolution fast and accurate computing in 0d, 1D, 2D in any combination. As a communication tool, 3Di has an interactive interface that works well in workshops and public sessions. After seven years of development, 3Di has become a mature product, which allows modelling specialists to work with decision makers to find optimal solutions in complex urban and rural areas worldwide.

Figure 11: *Analysis of calculation results with area managers on a Touch Table and iPad*

Availability and other information

- **For more information see www.3di.nu. Contact person Joep.Grispen@nelen-schuurmans.nl.**
- **Operating system: 3Di runs under any operating system and the web browsers like Chrome, Firefox, Microsoft Edge and Safari.**
- **License: An user license will be closed from 5000,- per year and is available from Nelen & Schuurmans, Utrecht.**

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