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Benchmarking the latest generation of 2D hydraulic modelling packages

Report – SC120002

Flood and Coastal Erosion Risk Management Research and Development Programme

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Director of Evidence

Executive summary

Two-dimensional (2D) hydraulic flood models are a vital tool in assessing flood risk and the effects of interventions. A wide range of hydraulic modelling tools are available. Scientific and technological progress means that modelling algorithms and tools continue to evolve and improve over time. This report describes the results from a benchmarking exercise assessing the latest generation of 2D hydraulic modelling tools for a variety of purposes in Flood and Coastal Risk Management to support Environment Agency decision making.

A 2009 report on the theoretical background to 2D flood inundation modelling highlighted the benefits of having a standard set of benchmark test cases with which to differentiate between the performance and predictive capability of different types of 2D flood inundation model. The results of an initial benchmarking exercise involving 10 benchmark test cases against which 12 software development organisations tested the performance of a total of 14 2D flood inundation modelling packages were published in 2010. Since then, many of the modelling packages have undergone further development and some new modelling packages have become available.

This report provides an up-to-date picture of the capabilities of the latest generation of 2D hydraulic modelling tools. It includes revised predictions where modelling software has been modified and improved, and results from other modelling packages that either did not participate in the 2010 exercise or have since become available on the market. The original 2010 results are given for those modelling packages where no updates have been provided. The report therefore consolidates all the modelling package simulations into a single volume and thus supersedes the 2010 report (now withdrawn).

The overall objectives of this research are to provide:

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

The report also reviews the fitness-for-purpose of the existing benchmark test cases against the background of changing Environment Agency needs and flood inundation modelling capability.

Modelling packages

The suppliers of 15 flood inundation modelling packages responded to the invitation to participate in the revision exercise, resulting in predictions in this report from a total of 19 packages (15 new or refreshed results plus four from the original report).

The shallow water equations (SWEs) include a mathematical description of the main physical processes that control the movement of flood waves in two spatial dimensions. In the report software packages of this type are referred to as using the ‘full’ equations. There are packages where some of these terms are neglected and the software solves simplified equations. Solving simpler equations requires less computer resource and means simulations will be undertaken in a shorter run time.

ANUGA, Flowroute-*i*™, InfoWorks ICM, ISIS 2D, ISIS 2D GPU, JFLOW+, MIKE FLOOD, SOBEK, TUFLOW, TUFLOW GPU, TUFLOW FV and XPSTORM solve the SWE. Ceasg arrives at its predictions through the application of the same physical processes contained in the SWE and, as a consequence, its predictions are presented alongside those from the SWE-based packages.

The six packages using simplified equations have been grouped in three categories:

1. LISFLOOD-FP and RFSM EDA, which solve a version of the SWEs neglecting the advective acceleration term (referred to as '3-term' models)
2. ISIS Fast Dynamic, which utilises Manning's uniform flow law and UIM which solves the SWE without the acceleration terms (referred to the '2-term' models)
3. ISIS Fast and RFSM Direct, which are based mainly on continuity and topographic connectivity, and therefore predict only a 'final' state of inundation, that is, no variations in time (referred to as '0-term' models)

Conclusions

The packages based on the shallow water equations are appropriate to support decision making across the full range of Environment Agency flood risk management activities. There are two exceptions to this. The first is where the area of application is large (>1000km^2) or a probabilistic approach requiring multiple simulations is required; in such instances, the time taken to run SWE simulations can be prohibitively long for practical application. The second is where the detail of supercritical to subcritical flow transition is required, such as in areas close to a dam or embankment breach. In such cases the numerical scheme used by the software has an influence on the ability of the model to capture the detail of the flow field. The results indicate that packages designed to handle supercritical flows and critical transitions perform better overall in such circumstances.

Water levels and velocities predicted by packages based on the 3-term approach (LISFLOOD-FP, RFSM-EDA) and UIM (a two-term model) are comparable with those predicted by SWE packages. Where their performance is less comparable is in the modelling of rapidly varying flows and in areas where momentum conservation is important, for example, the prediction of water levels and velocities in the complex flow field downstream of a dam failure. These models are also less robust in the prediction of high velocity and supercritical flows, such as those that can be encountered during urban flooding. In such circumstances they often predict oscillating values (particularly noticeable with UIM) and therefore produce higher estimates of peak values than the SWE models. Additionally, the use of RFSM EDA with a coarse spatial resolution (as is done routinely) is not appropriate for predicting flood flow patterns in detail. The comparisons of run times indicate that there may be some savings in computational effort in applying these packages compared with the 'full' SWE packages for the tests reported here (although not with UIM which has considerably longer run times).

The general conclusion regarding the other '2-term' package (ISIS Fast Dynamic) is that it predicts a final inundation extent and the dynamics of flooding similar to the SWE in situations involving very low momentum flow. However, it is not suitable where predictions of inundation velocities are required. The approach has some benefits in terms of computational cost, although this is not fully demonstrated by the current set of benchmark test cases.

The '0 term' flood spreading algorithms (ISIS Fast and RFSM Direct) produced approximate predictions of final inundation distributions, with clear benefits in terms of computational cost compared with the other models. However, their use is limited to some large-scale applications where only final water levels are required and dynamic effects are insignificant.

The benchmark comparisons also highlighted a number of other issues of practical relevance to Environment Agency's flood risk modelling activities.

Firstly, where 1D–2D model linking is used to simulate river to floodplain flood volume exchange, the flood inundation packages participating in this exercise use a variety of methods to link the 1D and 2D simulation domains. This results in significantly different predictions of the volume of water exchanged between the river and the floodplain. Predictions made using 1D river to 2D floodplain linking are therefore unlikely to be consistent between software packages. Further research is required to better understand the significance of this.

Secondly, large differences (up to 100%) in velocity predictions were obtained for high resolution (2m grid) inundation modelling in urban areas where the flood depth is relatively shallow. This suggests that a 2m grid may be too coarse to adequately resolve the underlying topography for this class of inundation and that predictions of velocity will not be consistent between modelling packages when applied to the same problem at grid resolutions greater than 2m. However, it is not currently clear that grid resolutions finer that 2m will improve the quality of velocity predictions. This is because:

- uncertainties in boundary conditions and errors in digital terrain model (DTM) data will also influence predictions to at least the same order as the grid resolution
- a grid resolution finer than 2m will have a significant adverse impact on computational efficiency and the potential to undertake multiple simulations to quantify modelling uncertainties and perform risk analysis

Recommendations for the future

The majority of the benchmark test cases remain fit-for-purpose. However, the following alterations are recommended before a further round of 2D flood modelling package benchmarking.

Tests 1 and 6A should be removed, the specification of the boundary conditions for Test 4 should be improved to avoid misinterpretation, the set-up instructions for Test 7 should be improved. and Tests 8A and 8B should be combined into a single test with consideration given to adding more detail on the storm water drainage system.

Consideration should also be given to including three additional benchmark test cases to account for developments in 2D flood inundation modelling since the original test cases were created. These include the testing of packages developed to utilise graphics processing unit (GPU) technology, developments in simplified methods for uncertainty analysis, and utilisation of the data set now available from the Water Research Laboratory, University of New South Wales, Sydney, Australia.

It is also recommended that a web-based format be adopted to present the results, using an envelope encapsulating the simulations achieved by all packages. Developers could then present their results and obtain instant feedback as to how their package's predictions compare with others in the same class. Were such an approach to be adopted it would essential for developers to complete a methodology disclosure template in which they would be required to make public information on the underlying equations, numerical approaches and assumptions used in their packages.

Acknowledgements

Gratitude is expressed to the following people and organisations for their contribution in generating the model predictions reported here.

Package	Organisation	Name
ANUGA	Geoscience Australia	Miriam Middelman
Ceasg	Amazi	Leigh Parratt
Flowroute-*i*™	Ambiental	David Martin and Justin Butler
InfoWorks ICM	Innovyze	Duncan Kitts, Jonatan Mulet-Marti and Ruth Clarke
ISIS suite	Halcrow (CH2M Hill)	Jon Wicks, Ricardo Santaella and Yong Wang
JFLOW+	JBA Consulting Ltd	Rob Lamb, Amanda Crossley and Neil Hunter
LISFLOOD	University of Bristol	Jeff Neal and Chris Sampson
	Leeds University	Thomas Willis
MIKE FLOOD	DHI	Steve Flood
RFSM	HR Wallingford Ltd	Julien Lhomme, Sam Jamieson and Ben Gouldby
SOBEK	Deltares	Thieu Van Mierlo and Edward Melger
TUFLOW suite	BMT WBM	Bill Syme, Greg Collecutt and Ian Teakle
UIM	University of Exeter	Albert Chen and Slobodan Djorjevic
XPSTORM	Micro Drainage Ltd (XP Solutions)	David Fortune and Netsanet Mebrate

The authors are also grateful to HR Wallingford for suggesting the categorisation approach described in Section 3.3.

Contents

1. Introduction

Two-dimensional (2D) hydraulic flood models are a vital tool in assessing flood risk and the effects of interventions. The models support a variety of practical applications, ranging from flood mapping, wider risk assessment, appraisal of options as well as supporting the design of specific measures such as flood defences.

A wide range of hydraulic modelling tools is available. However, scientific and technological progress means that modelling algorithms and tools continue to evolve and improve over time. This report describes the results from a benchmarking exercise assessing the latest generation of 2D hydraulic modelling tools for a variety of purposes in Flood and Coastal Risk Management (FCRM) to support Environment Agency decision making.

Readers interested in the theoretical aspects of 2D flood inundation modelling are referred to the Environment Agency report, *Desktop review of 2D hydraulic modelling packages* (Néelz and Pender 2009). This also makes recommendations for benchmark test cases to support Environment Agency flood risk management decision making by differentiating between the performance and predictive capability of 2D flood inundation model types.

These recommendations were taken forward in 2010 through the creation of 10 benchmark test cases against which 12 software development organisations tested the performance of a total of 14 2D flood inundation modelling packages. The outcomes and conclusions from this exercise were published in the Environment Agency report, *Benchmarking of 2D hydraulic modelling packages* (Néelz and Pender 2010). Since then, many of the modelling packages applied have undergone further development and some new modelling packages have become available. The purpose of this report is therefore to 'refresh' the previously published results through the inclusion of:

- revised predictions where modelling software has been modified and improved
- results from other modelling packages that either did not participate in the 2010 exercise or have since become available on the market

For modelling packages where no updates have been provided, the original 2010 results are included in the results and conclusions presented in this 'refresh' report. This report consolidates all the modelling package simulations into a single volume and therefore supersedes the 2010 report, which has been withdrawn.

As before, the objectives of this report are to provide:

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

In addition, the report reviews the fitness-for-purpose of the existing benchmark test cases against the background of changing Environment Agency needs and flood inundation modelling capability. Recommendations for future updates of the benchmark test cases are made in Section 5.

The performance of software packages for 2D flood inundation modelling is a function of the suitability of the modelling methodology embodied in the software including:

- the mathematical formulation of the physical processes controlling flood movement across a floodplain

- the numerical method used to solve the mathematical formulation
- the configuration of the numerical grid upon which the numerical solution is applied

It is also a function of the skill and judgement of the modeller in building the model to ensure:

- appropriate representation of boundary conditions (inflows to and outflows from) the modelled domain
- correct representation of problem geometry on the numerical grid upon which the numerical method is applied
- model calibration and choice of model parameters such as boundary roughness and choice of time increment

This report evaluates the former through a quantitative evaluation of modelling packages applied to the 10 benchmark case studies mentioned above. The benchmark test cases are summarised in Table 2.1 and described in detail in Appendix A.

As the purpose of the exercise is to evaluate software performance rather than modeller skill, tests have been tightly specified to limit the extent to which modeller skill influences the predictions made. In tests 7 and 8, however, the practical nature of the test requires a limited amount of judgement to be applied in creating the models. A discussion of the judgements made for each package is present in Appendix C.

2. Benchmarking tests

The range of possible approaches to benchmarking includes comparing hydraulic model predictions with analytical solutions, field data, physical model data and other model predictions of real or hypothetical flood events. The report, *Desktop review of 2D hydraulic modelling packages*, discusses the advantages and disadvantages of each of these approaches (Néelz and Pender 2009). In consultation with the software developers the outline test cases presented there were amended to the eight benchmarking tests reported here. These tests are summarised in Table 2.1 and described in detail in Appendix A.

Table 2.1 Summary of benchmark tests

Test number	Description	Purpose
1	Flooding a disconnected water body	Assess basic capability to simulate flooding of disconnected water bodies on floodplains or coastal areas.
2	Filling of floodplain depressions	Tests capability to predict inundation extent and final flood depth for low momentum flow over complex topographies.
3	Momentum conservation over a small (0.25m) obstruction	Tests capability to simulate flow at relatively low depths over an obstruction with an adverse slope.
4	Speed of flood propagation over an extended floodplain	Tests simulation of speed of propagation of flood wave and the prediction of velocities at the leading edge of the advancing flood.
5	Valley flooding	Tests simulation of major flood inundation at the valley scale.
6A and 6B	Dambreak	Tests simulation of shocks and wake zones close to a failing dam.
7	River to floodplain linking	Evaluates capability to simulate flood volume transfer between rivers and floodplains using 1D to 2D model linking.
8A and 8B	Rainfall and sewer surcharge flood in urban areas	Tests capability to simulate shallow flows in urban areas with inputs from rainfall (8A) and sewer surcharge (8B).

As shown in

Table 2.2, the tests have been designed and specified to evaluate software suitability for Environment Agency needs.

Table 2.2 Mapping of benchmark test case to model type and Environment Agency application

Application		Predictions required	Relevant benchmark test
No.	Name		
1	Large Scale[1] Flood Risk Mapping	Inundation extent	1 and 2
2	Catchment Flood Management Plan	Inundation extent	1, 2 and 7
		Maximum depth	
3	Flood Risk Assessment and detailed flood mapping	Inundation extent	1, 2, 3 and 7
		Maximum depth	
4	Strategic Flood Risk Assessment	Inundation extent	1, 2, 3, 4, 7 and 8
		Maximum depth	
		Maximum velocity	
5	Flood Hazard Mapping	Inundation extent	1, 2 3, 4, 7 and 8
		Maximum depth	
		Maximum velocity	
6	Contingency Planning for Real Time Flood Risk Management	Temporal variation in inundation extent	1, 2 3, 4, 5, 7 and 8
		Temporal variation in depth	
		Temporal variation in velocity	
7	Reservoir Inundation Mapping	Temporal variation in inundation extent	1, 2, 3, 4, 5, and 6
		Temporal variation in depth	
		Temporal variation in velocity	

Notes: [1] Can extend to catchments of thousands of 1000s km^2.

3. Participating software packages

3.1 History of the project

The questionnaire survey outcome presented in *Desktop review of 2D hydraulic modelling packages* (Néelz and Pender 2009) identified TUFLOW, InfoWorks2D, MIKE21 and JFLOW as the 2D packages most commonly applied to Environment Agency problems. The report therefore recommended that these packages be benchmarked against the eight standard test cases introduced in Section 2.

The design of the eight benchmarking cases was finalised at Heriot-Watt University, and an open invitation was issued in 2009 to all developers of 2D flood inundation software applied in the UK. This resulted in the submission of 14 sets of benchmarking test results, obtained at the developers' own cost, which were analysed in Benchmarking of 2D hydraulic modelling packages (Néelz and Pender 2010).

In 2011 a further open invitation was issued, with the intention to update the 2010 benchmarking exercise and expand it to a wider range of software packages. This resulted in the submission of a further 15 sets of benchmarking test results (finalised in 2012).

Of the 2012 submissions, nine superseded submissions made in 2010, either because a new version of a software package had become available (this was the case with InfoWorks, ISIS 2D, MIKE FLOOD, TUFLOW, TUFLOW FV), or because a new software package had been developed and was being promoted by the company in lieu of a now obsolete software package (this was the case with Flowroute-*i*™ replacing Flowroute, JFLOW+ replacing JFLOW GPU, RFSM-EDA replacing RFSM Dynamic, XPSTORM replacing Floodflow). The other six 2012 submissions concerned software packages that are used in this benchmarking exercise for the first time. These are Ceasg, ISIS Fast, ISIS Fast Dynamic, ISIS 2D GPU, LISFLOOD and TUFLOW GPU.

In addition to the 15 submissions from 2012 detailed above, four submissions from 2010 that had not been superseded in 2012 were included as wished by the relevant developers. These are ANUGA, RFSM Direct, SOBEK and UIM. Consequently, the present report considers the test results using a total of 19 software packages,[1] details of which are provided in Table 3.1.

3.2 Participating software packages

Table 3.1 contains a brief summary of the technical attributes of each of the 19 packages as provided by the developers. More detailed technical information (underlying theory, numerical approaches used and so on) is provided in Appendix B as well as miscellaneous comments made by the developers concerning, for example, known model limitations. These should be considered when interpreting the test results. Additional comments specific to each of the eight benchmarking tests provided by the developers are included in the results Sections 4.2 to 4.10. A more in-depth discussion of theoretical and numerical aspects of flood inundation modelling can be found, for example, in *Desktop review of 2D hydraulic modelling packages* (Néelz and Pender 2009).

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[1]Two TUFLOW FV submissions, first order and second order, are counted as one.

Table 3.1 Summary of software packages [1]

(1) Name	(2) Developer	(3) Version	(4) Underlying equations	(5) Numerical scheme(s)	(6) Gridding	(7) Shock capturing	(8) 1D–2D linkages
ANUGA (2009)	Geoscience Australia and Australian National University	1.1beta_7501	Shallow water equations (SWEs)	Finite volume explicit	Flexible	Yes	No
Ceasg	Ceasg Flow Modelling (Amazi Consulting Ltd)	1.12	Conservation of mass and momentum (same physical processes as those modelled by the SWEs)	Cellular automaton	Flexible (square grid used here)	No	Any, through the Open MI standard (no own 1D capabilities)
Flowroute-*i*™	Ambiental Ltd	3.2.0	Shallow water equations	Finite volume explicit	Square (to be confirmed)	No [2]	No
InfoWorks ICM	Innovyze	2.5.2	Shallow water equations	Finite volume explicit	Flexible	Yes (Roe's Riemann solver)	Yes Integrated 1D–2D package
ISIS 2D	Halcrow (a CH2M Hill company)	3.6	Shallow water equations	Finite differences (implicit ADI or explicit TVD)	Square	Yes (in the TVD version only)	Yes Integrated 1D–2D package Lateral exchange 1D river to 2D floodplains.
ISIS 2D GPU	Halcrow SINTEF (Norway)	1.17	Shallow water equations	Finite volume explicit (Kurganov–Petrova)	Square	Yes (TVD)	Not yet implemented

(1) Name	(2) Developer	(3) Version	(4) Underlying equations	(5) Numerical scheme(s)	(6) Gridding	(7) Shock capturing	(8) 1D–2D linkages
ISIS Fast	Halcrow		Volume spreading algorithm. Usually predicts only a 'final' state of inundation. See Appendix B.	No time discretisation	Space divided in 'depressions'	No	Yes laterally (open channel, pipes, structures)
ISIS Fast Dynamic	Halcrow	3.6	Similar to ISIS Fast + Manning's equation between depressions		Space divided in 'depressions'	No	Yes laterally (open channel, pipes, structures) Under development
JFLOW +	JBA Consulting	2.0	Shallow water equations	Finite volume explicit	? (square grid used here)	Yes (Roe's Riemann solver)	No
LISFLOOD FP	University of Bristol	5.5.2	1D shallow water equations, without the convective acceleration terms, on a regular 2D grid [3]	Finite difference explicit	Square (same resolution as raster DTM)	No	Yes, coupled to a diffusive wave 1D river model
MIKE FLOOD [4]	DHI	2012	Shallow water equations	Finite difference (ADI)	Square	Accommodates supercritical flows [5]	Yes, fully integrated 1D–D packages (pipes, rivers, floodplains , structures and so on)
RFSM (Direct) (2009)	HR Wallingford	3.5.4	Volume spreading algorithm. Predicts a 'final' state. See Appendix B.	No time discretisation	Irregular polygons built around topographic features	No	No

(1) Name	(2) Developer	(3) Version	(4) Underlying equations	(5) Numerical scheme(s)	(6) Gridding	(7) Shock capturing	(8) 1D–2D linkages
RFSM EDA	HR Wallingford and Heriot-Watt University	1.2	'Inertial' approximation to SWEs, ignoring the convective inertia term	Mixed finite differences / finite volume (explicit)	Irregular polygons built around topographic features	No	No
SOBEK (2009)	Deltares	2.13	Shallow water equations	Finite difference (implicit – staggered grid)	Square	Yes	Yes Integrated 1D–2D package [6]
TUFLOW	BMT WBM	2012-05-AA	Shallow water equations	Finite difference implicit (ADI)	Square	Accommodates supercritical flows	Yes. Fully integrated 1D–2D package (pipes, culverts, rivers and so on)
TUFLOW GPU	BMT WBM	2012-05-AA	Shallow water equations	Finite volume	Square	Yes	Not yet available
TUFLOW FV	BMT WBM	2012.000b	Shallow water equations	Finite volume (first and second order schemes tested)	Flexible	Yes	Under development
UIM (2009)	University of Exeter	2009–2012 (2009–2010 in Test 8)	Shallow water equations without the acceleration terms	Finite difference (explicit)	Square	No	Yes Integrated with 1D sewer network model (SIPSON)

(1) Name	(2) Developer	(3) Version	(4) Underlying equations	(5) Numerical scheme(s)	(6) Gridding	(7) Shock capturing	(8) 1D–2D linkages
XPSTORM	Micro Drainage Ltd	2010-10-AB-iDP-w32	Shallow water equations	Finite difference implicit (ADI)	Square	No (but switches btw sub- and supercritical)	Yes Fully integrated 1D–2D package(pipes, culverts, rivers and so on)

Notes: [1]The information provided is understood as follows: (1) software name; (2) name of organisation that develops the software; (3) software version used to carry out the benchmarking tests, with (2009) shown in the four cases where results from the first benchmarking exercise are re-published here without any update; (4) the (2D) equations of surface flood flow on which the software relies (most often the shallow water equations); (5) the type of numerical scheme used to solve the equations in column (4) – when the package relies on more than one scheme, only the one used in the testing is indicated; (6) the type of grid used to discretise space; (7) whether or not the software package is able to capture hydrodynamic shocks; and (8) whether or not the 2D inundation modelling software can be linked to components modelled in 1D, such as rivers, pipes, culverts and so on, whether externally (through for example the Open-MI), or internally (when 1D components can be built and connected to the 2D grid within the software package). In relation to the information provided in column (8), the designation used for some of the participating packages refers to an integrated 1D–2D package rather than to a 2D solver only (MIKE, FLOOD, ISIS 2D, InfoWorks ICM, TUFLOW and so on).

[2] ‘Implementation of a computationally-efficient shock capturing routine is included within our development pathway for 2013’.

[3] For Test8A: the same, although with a simple constant velocity routing method when flow depth between cells is below a user specified threshold.

[4] MIKE FLOOD is also available in a finite volume version, utilising an unstructured flexible mesh (triangular and/or quadrangular elements), with shock capturing capabilities (by way of a Riemann solver with a TVD slope limiter) and full 1D–2D connectivity.

[5] The robust numerical scheme can accommodate high Froude numbers and supercritical flows, and is considered to perform well in comparison with finite volume codes.

[6] Allows for both vertical and horizontal links between 2D overland flow and 1D flow.

ADI = alternating direction implicit; DTM = digital terrain model; TVD = total variation diminishing.

3.3 Model categories

The majority of software packages considered in this study (Table 3.1) solve the shallow water equations (SWEs), which are considered to provide a 'full' mathematical representation of the physical processes controlling floodplain inundation at the scale of interest to the Environment Agency. These equations involve at least four terms (convective acceleration, pressure, bottom slope and friction slope) and it is generally accepted (see Néelz and Pender 2009) that any further terms which may be included in the SWE (such as turbulence, Coriolis and so on) can be neglected in almost all practical applications of the SWEs to UK flood studies. Sub-grid scale turbulence may become an important term in deeper, larger rivers that are more typical of overseas countries such as Australia or the USA, or in UK tidal estuaries.

However, there are instances when software solving simpler equations may be appropriate. These equations are usually derived from the full shallow water equations, although with some of the terms omitted. Some of the software packages considered here rely on such simplified formulations of the SWE, involving not four but three or even just two terms in the SWE.

Consequently the models participating in this benchmarking exercise are categorised based on the number of terms of the shallow water equations considered (Table 3.2). In addition, this report considers RFSM Direct and ISIS Fast, which are volume-spreading algorithms which effectively only consider continuity and topographic connectivity, and predict only a 'final' state of inundation (see Appendix B for more details). These two models are not based in any way on the shallow water equations and are therefore referred to as the '0 term' models.

Table 3.2 Categorisation of models based on number of SWE terms considered

Category	SWE terms	Packages
Full SWE models	Convective acceleration, pressure, bottom slope, friction slope	ANUGA
		Flowroute-*i*™
		InfoWorks ICM
		ISIS 2D and ISIS 2D GPU
		JFLOW +
		MIKE FLOOD
		SOBEK
		TUFLOW, TUFLOW GPU and TUFLOW FV
		XPSTORM
'3-term' models	Pressure, bottom slope, friction slope	LISFLOOD-FP
		RFSM EDA
'2-term' models	Bottom slope, friction slope	ISIS Fast Dynamic
		UIM
'0-term' models	N/A	RFSM Direct
		ISIS Fast

The terminology introduced above is used extensively in the interpretation of model results in Section 4.

As mentioned in Table 3.2, Ceasg is based on the same conservation laws as those from which the shallow water equations were derived. It therefore considers the same physical processes as the full SWEs, and, for this reason, tests results obtained using Ceasg are presented alongside those obtained using the 'Full SWE models' category, despite not being based on the SWEs themselves (see also Appendix B.2).

3.4 Hardware specification and multi-processing

As part of their test results submission, participants were invited to provide details on the 'minimum recommended hardware specification' for their software, on the hardware used to carry out the testing, and on multi-processing aspects related to the software (Table 3.3). 'Multi-processing' refers here to parallelised coding and is relevant when considering the run times reported in Section 4.11.

Table 3.3 Hardware specification and multi-processing

Name	Minimum recommended hardware specification	Hardware specification used	Multi-processing
ANUGA (2009)	Windows or Linux PC RAM: 512MB	Intel Mobile Core 2 Duo T7500 (Merom) 2.2GHz RAM 2048MB (DDR2)	No
Ceasg	Cores: 1 RAM: 2GB Windows XP / Linux CPU: 32-bit or 64-bit Graphics card: NVIDIA Fermi GPU	CAD2 WS desktop PC Cores: 4 RAM: 4GB Windows XP CPU: 64-bit Graphics card: NVIDIA Geforce GTX 570	Fully heterogeneous parallel code, which can be used on GPU, multi-core CPU, and GPU + multi-core CPU (that is, domain decomposition across processors on a host), which can be run on one or more machines in a cluster.
Flowroute-*i*™	Cores: 1 RAM: 1GB Windows XP CPU: 32-bit	Intel/ASUS Intel Core i7-950 (4Ghz) Cores: 4 RAM: 6GB Windows 7 CPU: 64-bit Graphics card: Nvidia GeForce 470	Parallel code A four-core simulation will run in 30% of the run time of a one-core simulation.

InfoWorks ICM	Intel Core2Duo or AMD X2 Athlon processor RAM: 1GB (for best performance use latest Intel Core2Quad with at least 4Gb of RAM)	2 × Intel® Xeon™ E5645 2.4 GHz processor Cores: 12 RAM: 24GB (6 × 4GB) Nvidia Tesla C2050 GPU Processor, 3GB.	Parallel code Number of CPU cores irrelevant in mainly 2D simulations. 2D computations highly parallelised by default, on the GPU. The 448 cores of the Nvidia Tesla C2050 are all used.
ISIS 2D	Intel Pentium 4 or equivalent Cores: 1 RAM: 1GB Windows XP CPU: 32-bit Graphics card: Intel Graphic Accelerator 845	DELL Precision WorkStation T3500 Cores: 4 – Intel Xeon W3530 @ 2.8Ghz RAM: 12GB Windows XP CPU: 64-bit Graphics card: NVIDIA GeForce GTX 560	Not parallelised
ISIS 2D GPU	As for ISIS 2D, plus Graphics card: NVIDIA chipset with CUDA capability	As for ISIS 2D, except graphics card NVIDIA GeForce GTX 580 (instead of 560)	Highly parallelised solution technique which can be 10× faster than solving the same equations on standard CPUs.
ISIS Fast	As for ISIS 2D	As for ISIS 2D	Not parallelised
ISIS Fast Dynamic	As for ISIS 2D	As for ISIS 2D	Not parallelised
JFLOW +	Cores: 1 RAM: 1GB Windows XP or later CPU: 32-bit and 64-bit Graphics card: any NVIDIA card supporting Cuda	Cyberpower Desktop PC Cores: 4 RAM: 3.0GB Windows XP CPU: 32-bit Graphics card: NVIDIA GeForce GTX 285	Parallelised on the GPU

LISFLOOD-FP	Cores:1 RAM: 500MB Operating system: any CPU processing: any	Clustervision / IBM Cluster Intel Xeon 2.8 GHz E5440 Cores: 8 (4000 with MPI) RAM: 16GB Linux CPU: 64-bit Graphics card: No	Yes
MIKE FLOOD	Processor type: Intel or AMD Speed: 2.0GHz RAM: 2GB	Lenovo T520 8 core, Intel Core i7-2670QM CPU 2.2GHz RQ: 8GB CPU: 64-bit	CPU parallelised (Open MP) [1]
RFSM (Direct) (2009)	No specific needs – a standard recent computer	Intel Dual Xeon 2 cores 3GHz RAM 2GB	Not parallelised
RFSM EDA	Cores: 1 RAM: 1.5GB Windows XP CPU: 32-bit	Dell Workstation Cores: 4 RAM: 8 Windows XP CPU: 64-bit	Not parallelised.
SOBEK (2009)	Processor type: Pentium or compatible Processor speed: 1GHz RAM: minimum 500MB, recommended 2GB	Intel i7 8 core CPU 2.66GHz	Not parallelised

TUFLOW	Cores: 1 RAM: 2GB Any Windows operating system/S, but Windows 2000 onwards recommended CPU: 32 or 64-bit	Dell Intel Core i7-2600 3.4GHz 4 CPU cores RAM: 16GB Windows 7 CPU: 64-bit Graphics card: ATI Radeon HD 5450	Not parallelised
TUFLOW GPU	As for TUFLOW, plus graphics card (at present only functional for later NVidia GPUs)	Dell Intel Xeon X5355 2.66GHz 8 CPU cores RAM: 8GB Windows 7 CPU: 64-bit Graphics card: NVidia GeoForce 680	Parallelised on the GPU
TUFLOW FV	As for TUFLOW TUFLOW FV is parallelised and a simulation will run faster if more than one core is available. TUFLOW FV is compiled for Linux, but not yet commercially available under Linux.	Dell Intel Xeon X5690 3.47GHz Desktop 12 CPU cores RAM: 24GB Windows 7 CPU: 64-bit Graphics card: NVidia Quadro FX3800	Parallelised on the CPU (for example, a simulation on eight cores will run typically five times faster)

UIM (2009)	Desktop PC	Tests 1, 3, 8B: Intel Core™ 2 Duo CPU T7800, 2.60GHz, RAM: 3GB Tests 2, 4, 5, 8A: Dual Quad-core 2.83GHz Intel Xeon E5440 Harpertown node, RAM 16GB	Not parallelised
XPSTORM	RAM: 1GB Windows CPU: 1GHz	Intel Core i7 (Quad Core) RAM: 6GB CPU: 1.73GHz	Not parallelised

Notes: [1] See Appendix B for additional information.

4. Outcome of the benchmarking exercise

4.1 Introduction

This section contains a summary of the predictions from each package for the eight benchmarking tests discussed in Section 2 and presented in detail in Appendix A.

4.1.1 Participation in tests

For various reasons participants did not carry out certain tests. This is detailed in Table 4.1.

Table 4.1 Summary of participation in benchmarking exercise (indicated by +), with reasons (as provided by developers) for not undertaking individual tests [1]

Software	Test number								
	1	**2**	**3**	**4**	**5**	**6A**	**6B**	**7**	**8A**	**8B**
ANUGA	+	+	+	+	+	+	+	(2) or (5)	(2)	(2) or (6)
Ceasg	+	+	+	+	+	+	+	(7)	+	(7)
Flowroute-*i*™	+	+	+	+	+	(3)	(3)	(5)	+	(6)
InfoWorks ICM	+	+	+	+	+	+	+	+	+	+
ISIS 2D [2]	+	+	+	+	+	+	+	+	+	+
	ADI	ADI	TVD	ADI	ADI	TVD	TVD	ADI	ADI	ADI
ISIS Fast	(1)	(3)	(3)	(3)	+	(3)	(3)	+	+	+
ISIS Fast Dynamic	+	+	(3)	(3)	(3)	(3)	(3)	(3)	+	+
ISIS 2D GPU	+	+	+	+	+	+	+	(5)	+	(6)
JFLOW+	+	+	+	+	+	+	+	(5)	+	(6)
LISFLOOD	+	+	(3)	+	+	(3)	(3)	(2)	+	(6)
MIKE FLOOD	+	+	+	+	+	+	+	+	+	+
RFSM Direct	(1)	+	(3)	(3)	+	(1)(3)	(1)(3)	(5)	+	(6)
RFSM-EDA	+	+	(3)	+	+	(3)	(3)	(5)	+	(6)
SOBEK	+	+	+	+	+	+	+	+	+	+
TUFLOW	+	+	+	+	+	+	+	+	+	+
TUFLOW GPU	+	+	+	+	+	+	+	(5)	+	(6)
TUFLOW FV	+	+	+	+	+	+	+	(5)	+	(6)
UIM	+	+	(3)	+	+	(3)	(3)	(5)	+	+

Software	Test number								
	1	2	3	4	5	6A	6B	7	8A	8B
XPSTORM	+	+	+	+	+	+	+	+	+	+

Notes: [1] Reasons:

(1): Type of boundary or initial condition not supported.

(2): Resources were not available to undertake this test in the required time frame.

(3): Model unlikely to produce useful results. Model not appropriate or not appropriate yet.

(4): Scale of test too small for software.

(5): Linked 1D River + 2D Floodplain modelling not supported (or in development)

(6): Linked 1D Pipe + 2D Floodplain modelling not supported (or in development)

(7): 'Although linkage with other software packages is supported (Open-MI), the software package does not do 1D, so results are not possible with the software package alone.'

[2] ADI / TVD: version of ISIS 2D used.

Decisions to not run certain tests, and the conclusions drawn in this report, are based on the current capabilities of the packages participating in the benchmarking exercise. NB Future releases of the packages may include the ability to run tests that have not yet been run.

RFSM Direct and ISIS Fast are simplified models that do not output any time variations or any velocity predictions. Velocities predicted by ISIS Fast Dynamic are not presented in this report as they are considered to be 'not sensible for these types of test due to the simplicity of the routing mechanism' (as indicated by Halcrow).

Results from TUFLOW FV were provided with two different numerical approaches (first order and second- order discretisation).

4.1.2 Structure and content of results sections

Model results from Tests 1 to 8B are presented in detail in Sections 4.2 to 4.10. Each of these sections follows the same format starting with a brief introduction reminding the reader of the main features of the test, its purpose and expected outcomes. A representative selection of results is then presented, first in the form of comparative plots of time series, followed wherever appropriate by cross-section and/or contour plots constructed using the results provided by participants in 2D grid format. A subsection is then devoted to a summary of observations that can be made from the results presented and to their interpretation. Use is made in this of the categorisation introduced in Section 3.3.

A summary table is then presented containing information on the model run as required by the test specification (hardware, time-stepping, grid resolution, run times and so on), followed by any relevant information provided by the participants concerning each test in particular. Each section ends with a short paragraph summarising the main conclusions that can be drawn from the tests.

4.2 Test 1: Flooding a disconnect water body

4.2.1 Introduction

The test (see Appendix A.1 for details) consists of a 100m wide, 700m long domain with a longitudinal profile as illustrated in Figure 4.1. A water level boundary condition (Figure 4.2) is applied at the left-hand end of the domain, with a peak level of 10.35m maintained for sufficiently long for the depression on the right-hand side to fill up to a level of 10.35m. The level is then lowered to 9.7m at the boundary.

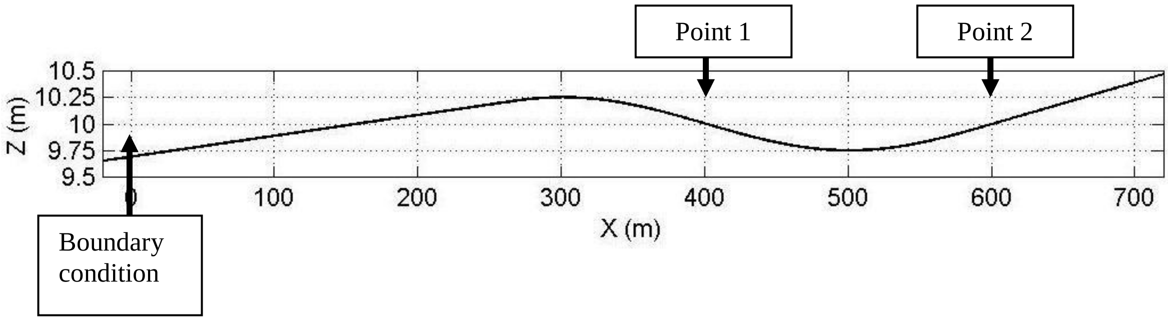


Figure 4.1 Profile of digital elevation model (DEM) used in Test 1

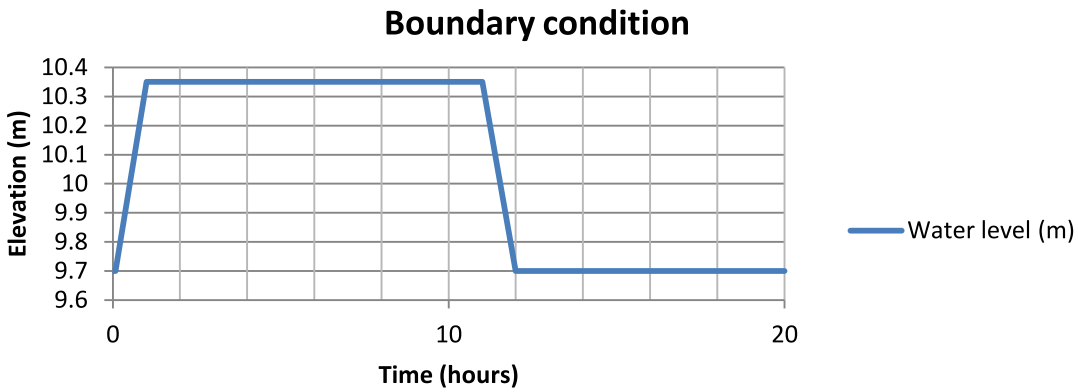


Figure 4.2 Boundary condition applied in Test 1

The objective of the test is to assess basic capabilities such as handling disconnected water bodies, and the wetting and drying of floodplains. Expected outcomes are as follows:

- peak level of ~10.35m at points 1 and 2
- final level of ~10.25m at points 1 and 2

4.2.2 Results: water levels

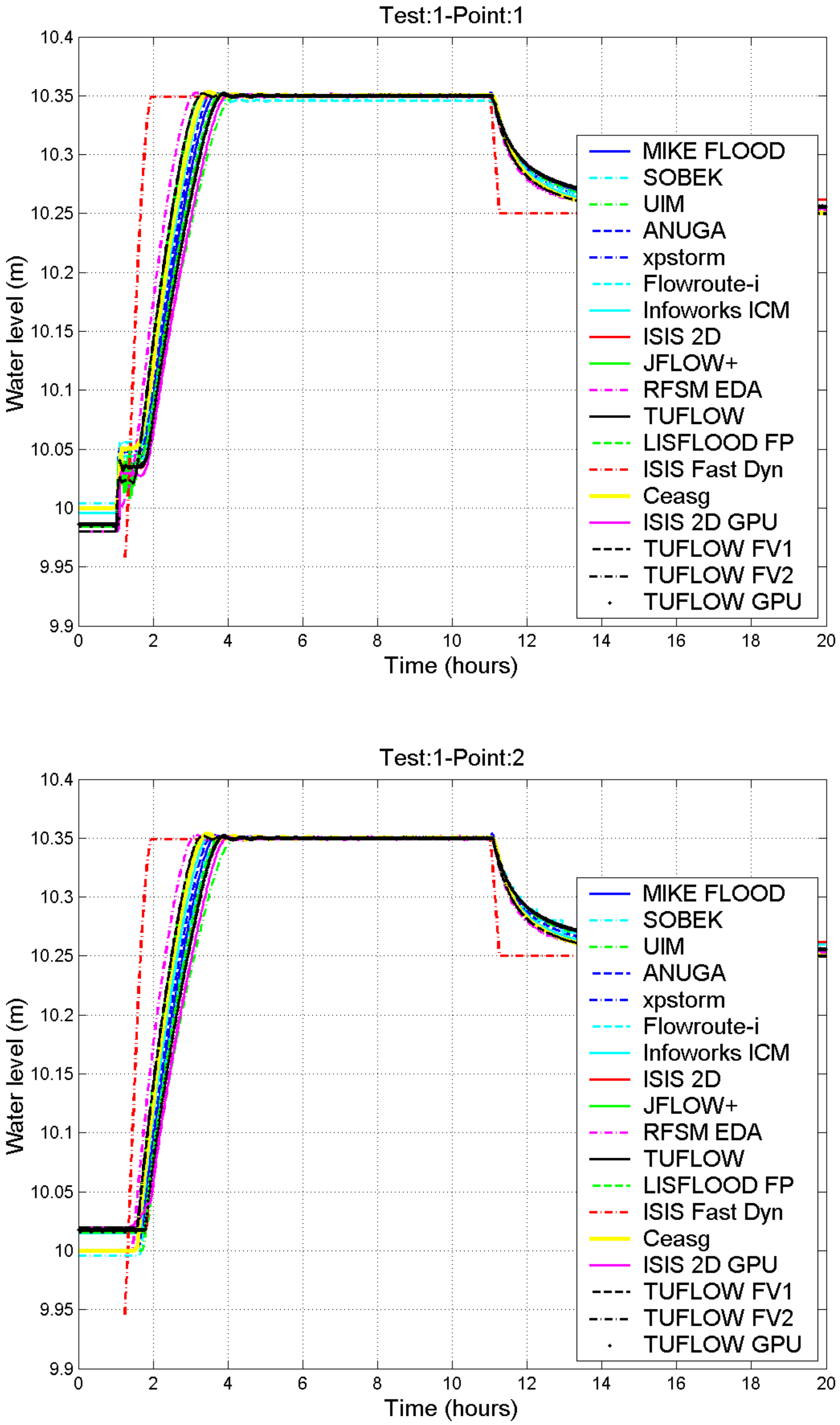


Figure 4.3 Results from Test 1

The following observations can be made from Figure 4.3.

- All models except ISIS Fast Dynamic and RFSM EDA predicted an initial sheet flow at point 1 (depth up to ~5cm), starting at t ≈ 1h and lasting for ~45min until the water level in the pond reached the ground elevation of the two output points.
- The water level difference between point 1 and point 2 (located 200m from each other) was negligible (to within a few mm) for all models after t ≈ 2h.
- The rate of water level rise in the pond, mainly between t ≈ 2h and t ≈ 4h was broadly the same between models except in the case of ISIS Fast Dynamic which predicted a much quicker level rise. (This can be verified by comparing the computed water level curves with the boundary condition in Figure 4.2 which shows that the levels predicted by ISIS Fast Dynamic followed variations in the boundary condition with negligible time delay).
- All models predict a final level elevation of ~10.25m at both points, in accordance with expectations. Discrepancies of up to +0.01m compared with this expected value may be due to the choice of dry/wet threshold depth value.

4.2.3 Miscellaneous model parameters

Table 4.2 Miscellaneous model parameters for Test 1

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 10m or 700 elements)	(5) Time-stepping	(6) 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
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+	2.0	Yes – GPU	10m	Adaptive Average 2.12s	28s
LISFLOOD-FP	5.5.2	Yes	10m	Adaptive	1.8s
MIKE FLOOD	2012	Yes – 8 CPU cores	10m	20s	1.9s
RFSM EDA	1.2	No	18 elements [1]	Adaptive (7–9s)	1.9s
SOBEK	2.13	No	10m	15s	17s
TUFLOW	2012-05-AA single precision	No	10m	Adaptive (15–60s)	2.1s

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 10m or 700 elements)	(5) Time-stepping	(6) Run time
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	10m	Adaptive (1.7–2.1s)	15s [2]
TUFLOW FV [3]	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

Notes: [1] See Appendix B.

[2] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[3] Run times: first order solution (second order solution)

Other information provided

ISIS 2D: 'Dry depth parameter set as 0.01m which gives sense to the final water elevation being 0.01m above the crest'.

ISIS GPU: The simulation time can be seen to be approximately 15× slower than that of ISIS 2D. The comparatively slow performance is due to underutilisation of the GPU in small models such as the present one. The full potential of the GPU is realised in larger models.

TUFLOW: Enhancements in the 2012-05-AA release mean the model can be run on larger time steps (than in the 2010 report), with or without adaptive time-stepping, and with no significant mass error (-0.6% in 2010 vs. 0.0% in 2012).

TUFLOW GPU: Gives near identical results to TUFLOW.

TUFLOW FV: Further developments to the second order solution have produced a quicker response from that in the 2010 report.'

4.2.4 Conclusions from Test 1

All the packages participating in Test 1 demonstrated the basic ability to correctly predict the final state of inundation in a case involving the filling of a depression and subsequent dewatering, resulting in a horizontal water surface in the depression, at the elevation of the lowest point separating the depression from the origin of the flooding.

4.3 Test 2: Filling of floodplain depressions

4.3.1 Introduction

The test (see Appendix A.2 for details) consists of a 2000m × 2000m domain with a 'flattened egg box' shaped topography as illustrated in Figure 4.4. An inflow hydrograph boundary condition with a peak flow of 20m^3/s and time base of ~85min is applied at the top left corner of the domain.

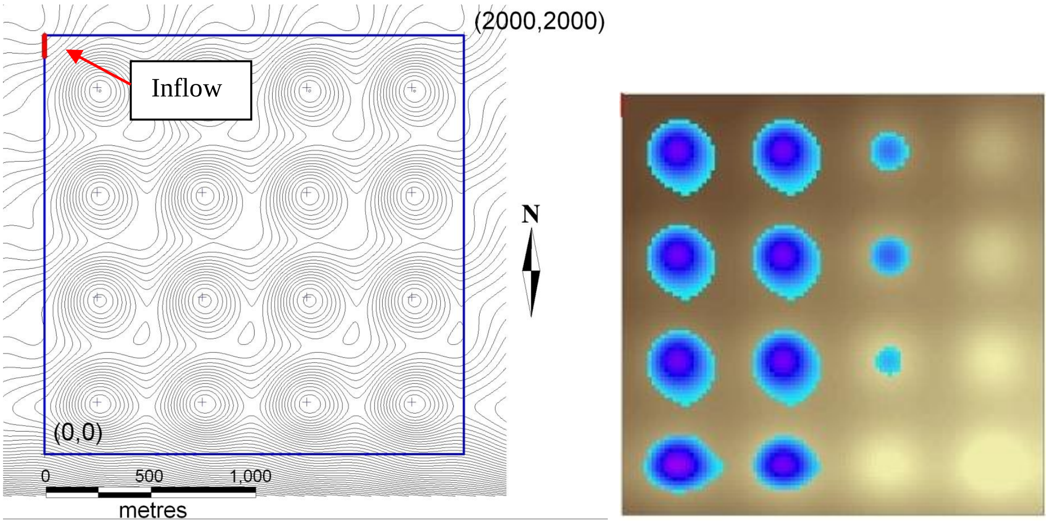


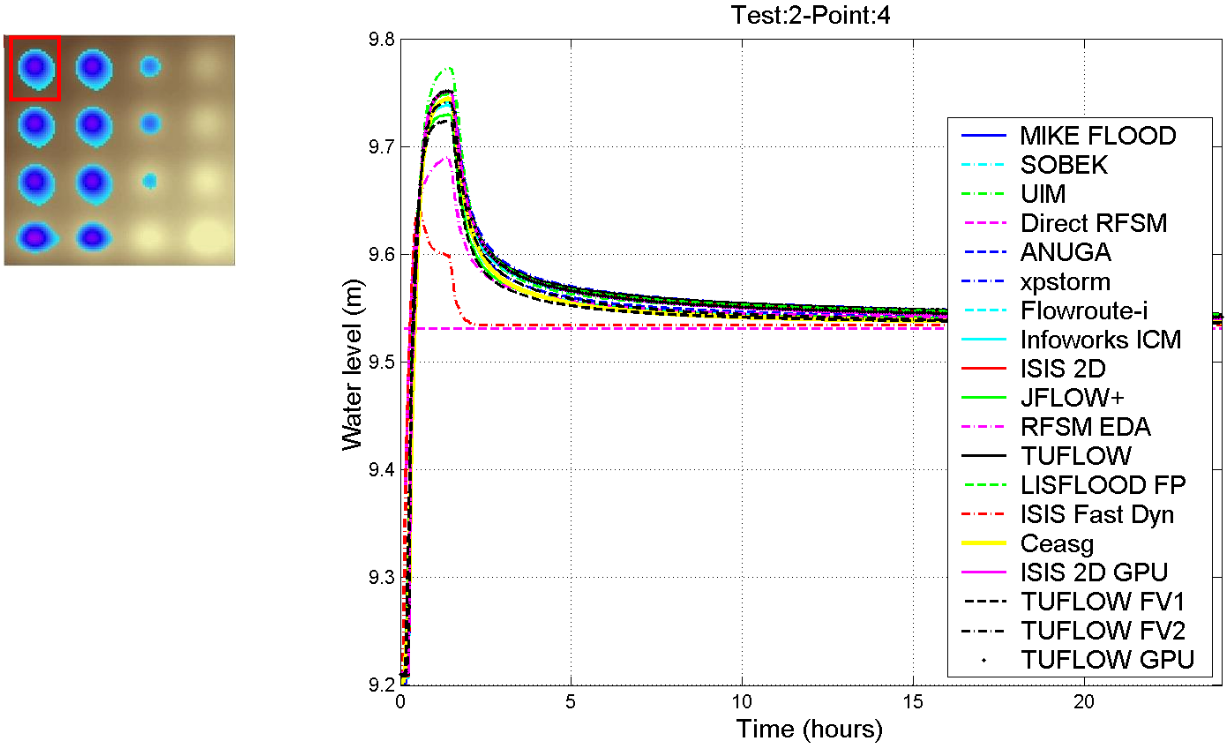
Figure 4.4 Left: map of the DEM showing the location of the inflow boundary condition, ground elevation contour lines every 0.05m and output point locations (+ signs). Right: final inundation predicted by most models.

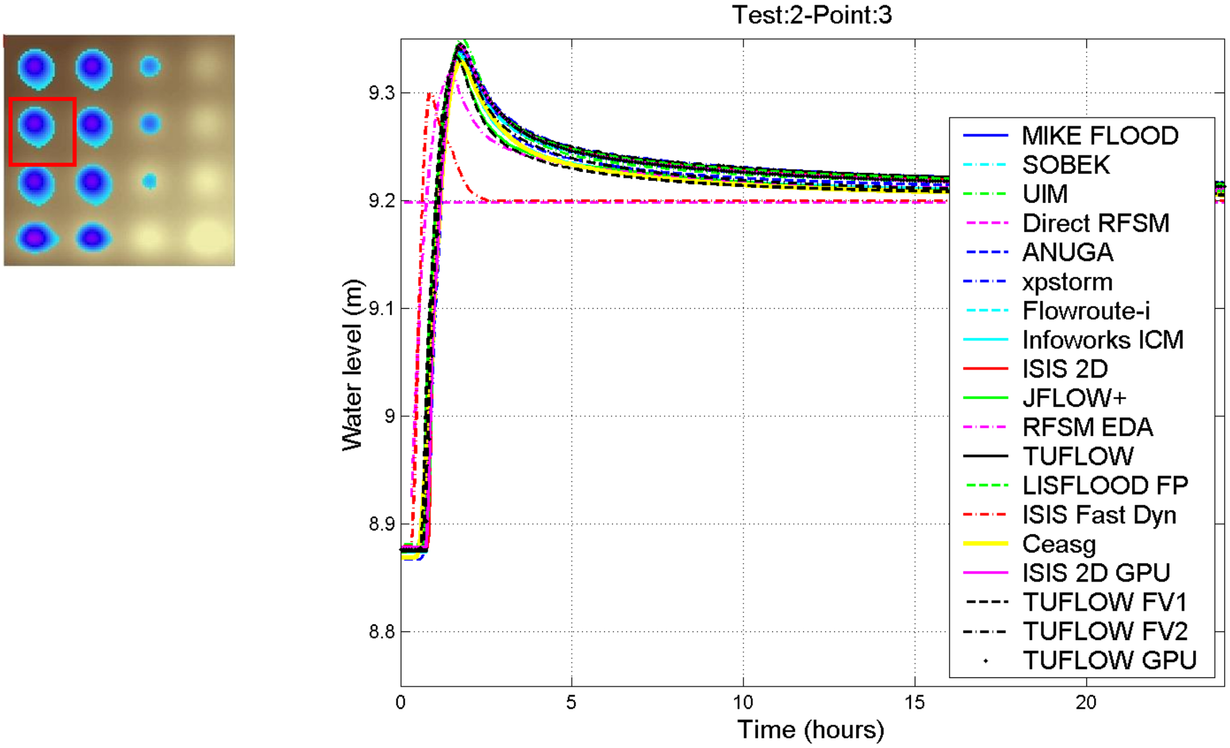
The objective of the test is to assess the package's ability to handle disconnected water bodies, wetting and drying of floodplains, and to predict the inundation extent due to momentum flooding on a complex topography, with an emphasis on the final distribution of flood water rather than peak levels.

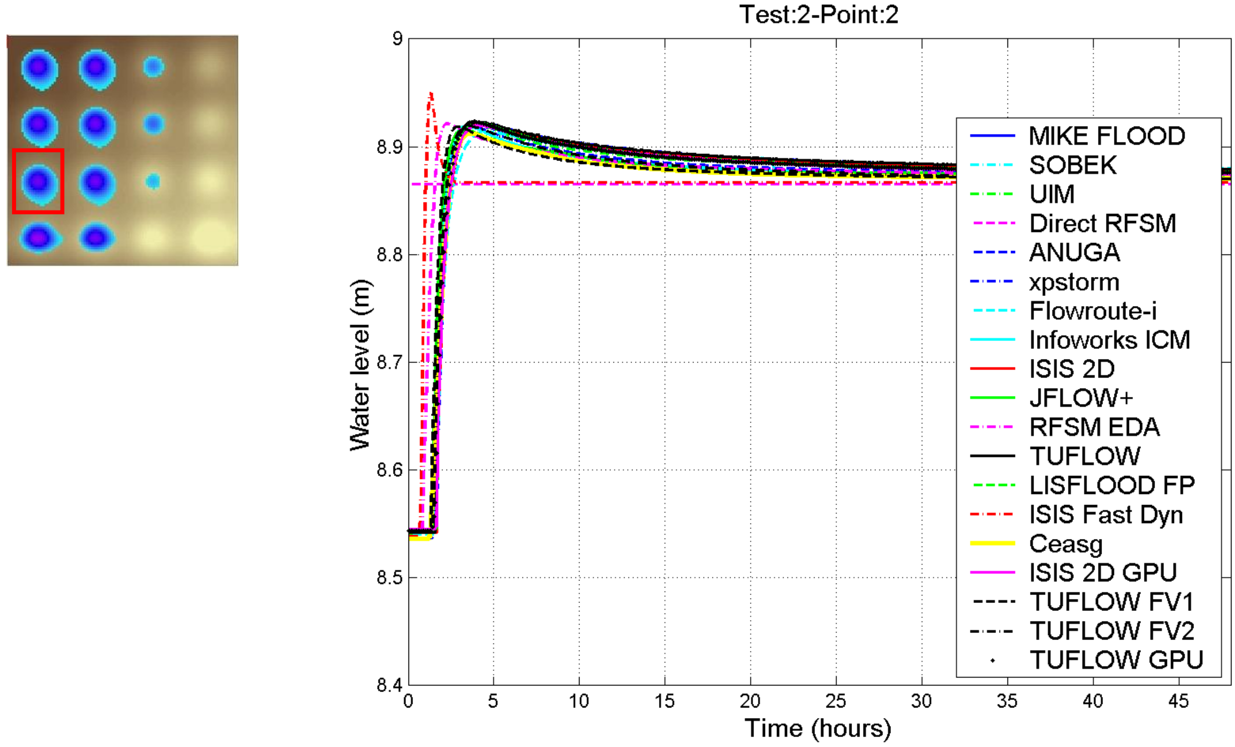
4.3.2 Results: water levels

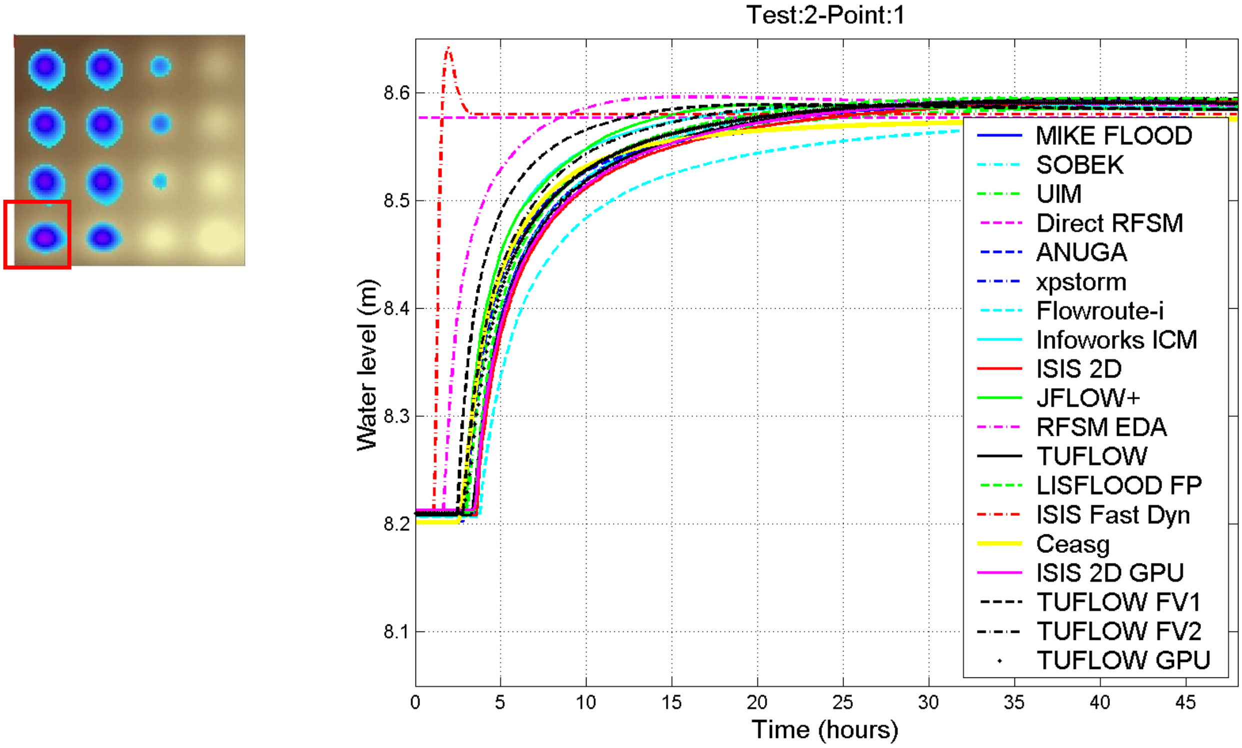
Test 2 specified 16 output points 2, located at the centres of the 16 depressions. For the purpose of result comparison the depressions are numbered 1 to 16 in columns starting at the bottom left in Figure 4.4. The elements of Figure 4.5 represent time series of water levels in the depressions as illustrated on the plan sketches accompanying all the graphs.

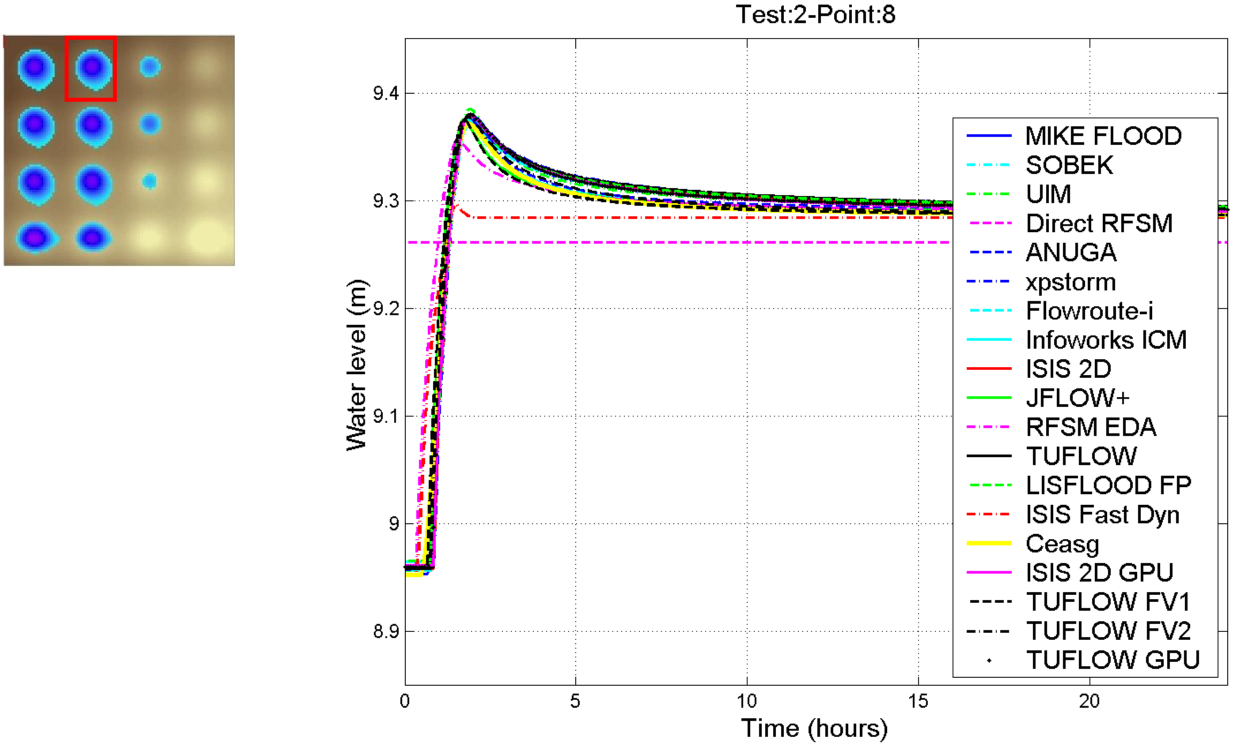
NB Direct RFSM computes a 'final' water level, represented as a horizontal line spanning the entire time domain.


Test:2-Point:4
Water level (m)
Time (hours)
9.8
9.7
9.6
9.5
9.4
9.3
9.2
0
5
10
15
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

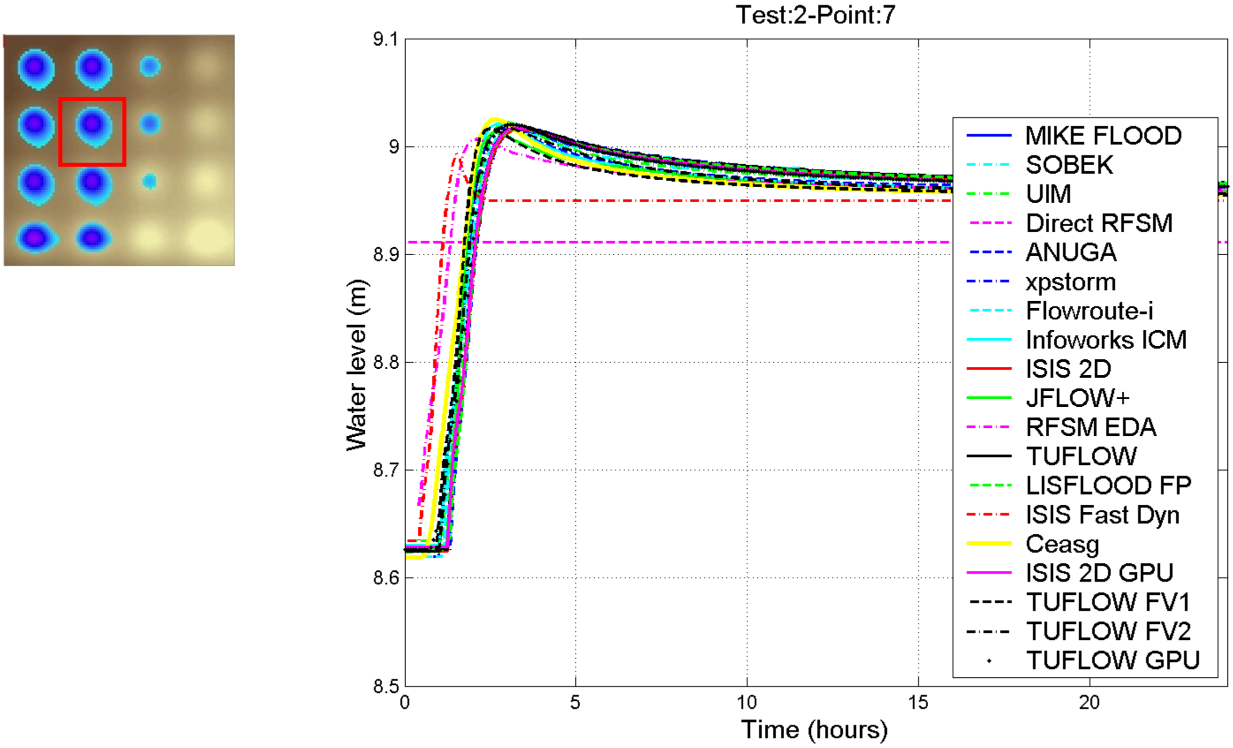

Test:2-Point:3
Water level (m)
Time (hours)
9.3
9.2
9.1
9
8.9
8.8
0
5
10
15
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU


Test:2-Point:2
Water level (m)
9
8.9
8.8
8.7
8.6
8.5
8.4
0
5
10
15
20
25
30
35
40
45
Time (hours)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

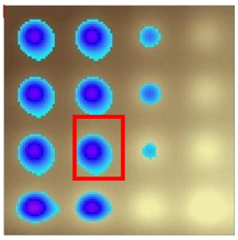

Test:2-Point:1
Water level (m)
8.6
8.5
8.4
8.3
8.2
8.1
0
5
10
15
20
25
30
35
40
45
Time (hours)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

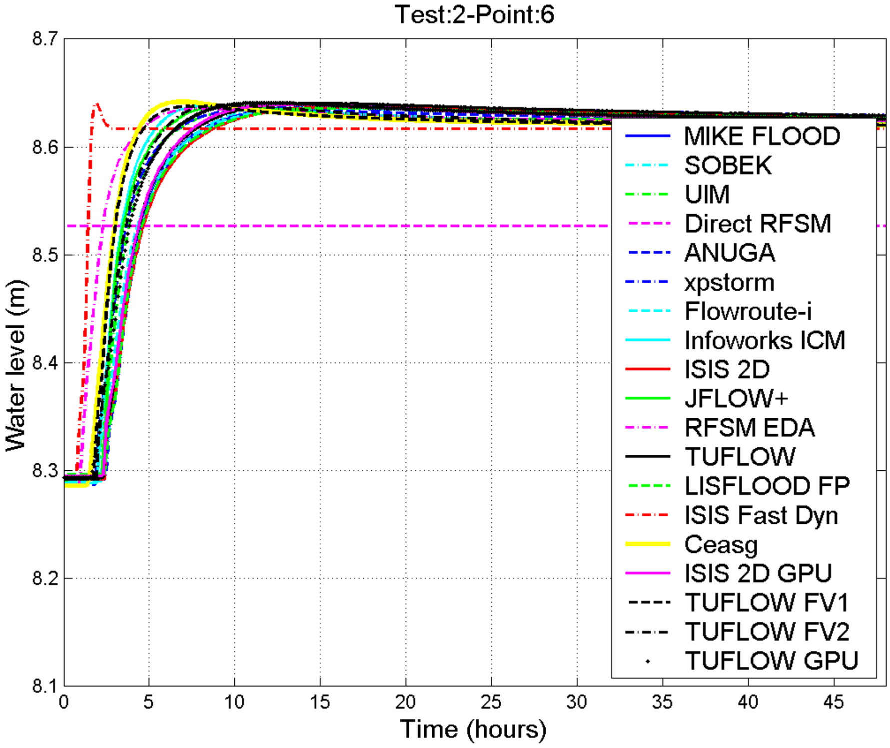


Test:2-Point:8
Water level (m)
Time (hours)
9.4
9.3
9.2
9.1
9
8.9
0
5
10
15
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

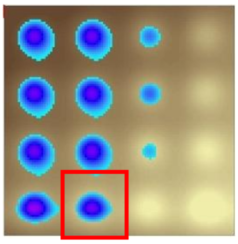


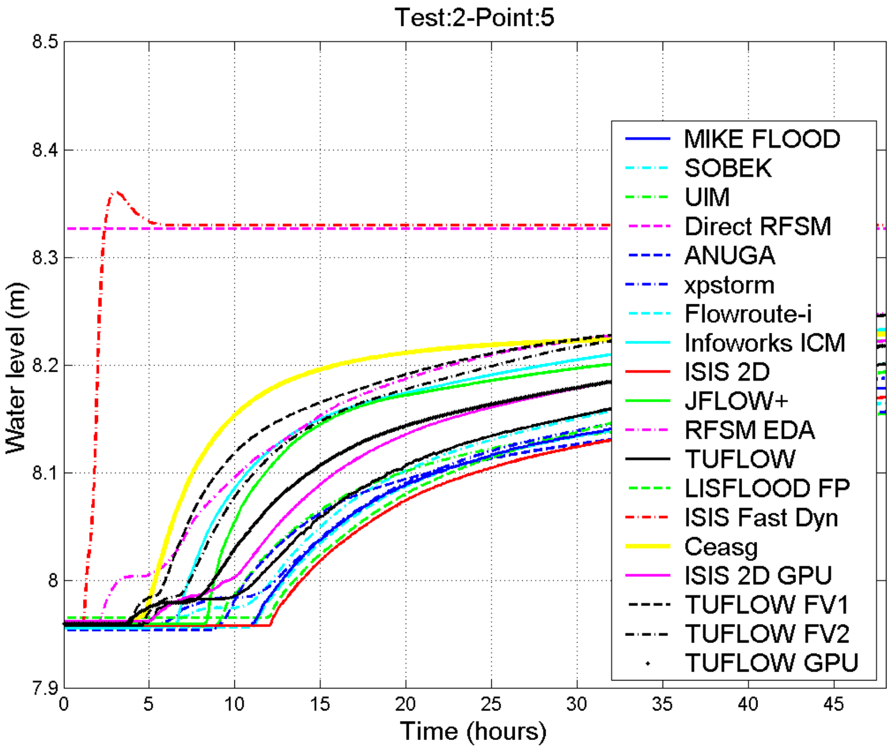
Test:2-Point:7
Water level (m)
Time (hours)
9.1
9
8.9
8.8
8.7
8.6
8.5
0
5
10
15
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



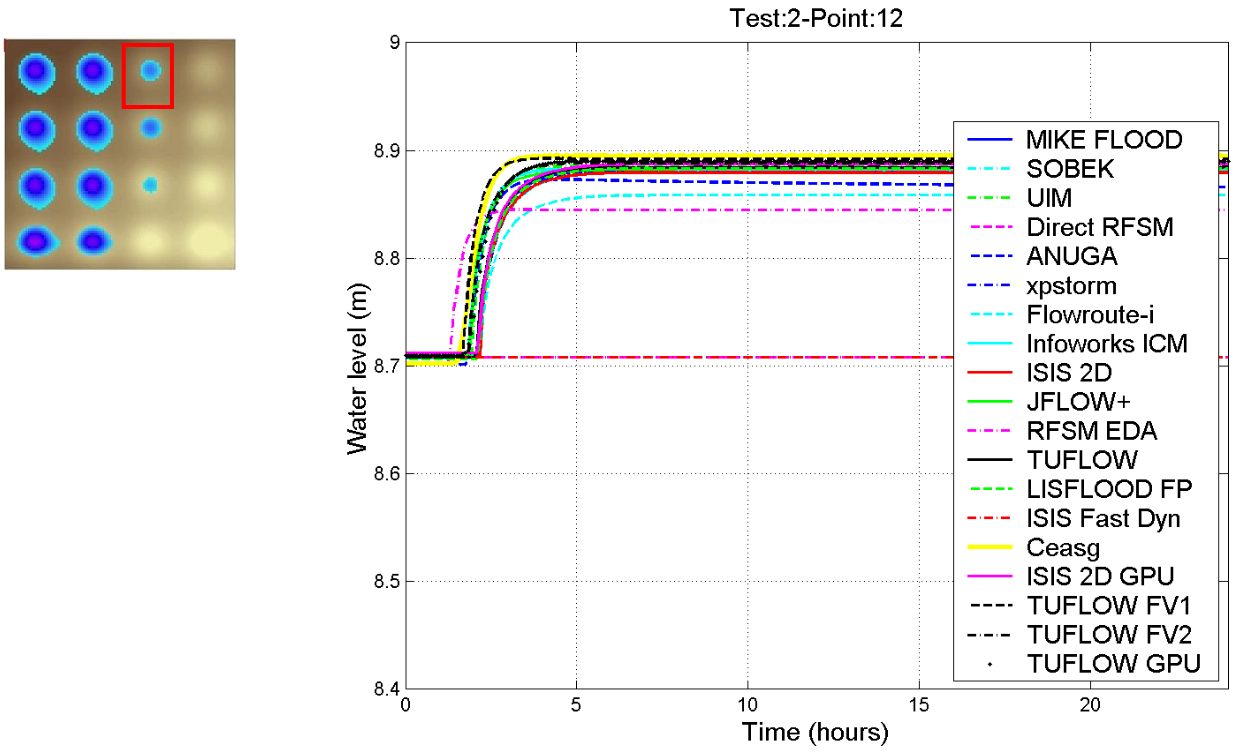


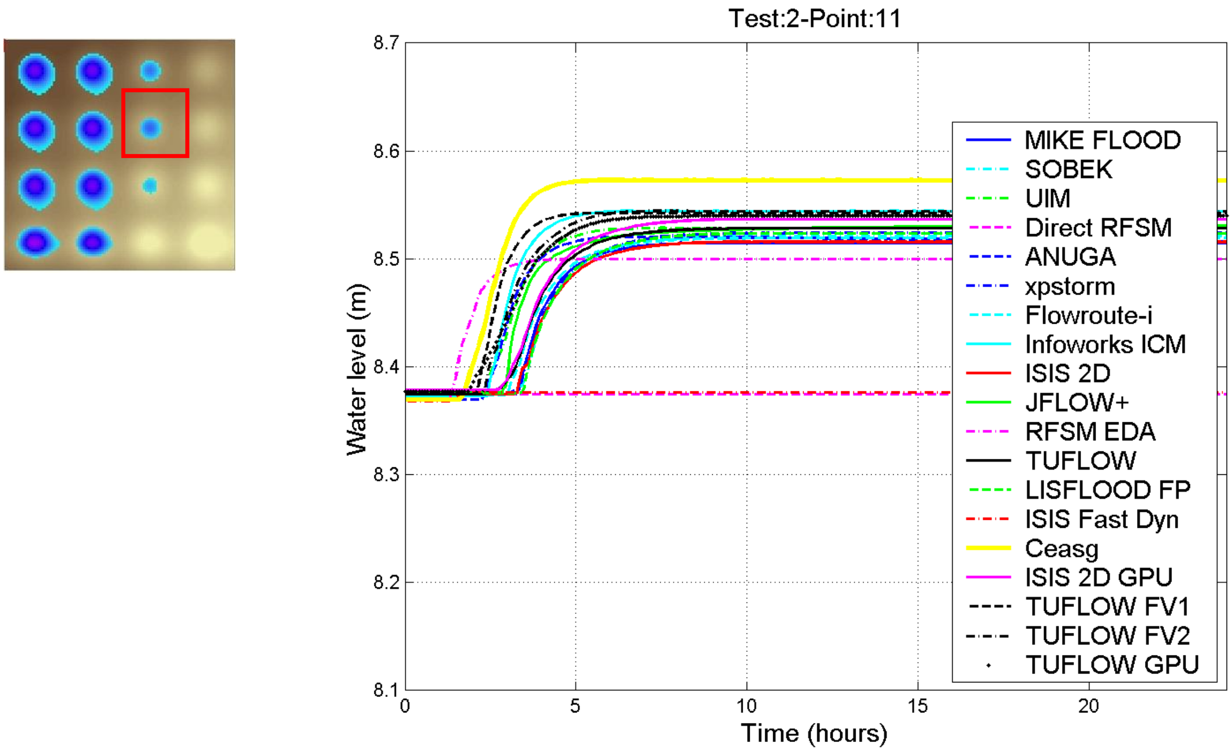
Test:2-Point:6
Water level (m)
Time (hours)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

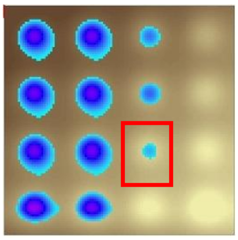


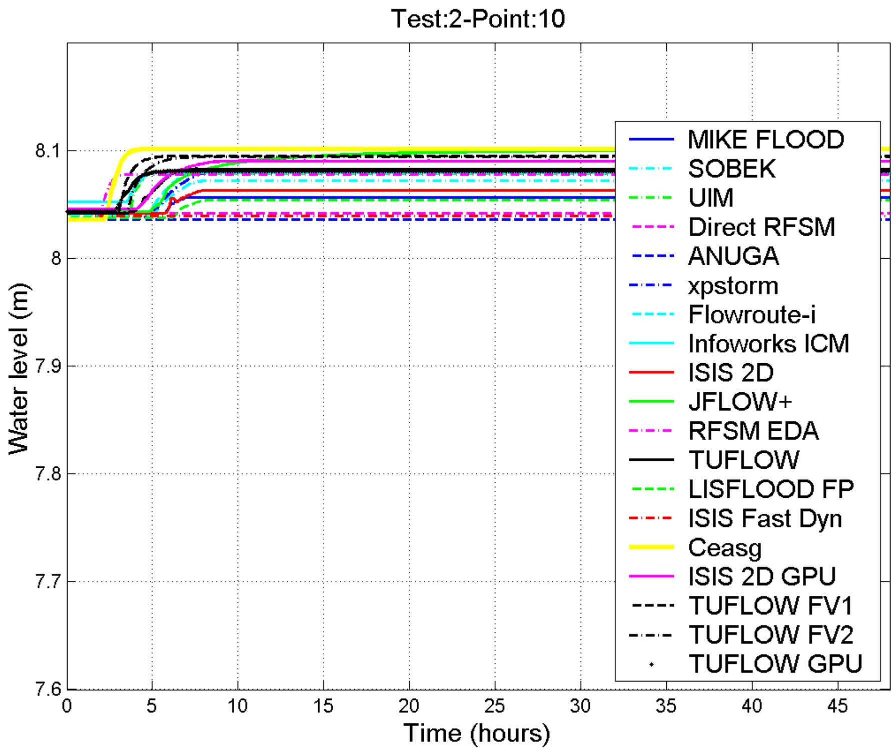


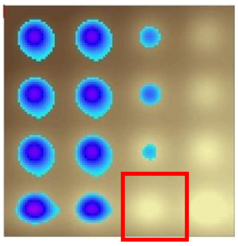
Test:2-Point:5
Water level (m)
Time (hours)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

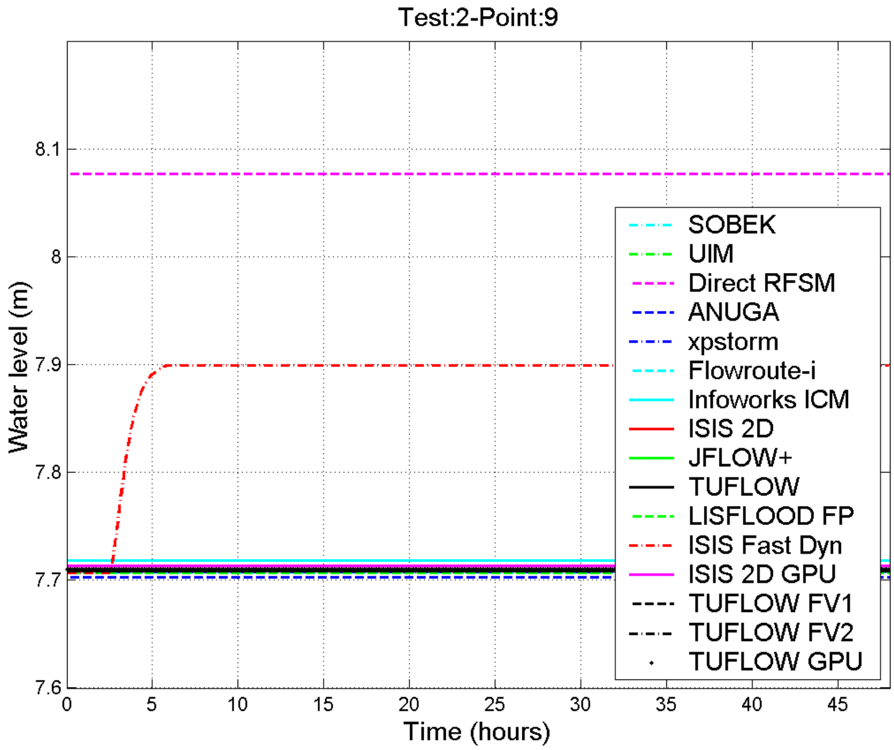

Test:2-Point:12
Water level (m)
Time (hours)
9
8.9
8.8
8.7
8.6
8.5
8.4
0
5
10
15
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

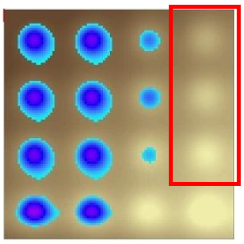

Test:2-Point:11
Water level (m)
Time (hours)
8.7
8.6
8.5
8.4
8.3
8.2
8.1
0
5
10
15
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



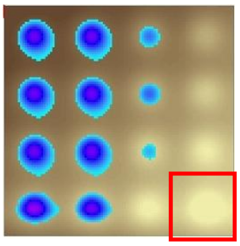

Test:2-Point:10
Water level (m)
Time (hours)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU




Test:2-Point:9
Water level (m)
Time (hours)
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
TUFLOW
LISFLOOD FP
ISIS Fast Dyn
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



Points 16, 15, 14: These were predicted to remain dry by all models.

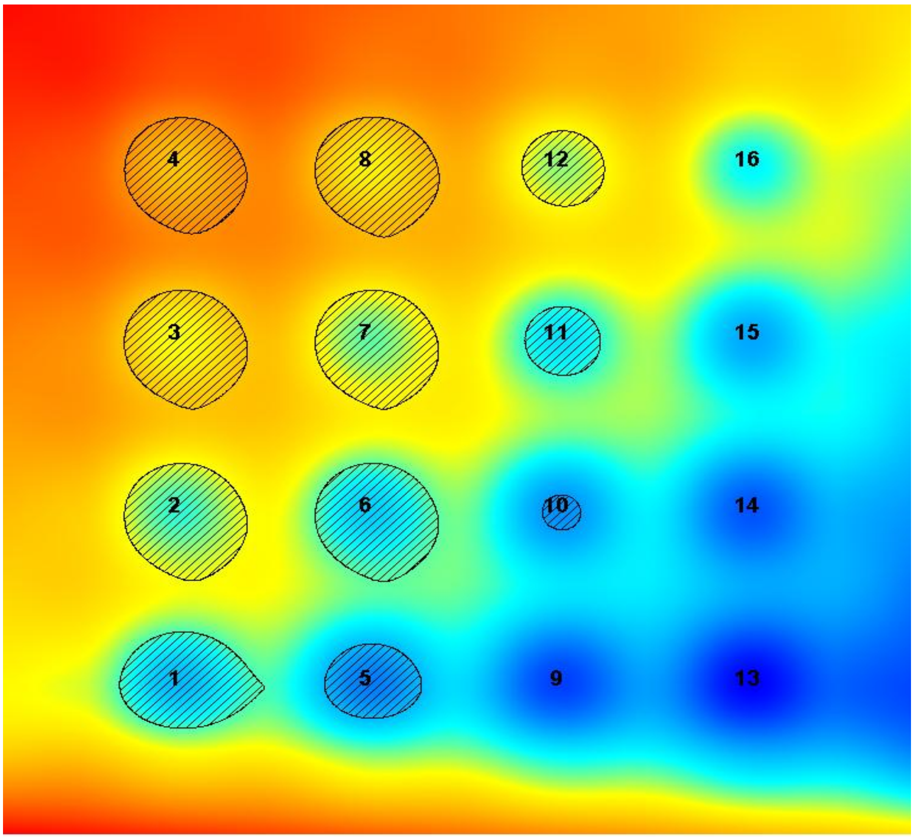


Point 13: This was predicted to remain dry by all models, except RFSM Direct which predicted a water depth of 0.15m.

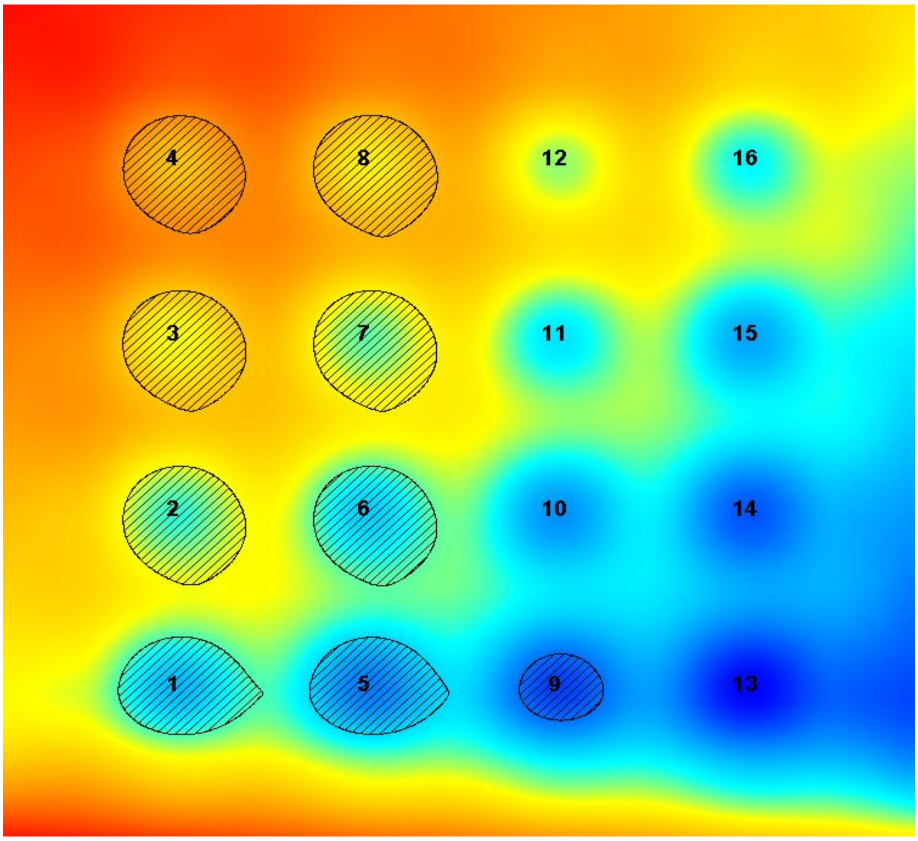
Figure 4.5 Time series of water levels in the depressions

The final inundation extent predicted by the models is represented in Figure 4.6. Almost all models predicted the extent illustrated in Figure 4.6(a).

(a)



(b)



(c)

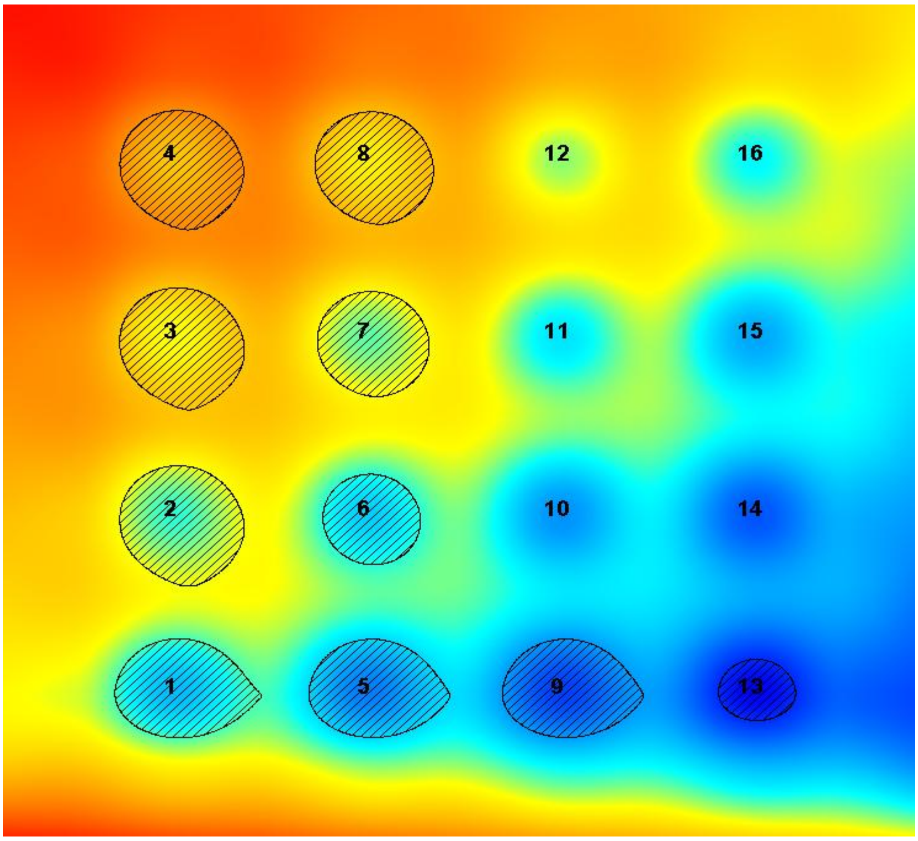


Figure 4.6 Final inundation extent as predicted by (b) ISIS Fast Dynamic, (c) RFSM Direct and (a) all except the latter two

Notes: These figures were constructed by assuming a horizontal final water surface in each depression.

4.3.3 Summary and interpretation of results

Full SWE models

The behaviour observed in the results by the full models is as follows. A transient water level peak is observed near the inflow while the inflow takes place. After the inflow has stopped, the water level in every depression gradually decreases until it eventually reaches the level of the lowest ‘sill’ separating it from surrounding depressions (Points 1, 2, 3, 4, 6, 7 and 8). Insufficient water has flowed to depressions 5, 10, 11 and12 to fill them and at these points the water stabilises eventually at a level below the next ‘sill’. The transient peak level is ~20cm above the final level at point 4 (near the inflow), ~10cm at points 3 and 8, ~5cm at points 2 and 7, becoming imperceptible or non-existent at points further away from the inflow (and more diffused in time away from the inflow). Flood arrival times are similar between models at most points, although discrepancies up to several hours are observed at points 5 and 10, which can mainly be attributed to the fact that the flow of water between the depressions over the thresholds is very shallow (and so small differences in wave dynamics can significantly affect the timing of the overtopping of these thresholds).

Differences in the final levels predicted by the full models are negligible (a few cm at most) except at point 5 where the levels are still rising at the end of the simulation (final levels are therefore not known), and at points 10, 11 and 12, where, considering the bowl-shaped topography and the shallower depths reached, the slightly larger differences correspond to relatively small quantities of water.

3-term models

Although the predictions of transient water levels by this class of models (LISFLOOD-FP, RFSM EDA) differ somewhat from the predictions by the full models in the higher momentum region near the inflow location (especially point 4) and the travel times predicted by RFSM EDA are significantly shorter (by up to several hours), the final distribution of inundation by these three models is consistent with that predicted by the full models, see Figure 4.6 (a).

2-term models

As in Test 1, ISIS Fast Dynamic predicted a much faster response of floodplain inundation to boundary inflow than all the models including more SWE terms. In addition, the final inundation is significantly different, with the flow taking a preferential route along the steepest (‘southward’) slope, then flowing ‘eastwards’ to point 9. In contrast, the full SWE and ‘3-term’ models predicted the flow to also flow eastwards by conservation of momentum to points 12, 11 and 10, which remained dry in the ISIS Fast Dynamic simulation.

Observations from the UIM results are comparable to those from the 3-term models (albeit with a much longer run time, see below).

0-term model (RFSM Direct)

The behaviour predicted is similar to that of ISIS Fast Dynamic, although more marked, with less water flowing to point 6 and more instead to point 13.

Volume conservation

The largest volume change reported is a 1.46% volume loss by Flowroute-*i*™ (Table 4.3). This did not have any identifiable consequence in the results and the effect of model choice was clearly more significant than a lack of volume conservation of this magnitude.

4.3.4 Miscellaneous model parameters

Table 4.3 Miscellaneous model parameters for Test 2

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 20m or 10000 elements)	(5) Time-stepping	(6) Run time	(7) Final volume (m^3)
ANUGA	1.1beta_7501	No	10,088 elements	Adaptive	1130s	97,223.15
Ceasg	1.12	Yes –GPU	20m	2.5s	15s	97,200
Flowroute-*i*™	3.2.0	Yes –4 CPUs	20m	Adaptive	6s	95,583.6
InfoWorks ICM	2.5.2	Yes – GPU	9997	60s	11s	97,200
ISIS 2D	3.6 (ADI)	Partial [1]	20m	15s	22s	96,275.61
ISIS 2D GPU	1.17	Yes	20m	Adaptive	22s	97,204
ISIS Fast Dynamic	3.6		20m	5s	2s	97,200
JFLOW+	2.0	Yes – GPU	20m	Adaptive average 5.17s	10s	97,200
LISFLOOD-FP	5.5.2	Yes	20m	Adaptive	7.2s	97,162
MIKE FLOOD	2012	Yes – 8 CPUs	20m	25s	9.6s	97,252
RFSM (Direct)	3.5.4	No	16 elements [1]	N/A	1s	97,200
RFSM - EDA	1.2	no	16 elements [1]	Adaptive typically 60s	11s	97,200
SOBEK	2.13	No	20m	15s	100s	97,200

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 20m or 10000 elements)	(5) Time-stepping	(6) Run time	(7) Final volume (m^3)
TUFLOW	2012-05-AA Single precision	No	20m	Adaptive (5–120s)	7.3s	97,195
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	20m	Adaptive (4– 5s)	16s [2]	97,200
TUFLOW FV [3]	2012.000b First order (and second order)	Yes – 12 CPU cores	20m	Adaptive (~5s)	26s (41s)	97,192 (97,189)
UIM	2009.12	OMP	20m	1s	712s	97,200
XPSTORM	2011; 2010-10-AB-iDP-w32	No	20m	10s	12.1s	97,393

Notes: [1] See Appendix B.

[2] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[3] Run times: 1st order solution (2nd order solution)

Other information provided

ISIS Fast Dynamic: ISIS FAST Dynamic simulates the filling of floodplain depression. However, due to the absence of component of momentum in the routing method, the flood extent and water depths differ slightly from full hydrodynamic models.

Ceasg: 'Due to the discrete nature of the computational grid, the results are not guaranteed to relate to the exact centre of each depression of the resampled DTM.' Response by report's authors: this had negligible implications as the DTM was designed to feature a very smoothly varying shape.

TUFLOW: The enhancements in the 2012-05-AA release means the model can be run using single precision (2010 needed double precision to keep mass error below 1%), on larger time steps, with or without adaptive time-stepping, and no with significant mass error (-0.1% in 2010 using DP vs. 0.0% in 2012 using SP). 'Number Iterations == 4' was specified to give improved convergence of the solution, especially during the initial phase where there are rapid changes in the inflow hydrograph.

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

TUFLOW FV: Results consistent with other full 2D solvers. The first order solution disperses more quickly than the second order solution.'

4.3.5 Conclusions from Test 2

All **full models** predicted very similar results in terms of the final inundation extent (that is, final water levels). Differences between water level predictions were small and within the range of desirable precision for practical applications to a problem of this type. The high level of consistency in the results of the full models, obtained using numerical algorithms of a wide variety of classes (see Table 3.1), provides grounds for a high level of confidence in the accuracy of these results.

The **3-term models** (and UIM) predicted an outcome in terms of the final inundation extent similar to that predicted by the full models, albeit with some slight differences in the prediction of the hydrodynamic spreading. This suggests that 3-term models neglecting convective acceleration (such as LISFLOOD-FP, UIM and RFSM EDA) are suitable for the modelling of low momentum flood spreading situations.

2- and 0-term models such as ISIS Fast Dynamic, RFSM Direct, tended to provide noticeably different final inundation distributions.[2] ISIS Fast was considered to be inappropriate and was therefore not tested.

[2] It is acknowledged that the run times were up to an order of magnitude shorter than any other models.

4.4 Test 3: Momentum conservation over a small obstruction

4.4.1 Introduction

This test (see Appendix A.3 for details) consists of a sloping topography with two depressions separated by an obstruction as illustrated in Figure 4.7, and of width 100m. A varying inflow discharge is applied as an upstream boundary condition at the left-hand end, causing a flood wave to travel down the 1:200 slope. While the total inflow volume is just sufficient to fill the left-hand side depression at X = 150m, some of this volume is expected to overtop the obstruction because of momentum conservation and settle in the depression on the right-hand side at X = 250m.

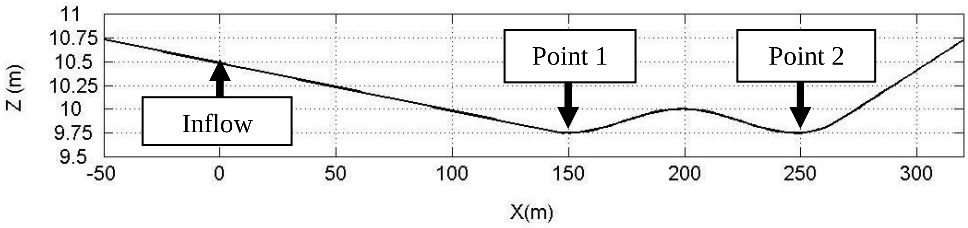
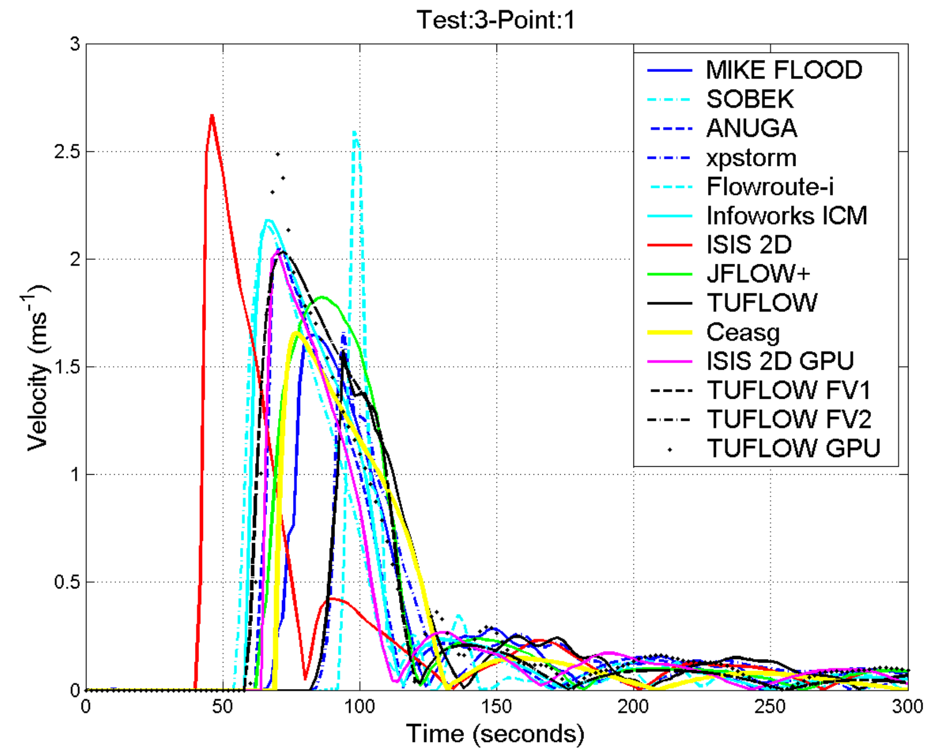


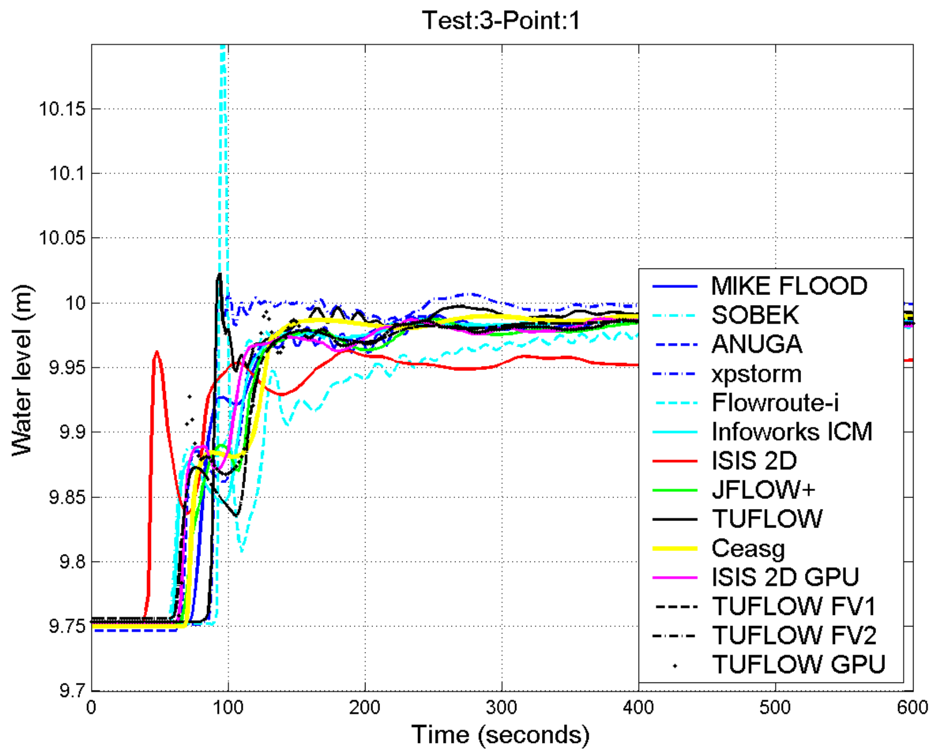
Figure 4.7 Profile of DEM used in Test 3

The objective of the test is to assess each package's ability to conserve momentum over an obstruction in the topography.

Although no exact solution exists for Test 3, any model relying on the full shallow water equations (that is, momentum conservation including the acceleration terms) is expected to predict a water level rise at point 2.

4.4.2 Results: water level and velocity





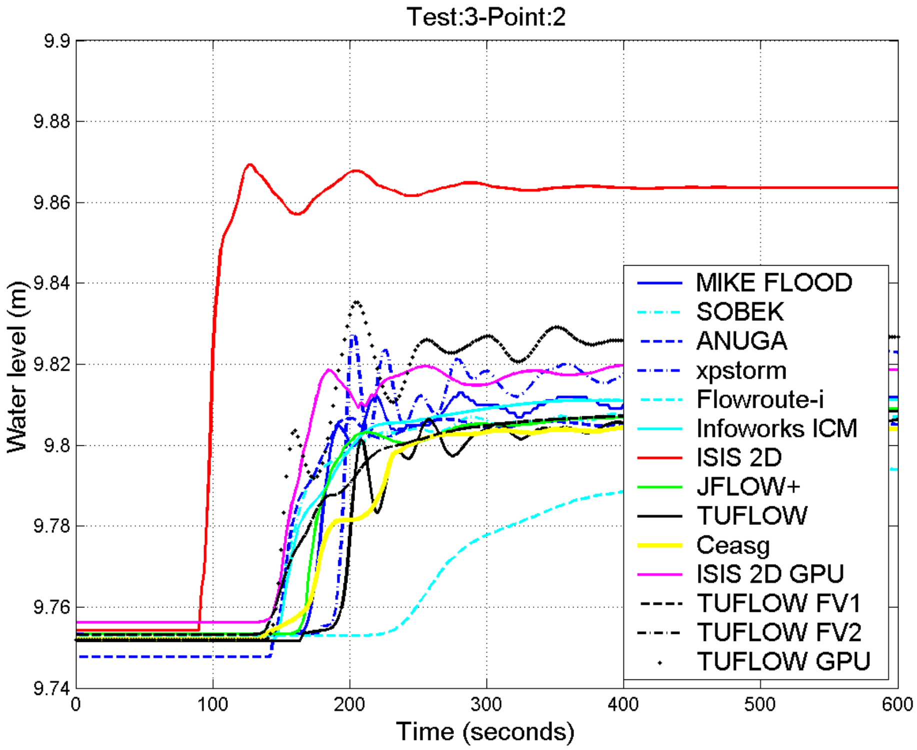


Figure 4.8 Results from Test 3

4.4.3 Summary and interpretation of results

Expectedly, no simulation results using RFSM EDA, LISFLOOD-FP, ISIS Fast Dynamic, ISIS Fast, RFSM Direct or UIM were submitted as these do not fully conserve momentum.

Full SWE models

At point 1, most full models predicted a rapid increase of the water level from height 9.75m at t ≈ 60s to height ~9.98/9.99m at t ≈ 120s. After t ≈ 150s, the level rose quickly by ~5cm to ~6cm at point 2 on the other side of the obstruction. ISIS 2D was implemented using two different setups for the boundary condition, producing results which were either (1) similar to most other full models (not shown here) or (2) as shown on the plots, that is, with a more rapidly advancing wave front, more water overtopping the 10m threshold, and consequently a higher final level at point 2.

Differences between models may be partly due to the treatment of shocks on the left-hand side of the obstruction (or lack of, for example, Flowroute-*i*™), or to the implementation of the boundary condition. Flowroute-*i*™ predicted a less rapidly moving wave front, some oscillatory behaviour, and a less rapid rise of the level at point 2. This is partly due to the use of Manning's n = 0.03 instead of 0.01 (see Section 0).

4.4.4 Miscellaneous model parameters

Table 4.4 Miscellaneous model parameters for Test 3

(1) Name	(2) Version	(3) Multi-processing	(4) Grid resolution (expected: 5m or 1200 elements)	(5) Time-stepping	(6) 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
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+	2.0	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
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 [1]
TUFLOW FV [2]	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

Notes: [1] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[2] Run times: first order solution (second order solution)

Additional information provided

Flowroute-*i*™: 'For stability reasons, this test was run using a Manning's *n* value of 0.03 (instead of 0.01). As such, we would expect slightly less water to flow over the 'bump' (point 2). We note that some oscillatory behaviour is present, which is likely to be as result of Flowroute-*i*™ not using a shock capturing routine.'

ISIS 2D: 'For this case the TVD solver was selected, since the steep slope in the domain creates predominant supercritical flow. Depending on the type of boundary condition applied the results may vary significantly. This is expected since a total flow boundary condition gives an initial velocity to the inflow depending on the bed slope. Since no additional context was given for the test, there is no sufficient information to select which is the best alternative for the boundary condition type choice'.

Note from Heriot-Watt University: Halcrow provided two sets of results based on two different settings for the boundary condition type ('total flow' and 'vertical flow'). The results shown above are the ones using the 'total flow' setting. The results using 'vertical flow' resulted in less high velocity at point 1 and less water going over the bump to point 2, in a similar manner to what is predicted by the other full SWE models (with JFLOW+ being the closest).

LISFLOOD-FP: 'The supercritical flow in this test case in not suitable for the model.'

4.4.5 Conclusions from Test 3

All **full SWE models** predicted very similar results, predicting that the water contained sufficient momentum to flow over the obstruction.

As expected none of the **simplified models** are found to be suitable for this simulation, demonstrating the importance of using the full hydrodynamic equations when momentum conservation is important to satisfactory simulations.

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

4.5.1 Introduction

The test (see Appendix A.4 for details) consists of a flat horizontal floodplain of dimensions 1000m $\times$ 2000m, with a single inflow boundary condition, simulating the failure of an embankment by breaching or overtopping, with a peak flow of 20m^3/s and time base of ~5h. The boundary condition is applied along a 20m line in the middle of the western side of the floodplain.

The objective of the test is to assess the package's ability to simulate the celerity of propagation of a flood wave and predict transient velocities and depths. It is relevant in particular to the modelling of fluvial and coastal inundation resulting from breached embankments.

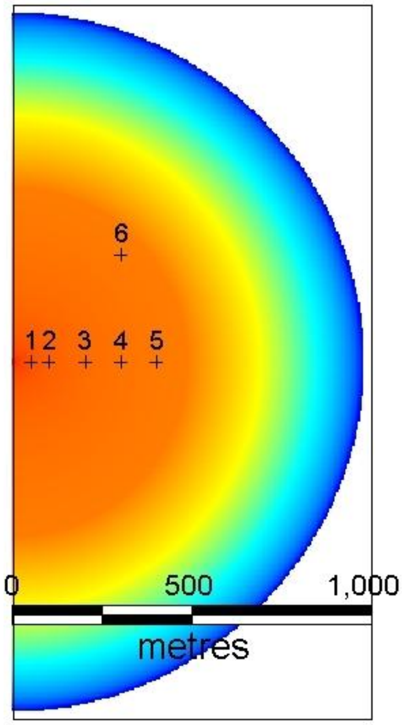
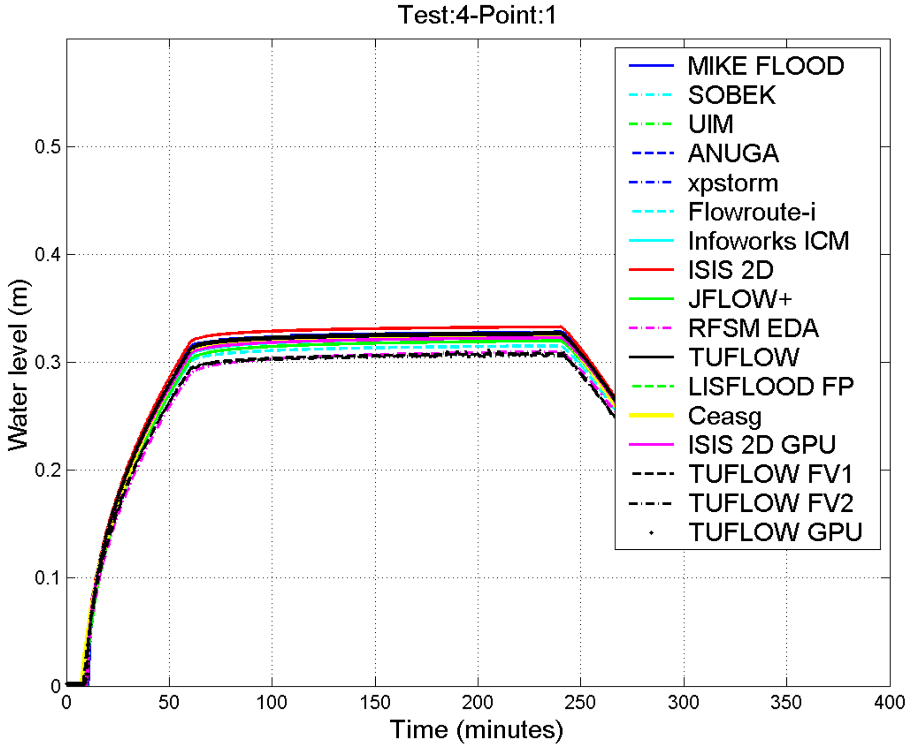
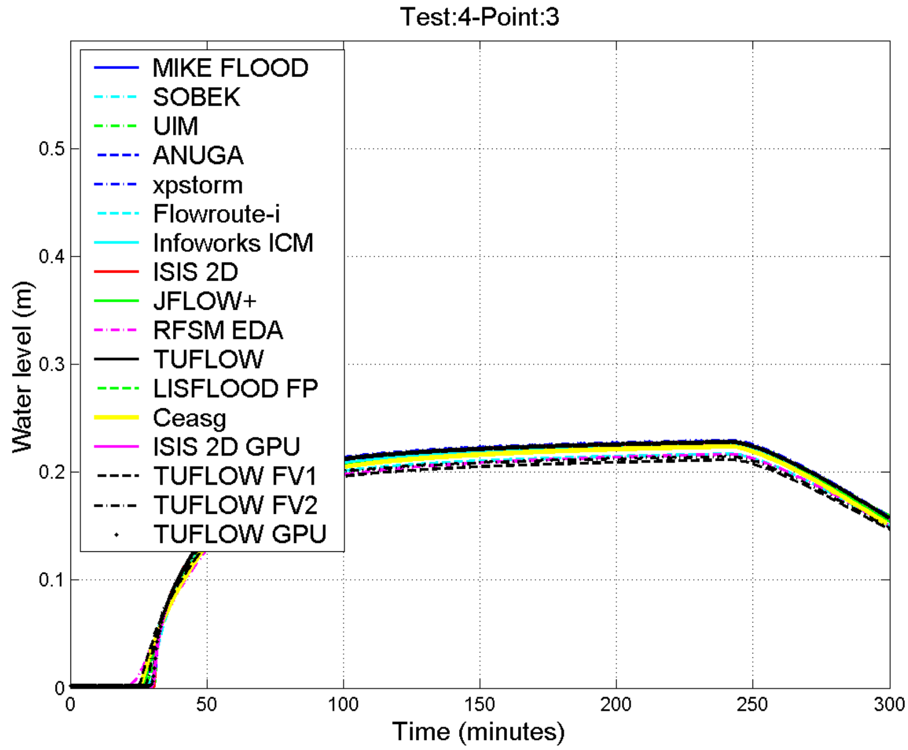
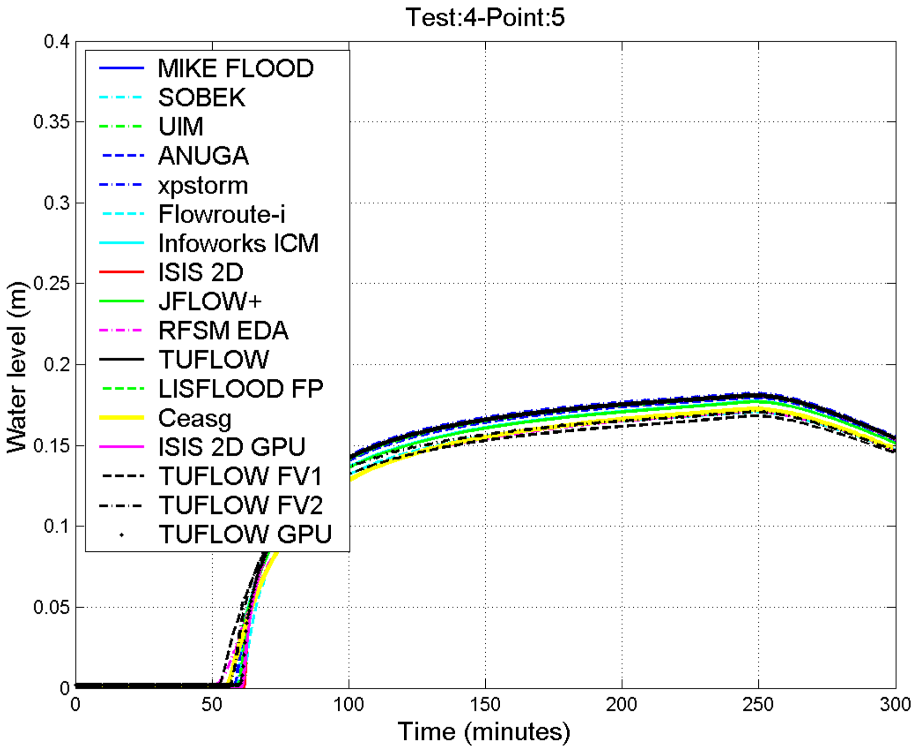


Figure 4.9 **Location of output points, with a typical flood distribution at time 3h**

4.5.2 Water levels (depths) and velocities




Test:4-Point:3
Water level (m)
Time (minutes)
MIKE FLOOD
SOBEK
UIM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU


Test:4-Point:5
Water level (m)
Time (minutes)
MIKE FLOOD
SOBEK
UIM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

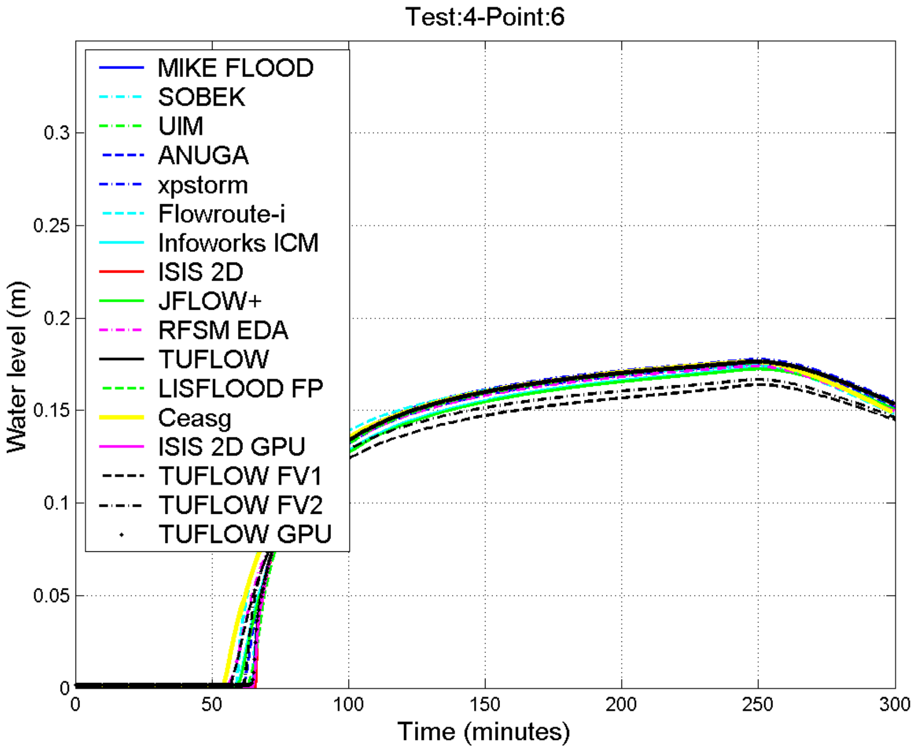
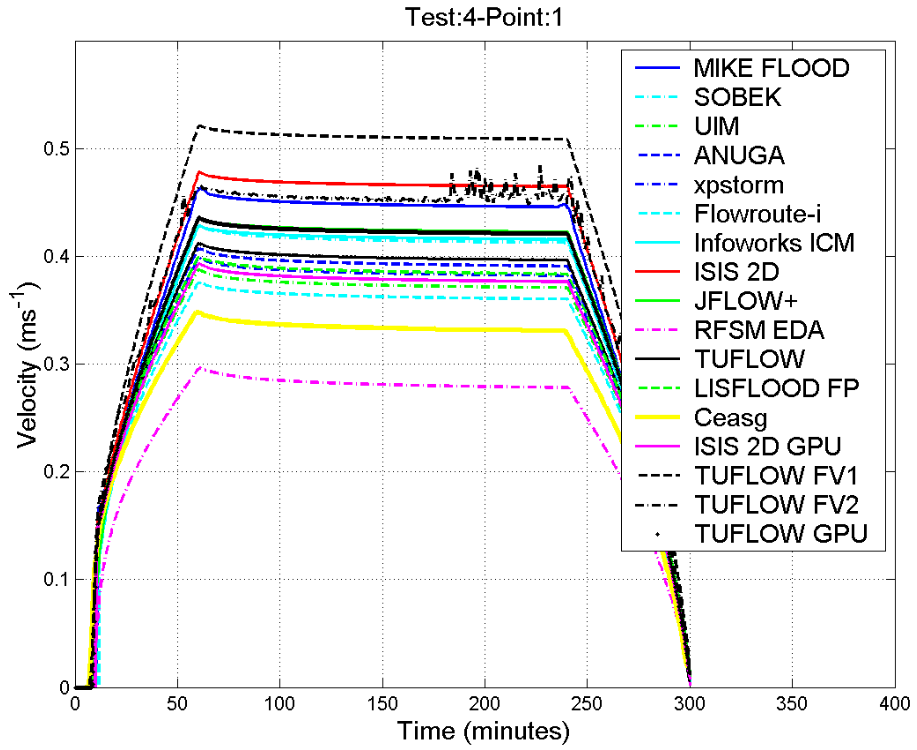
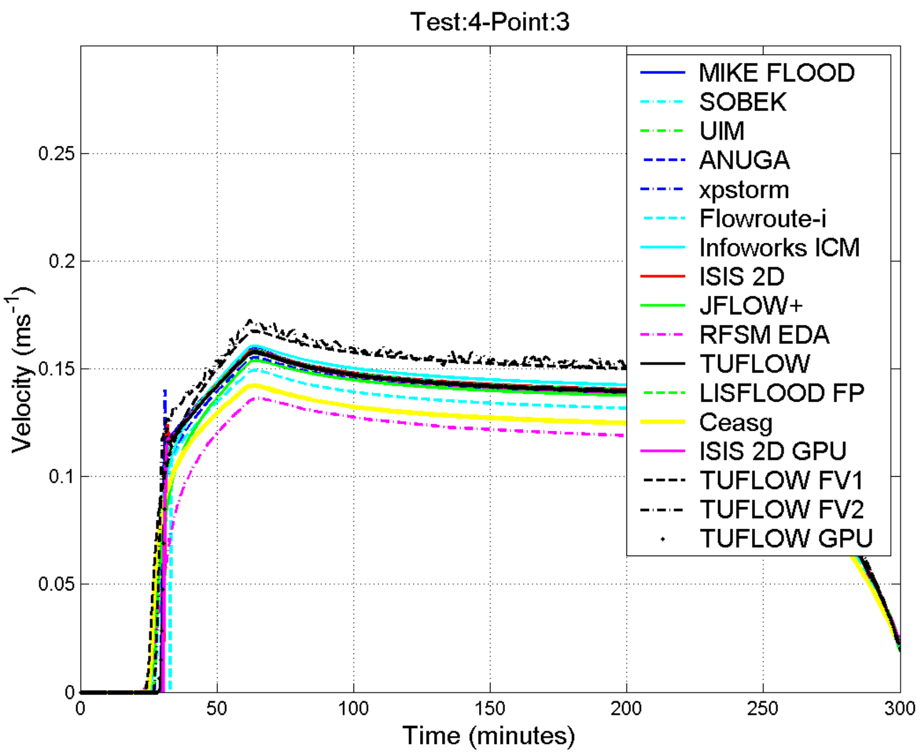
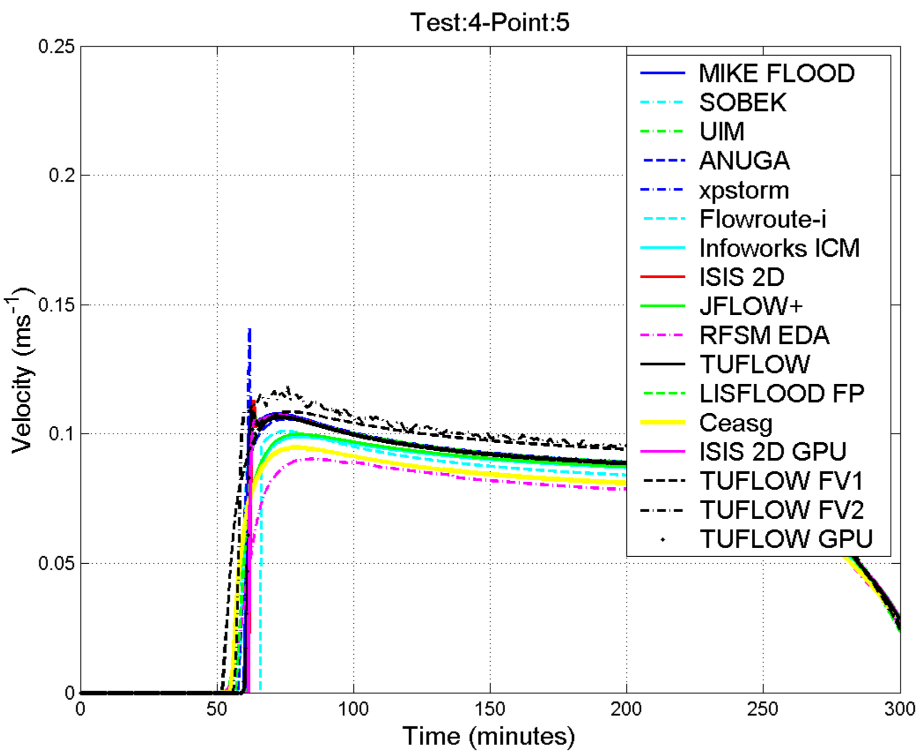


Figure 4.10 Water level time series (results at a selection of points: 1, 3, 5 and 6)




Test:4-Point:3
Velocity (ms-1)
Time (minutes)
MIKE FLOOD
SOBEK
UIM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU


Test:4-Point:5
Velocity (ms-1)
Time (minutes)
MIKE FLOOD
SOBEK
UIM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU

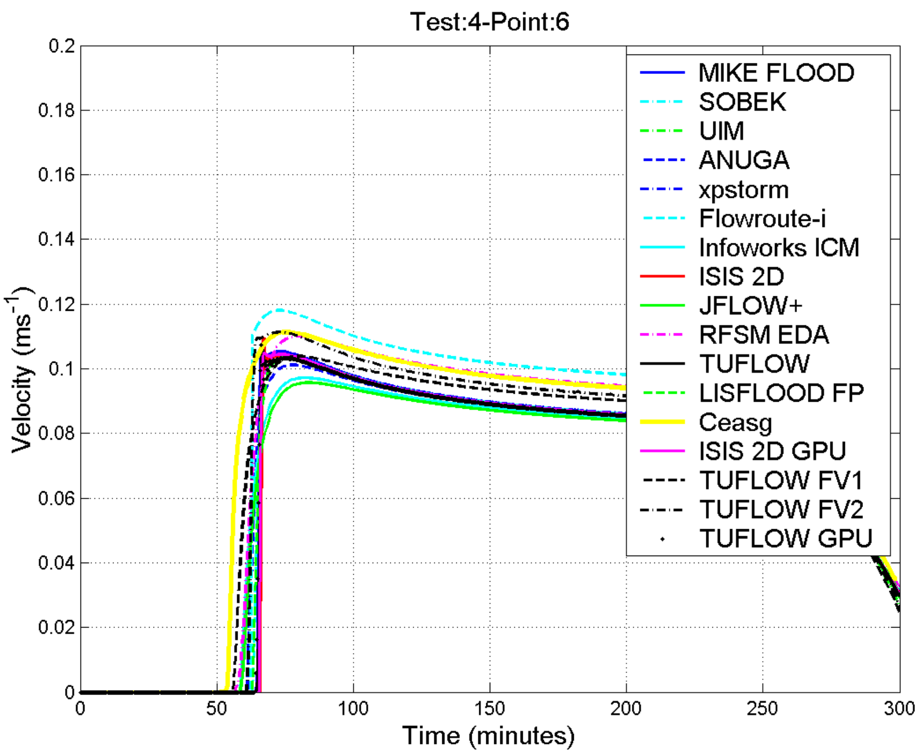


Figure 4.11 Velocities time series (results at a selection of points: 1, 3, 5 and 6)

4.5.3 Depth and velocity grids

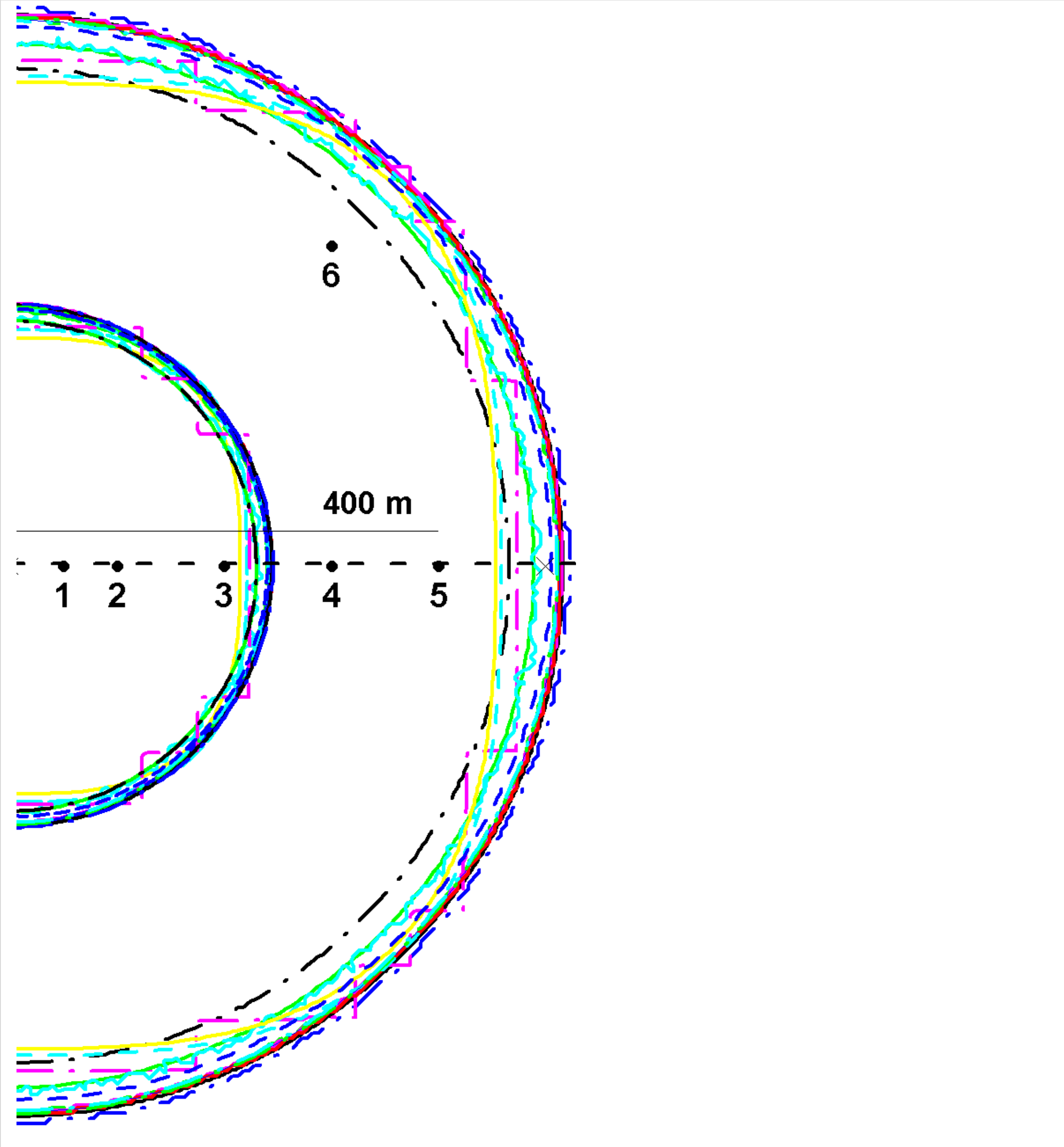


Figure 4.12 0.15m depth contours at times 1h (smaller half circles) and 3h (larger half circles)

Notes: The colour coding is consistent with the one used in the rest of this report.

Cross-sections shown in Figures 4.13 and 4.14 were taken along the black dashed line, which starts at the left boundary and runs through points 1 to 5.

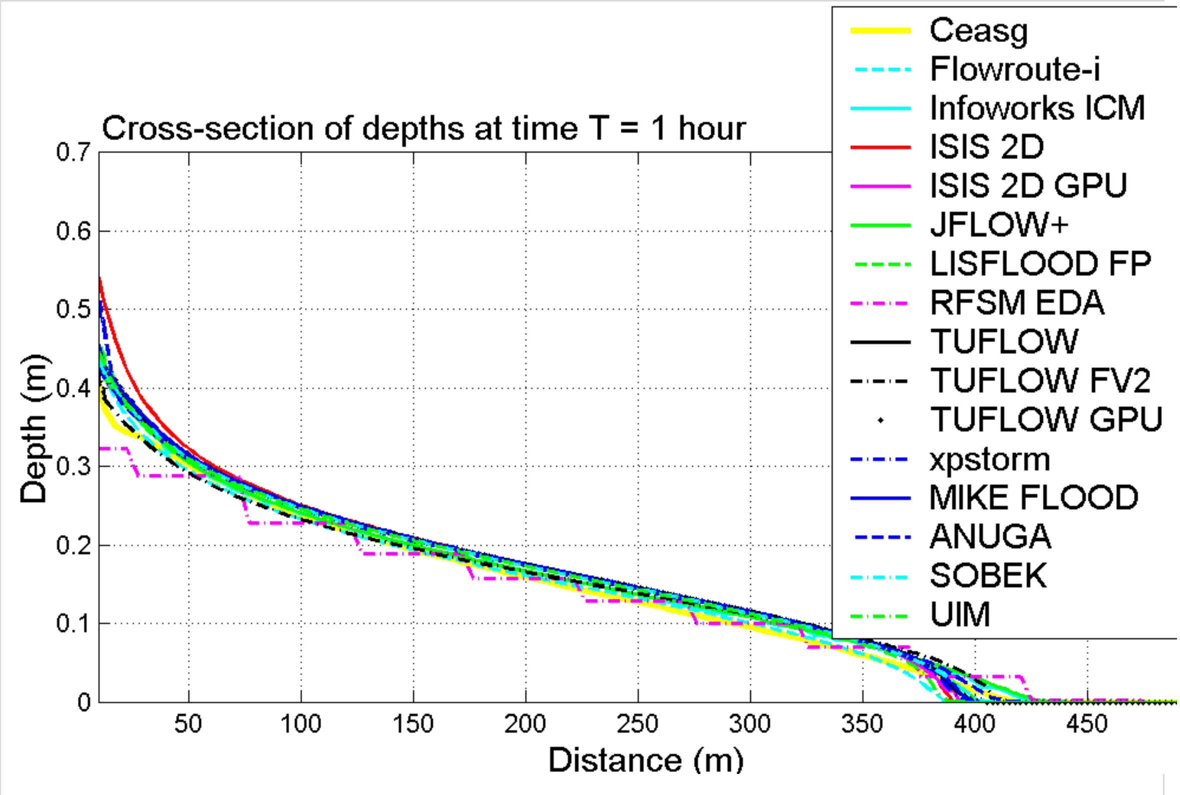


Figure 4.13 Cross-section of depths along the dashed line in Figure 4.12 at time t = 1h

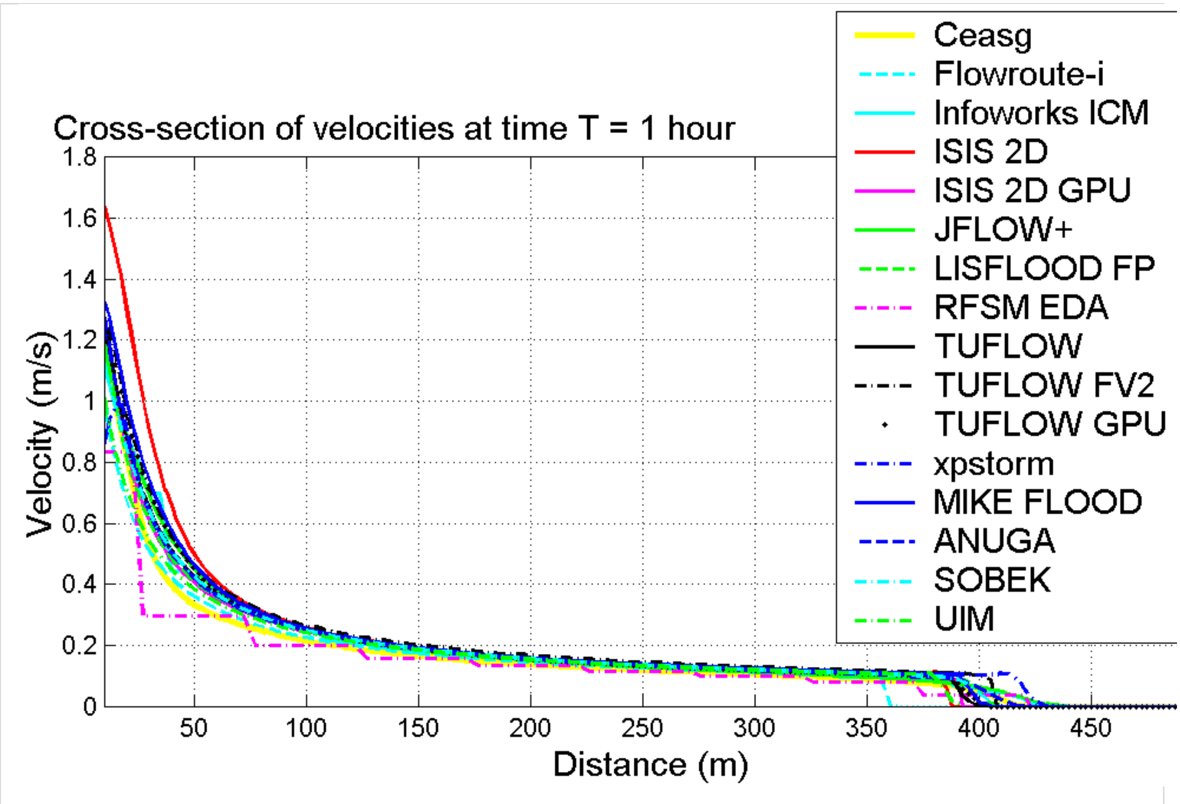


Figure 4.14 Cross-section of velocities along the same line as Figure 4.12 at time t = 1h

4.5.4 Summary and interpretation of results

Full SWE models

It can be observed on the time series graphs in Figures 4.10 and 4.11 that the full SWE models predicted depths and velocities respectively (at most output points) within a few per cent of each other during the entire duration of the event. However, there were small differences in timing during the initial rise of the flood at each output point, with arrival times being at most (points 5 and 6) within ~5min of each other (compared with a travel time of ~1h).

Exceptions from this general behaviour only concern velocity predictions, as follows.

- At point 1 near the source, differences between models were up to ~30% (this decreased sharply with distance from the source, see for example point 3). This may be due to differences in the model approaches to implementing the boundary condition.
- Some finite difference models (for example, XPSTORM at points 3 and 5) predicted an initial sharp peak in the velocity (perhaps reflecting shortcomings in the handling of shocks and supercritical flows). This did not significantly affect their other results predictions.

3-term models (LISFLOOD-FP, RFSM-EDA) and 2-term model (UIM)

Water depth and velocity predictions by UIM, LISFLOOD-FP and RFSM-EDA were generally consistent with the predictions by the full SWE models at all points. However, the coarser spatial resolution used by RFSM EDA (clearly visible in the contour and cross-section plots in Section 4.5.3) meant that the sharp changes in the vicinity of the inflow could not be resolved with the same accuracy as other models (for example, the velocity at point 1 was predicted to be significantly lower).

4.5.5 Miscellaneous model parameters

Table 4.5 Miscellaneous model parameters for Test 4

(1) Name	(2) Version	(3) Multi-processing	(4) Grid resolution (expected: 5m or 80,000 elements)	(5) Time-stepping	(6) Run time
ANUGA	1.1beta_7501	No	80,149 elements	Adaptive	3650s
Ceasg	1.12	Yes – GPU	5m	0.5s	72s
Flowroute-*i*™	3.2.0	Yes – 4 CPUs	5m	Adaptive	21s
InfoWorks ICM	2.5.2	Yes – GPU	79,857 triangles	20s	44s
ISIS 2D	3.6 (ADI)	Partial [1]	5m	5s	82s
ISIS 2D GPU	1.17	Yes	5m	Adaptive	25s
JFLOW+	2.0	Yes – GPU	5m	Adaptive Average 0.9s	17.6s
LISFLOOD-FP	5.5.2	Yes	5m	Adaptive	21s
MIKE FLOOD	2012	Yes – 8 CPUs	5m	10s	32.1s
RFSM- EDA	1.2	No	861 [1]	Adaptive, typically 12s	13s
SOBEK	2.13	No	5m	2s	1014s
TUFLOW	2012-05-AA Single precision	No	5m	Adaptive (1–30s)	47s
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	5m	Adaptive (0.8–1.7s)	25s [2]
TUFLOW FV [3]	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

Notes: [1] See Appendix B.

[2] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[3] Run times: first order solution (second order solution)

Other information provided

Ceasg: 'The simplified nature of the Ceasg model is evident in the results for Test 4. Simplified regular-grid models can exhibit an unexpected preference for diagonal flow on perfectly flat terrain which is not evident on more realistic topography. This can be seen both in the arrival time of the flood wave on diagonal lines and the peak water levels/velocities reached during the simulation. The accompanying raster images show the effect clearly, which appears as a pronounced 'flattening' of the flood wave. The underlying behaviour predicted by the model will otherwise be in line with full hydrodynamic models'.

LISFLOOD-FP: 'Unlike a previous version of LISFLOOD-FP which was found to simulate preferential diagonal flow (Neal et al. 2012), this version includes a 2D (coupled) treatment of friction. Although resulting in no additional computational cost the 2D coupled friction scheme prevents the simulation of preferential diagonal flow seen in the previous version.'

RFSM-EDA: 'The effects of having a coarse grid resolution are particularly evident when considering the spatial cross-sections at time 1h. At this scale it is not possible to resolve the steep gradients close to the source or at the wetting front. This is not a failure of the numerical scheme, rather a consequence of a coarse mesh resolution on perfectly flat topography'.

ISIS 2D: '(a) A TVD scheme was also used; final results are similar except for point 1, where velocities are around 7.5% greater. For the rest of the points there are also increases but not significant (<2%). Time step is smaller for this case leading to higher run time (double compared to ADI). (b) Since the test is aim to evaluate due to a breach in an embankment, a total flow boundary condition was implemented in order to be closer to real conditions'.

TUFLOW: The enhancements in the 2012-05-AA release allows the model to be run on larger time steps, with or without adaptive time-stepping, while yielding little or no mass error compared with 2010.

TUFLOW GPU: Gives near identical results to TUFLOW.

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

4.5.6 Conclusions from Test 4

All **full models** and **3-term models** predicted very similar results in terms of travel times, peak water levels and peak velocities. Discrepancies between models were relatively small: ~10% for travel times; and a few per cent for peak levels and velocities. This is unlikely to be larger than typical accuracy expectations in a problem of this type in a practical application.

The high level of consistency in the results of the full models provides grounds for a high level of confidence in the accuracy of these predictions. It also suggests that, in practical applications of flow modelling in the vicinity of a breach, topography effects (which are non-existent in Test 4 due to the perfectly horizontal ground) are in practice more significant in influencing model predictions than differences in the numerical solution of the full shallow water equations.

Predictions of velocities in the immediate vicinity of the inflow shows less consistency and is found to be sensitive to the approach used to implement the boundary condition (which was specified as a discharge vs. time as can be considered normal in a practical application). In the RFSM-EDA model, which relied on a resolution coarser than specified, rapid changes (with distance) in the vicinity of the breach resulted in significant differences between this and the other model predictions.

These conclusions suggest that advective acceleration may not always be a dominant process in the calculation of flood spreading arising from a breach.

2-term and 0-term models such as ISIS Fast Dynamic, ISIS Fast, and RFSM Direct are, understandably, inappropriate for simulating flow following a breach. UIM results are, however, comparable with those of the full and 3-term models, at the cost of a much longer run time.

Before drawing wider conclusions, it should be noted that this test case is more akin to a test of spreading rather than a test of the propagation of a rapidly advancing wave. It is likely that differences in performance between the full models and the simplified models would be larger in a case involving a rapidly advancing wave.

4.6 Test 5: Valley flooding

4.6.1 Introduction

This test (see Appendix A.5 for details) is designed to simulate flood wave propagation down a river valley following the failure of a dam, represented by a skewed trapezoidal inflow hydrograph with a short early peak at $3000m^3/s$. The valley is represented in Figure 4.15.

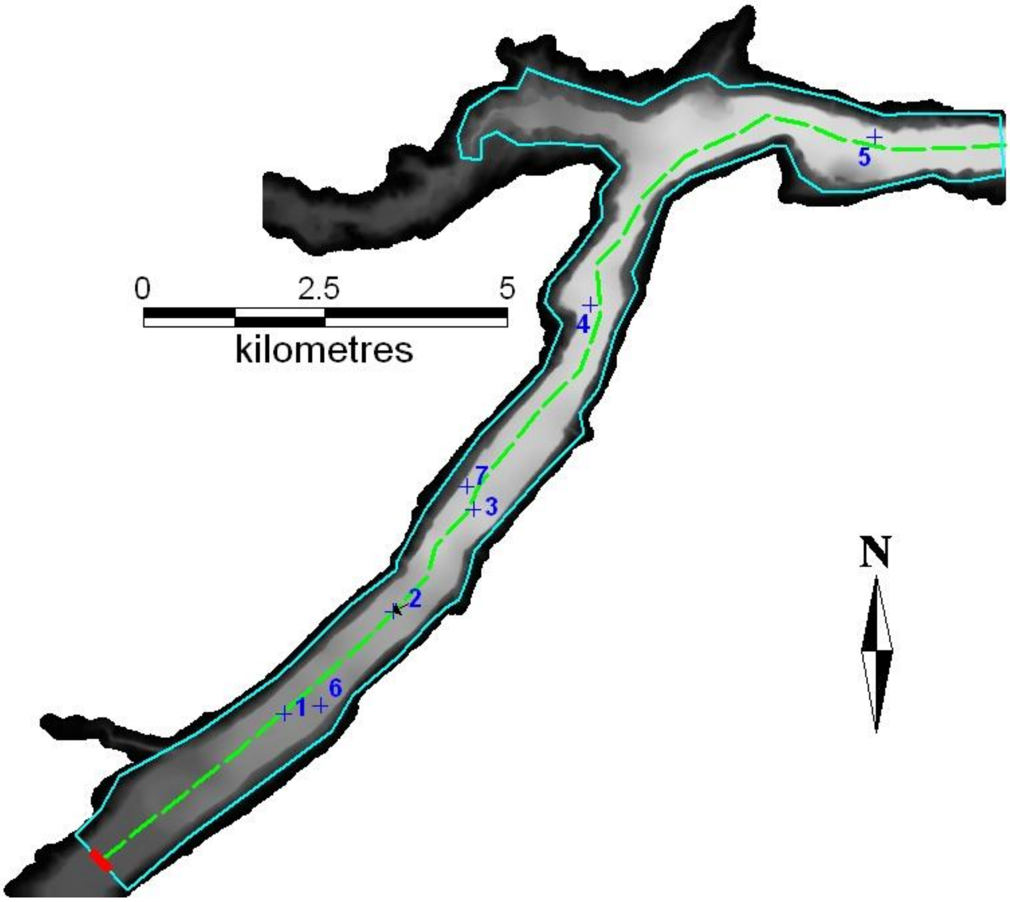
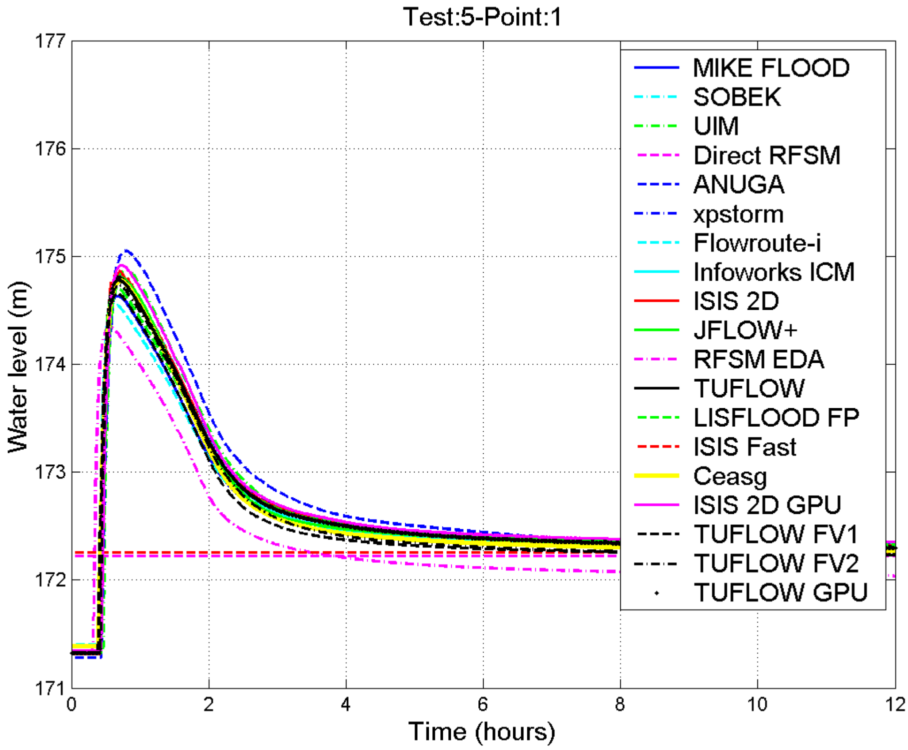


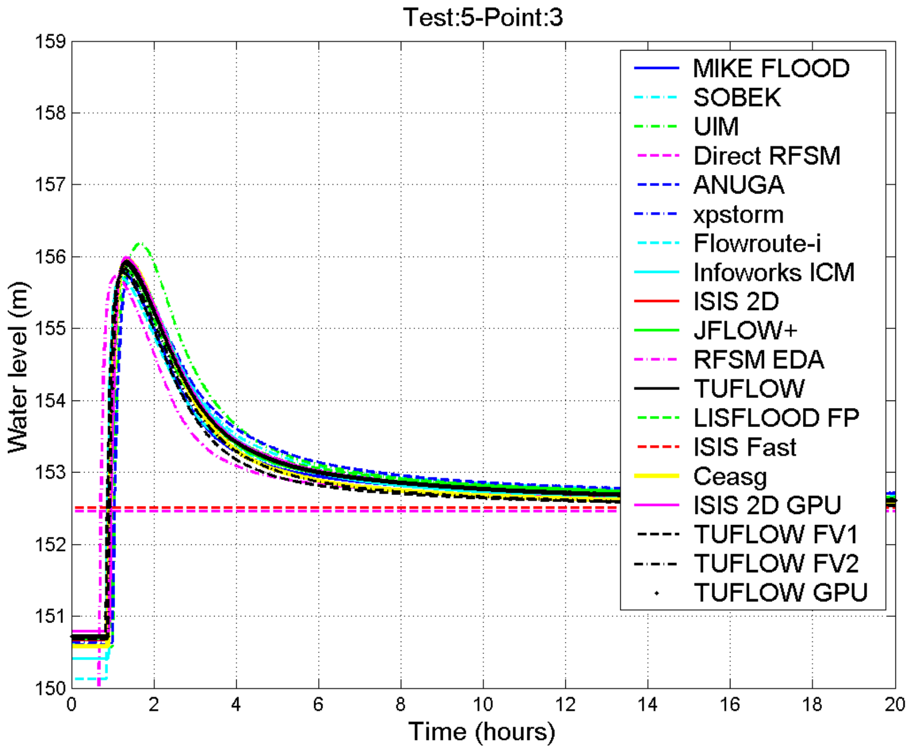
Figure 4.15 Map of the valley used in Test 5, with the inflow at the red line and 7 output points

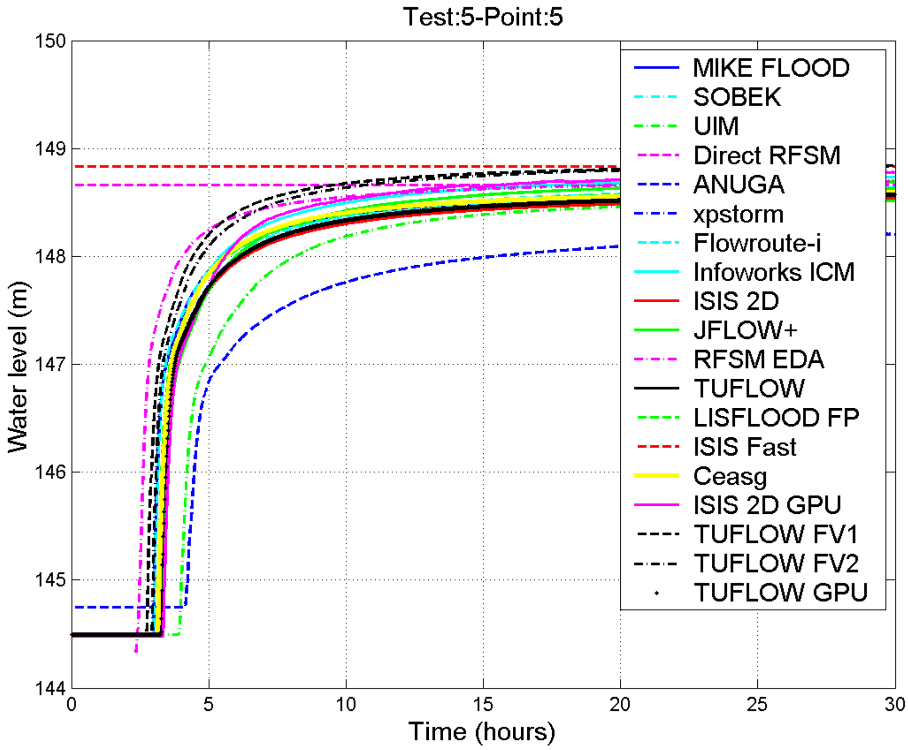
The objective of the test is to assess the package’s ability to simulate major flood inundation and predict flood hazard arising from dam failure (peak levels, velocities, and travel times).

4.6.2 Results: water level and velocity time series

NB Direct RFSM and ISIS Fast are ‘final water level’ models. The final water levels predicted are represented as horizontal lines spanning the entire time domain.


Test:5-Point:1
Water level (m)
Time (hours)
177
176
175
174
173
172
171
0
2
4
6
8
10
12
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU


Test:5-Point:3
Water level (m)
Time (hours)
159
158
157
156
155
154
153
152
151
150
0
2
4
6
8
10
12
14
16
18
20
MIKE FLOOD
SOBEK
UIM
Direct RFSM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



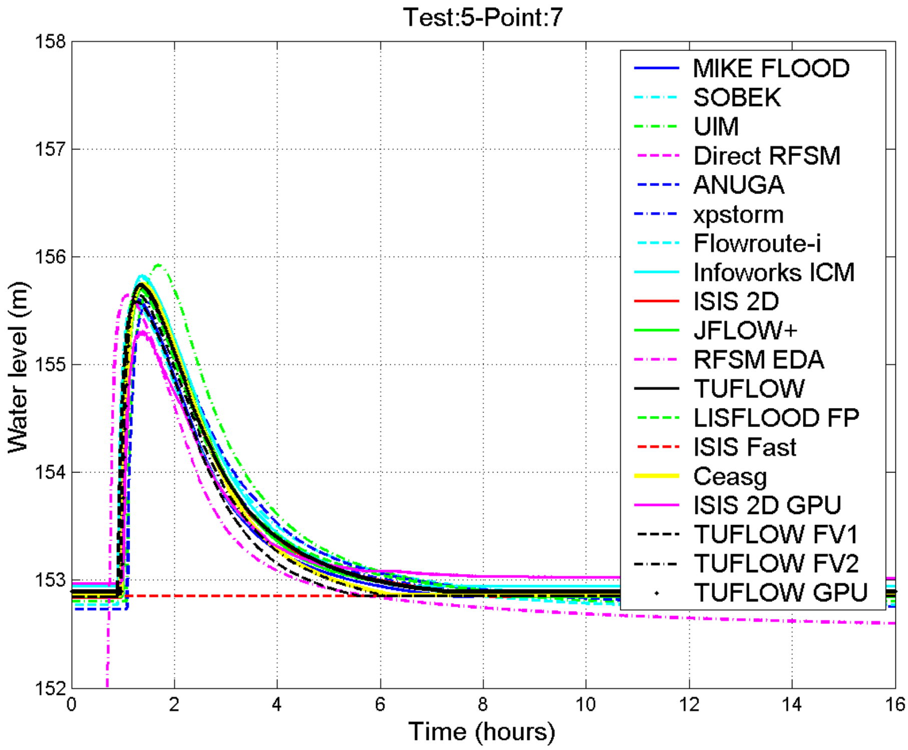
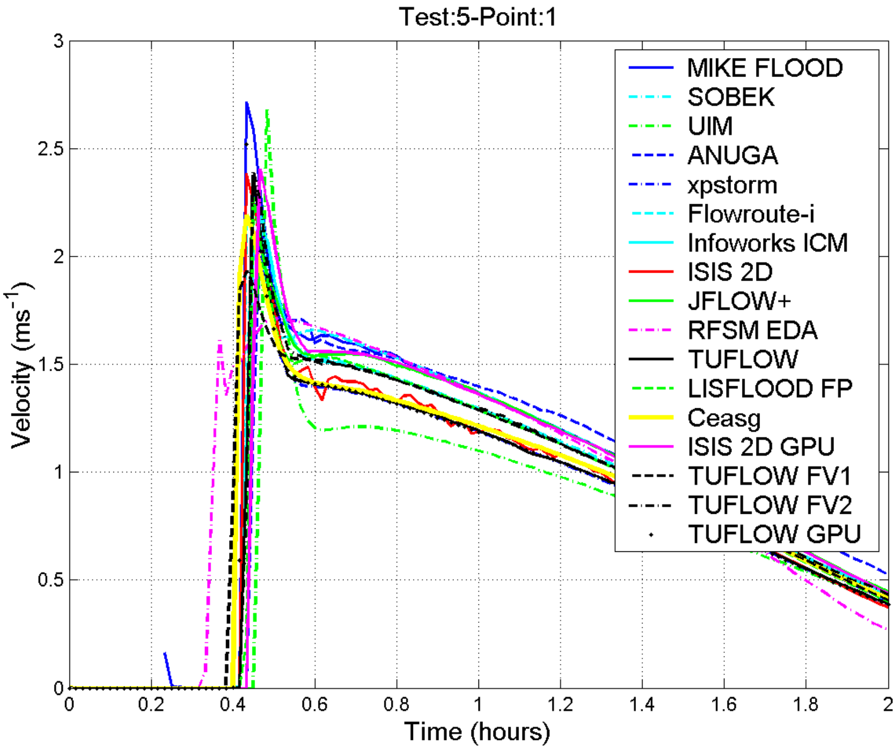
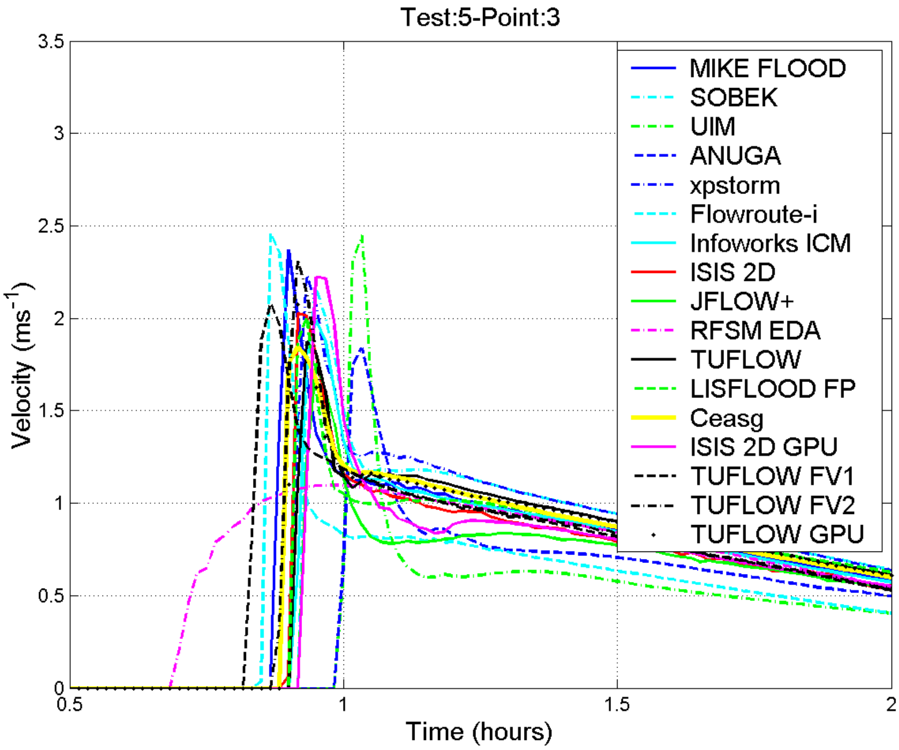
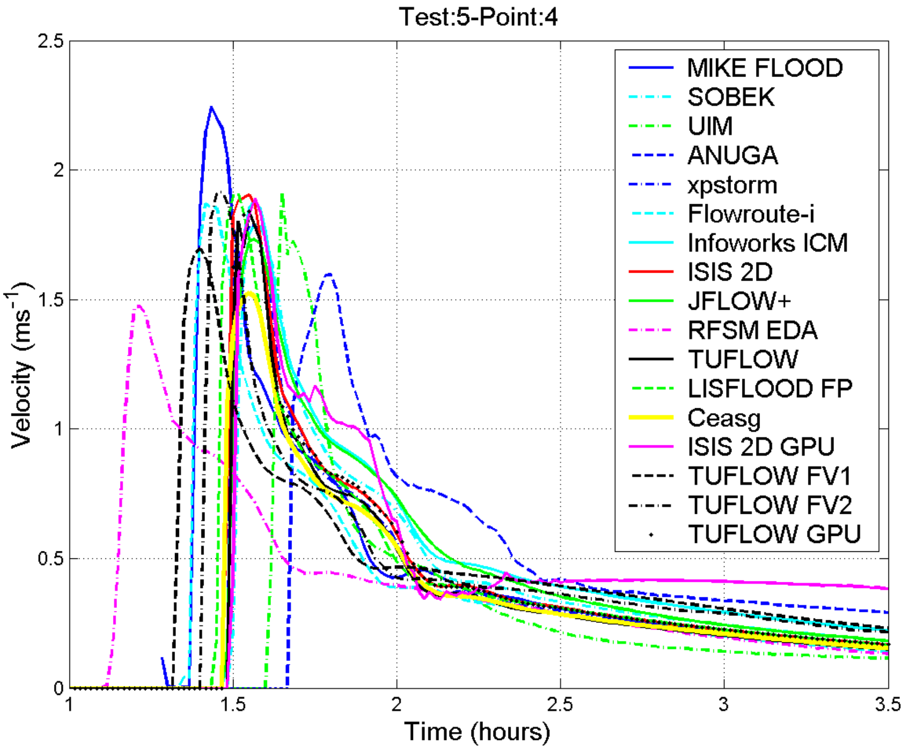


Figure 4.16 Water levels time series (results at a selection of points: 1, 3, 5 and 7)


Test:5-Point:1
Velocity (ms^{-1})
Time (hours)
MIKE FLOOD
SOBEK
UIM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU


Test:5-Point:3
Velocity (ms^{-1})
Time (hours)
MIKE FLOOD
SOBEK
UIM
ANUGA
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



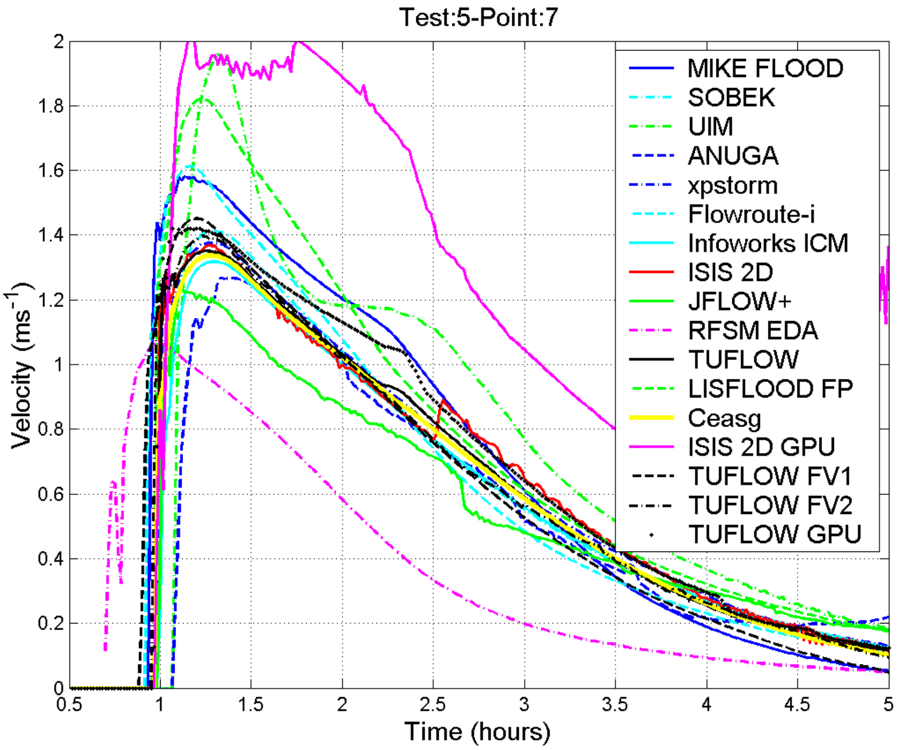


Figure 4.17 Velocities time series (results at a selection of points: 1, 3, 4 and 7)

4.6.3 Results: water level and velocity grids

NB ANUGA water level grids were provided but could not be processed by the software used by the authors.

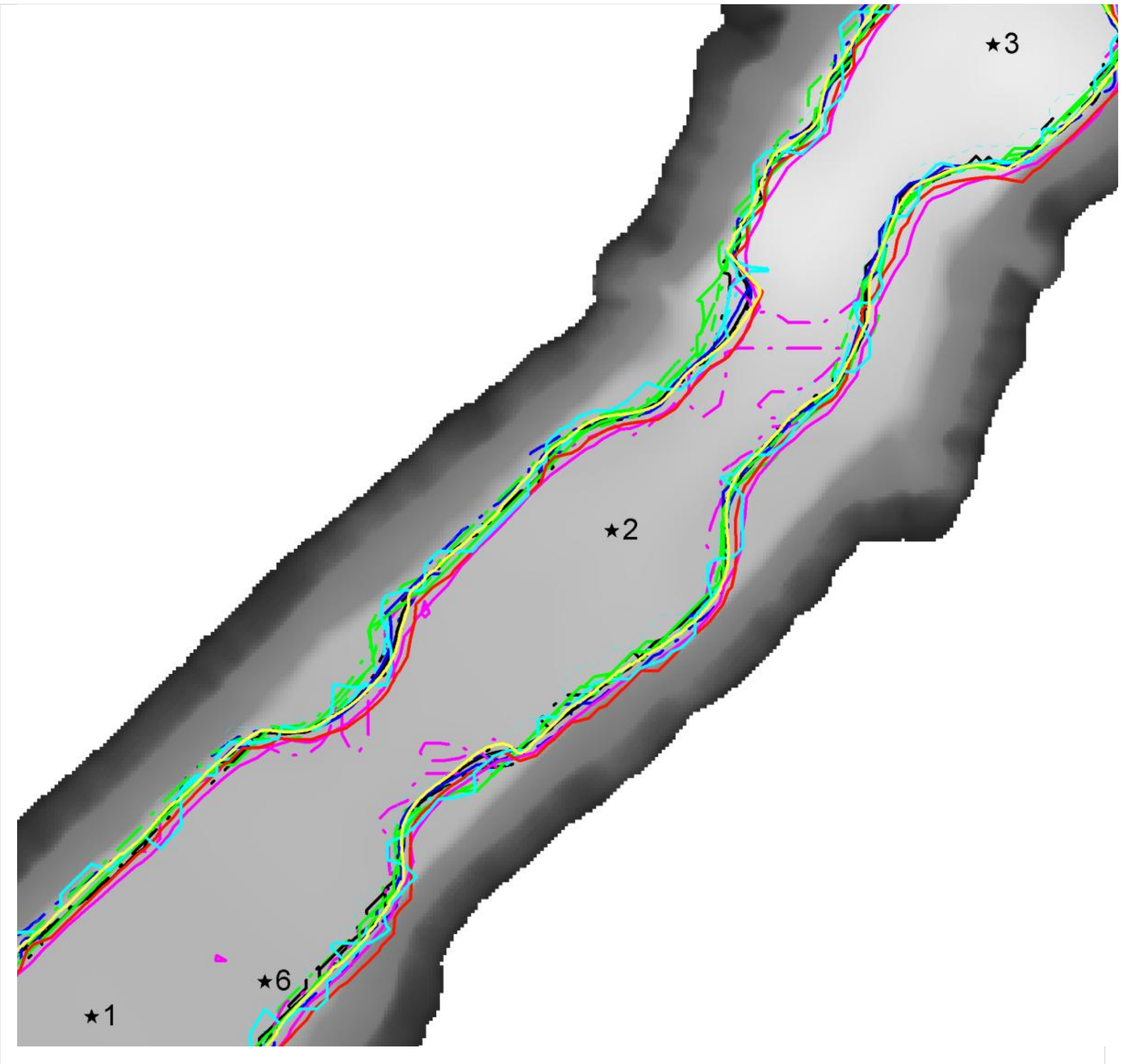


Figure 4.18 0.5m contour lines of peak depths for a section of floodplain in the vicinity of points 1, 2, 3 and 6

Notes: Colour coding as in the rest of the report. For scale, the DEM is approximately 1100m wide.

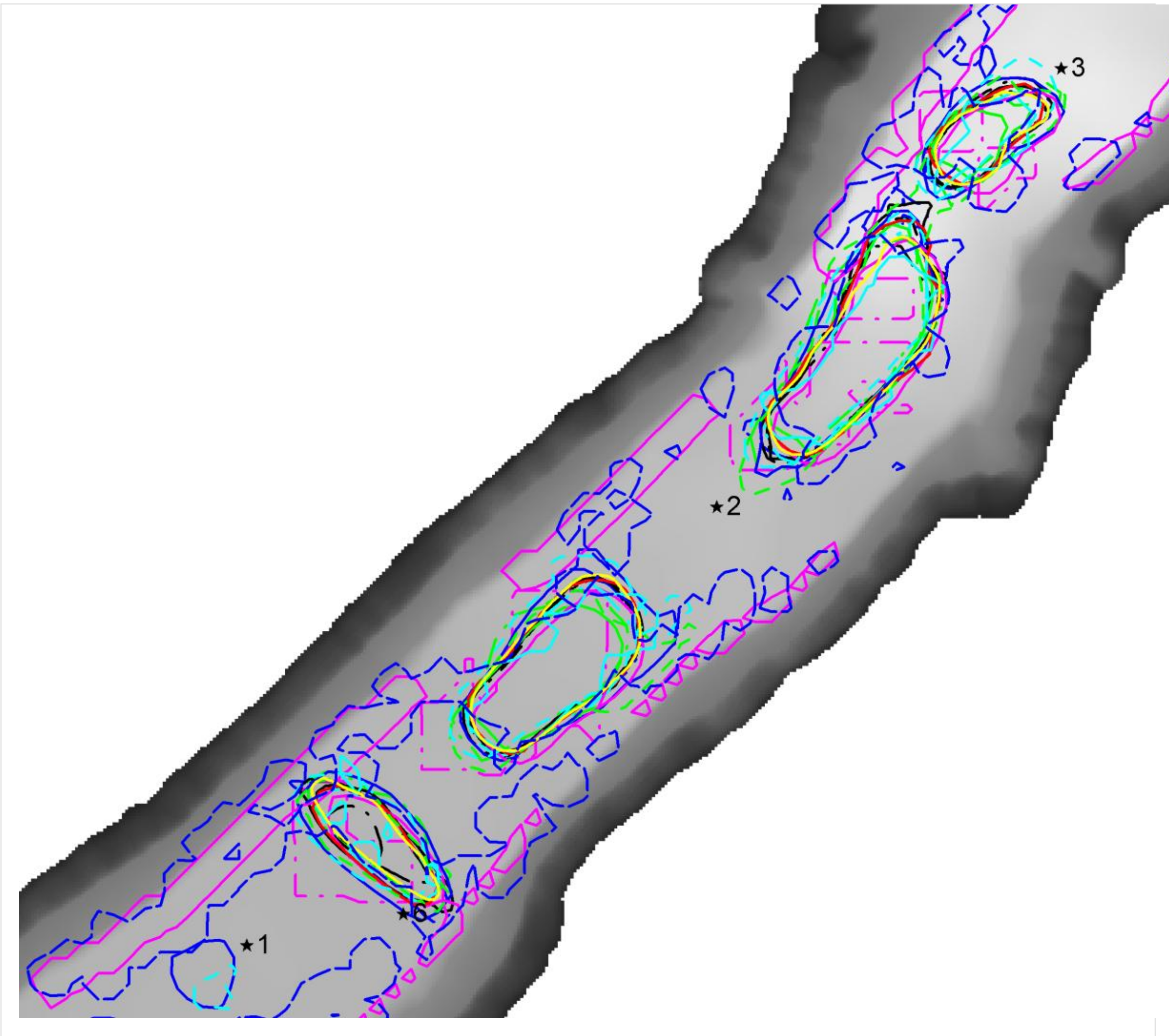


Figure 4.19 3m/s contour lines of peak velocities in the same area as Figure 4.18

Notes: Colour coding as in the rest of the report.

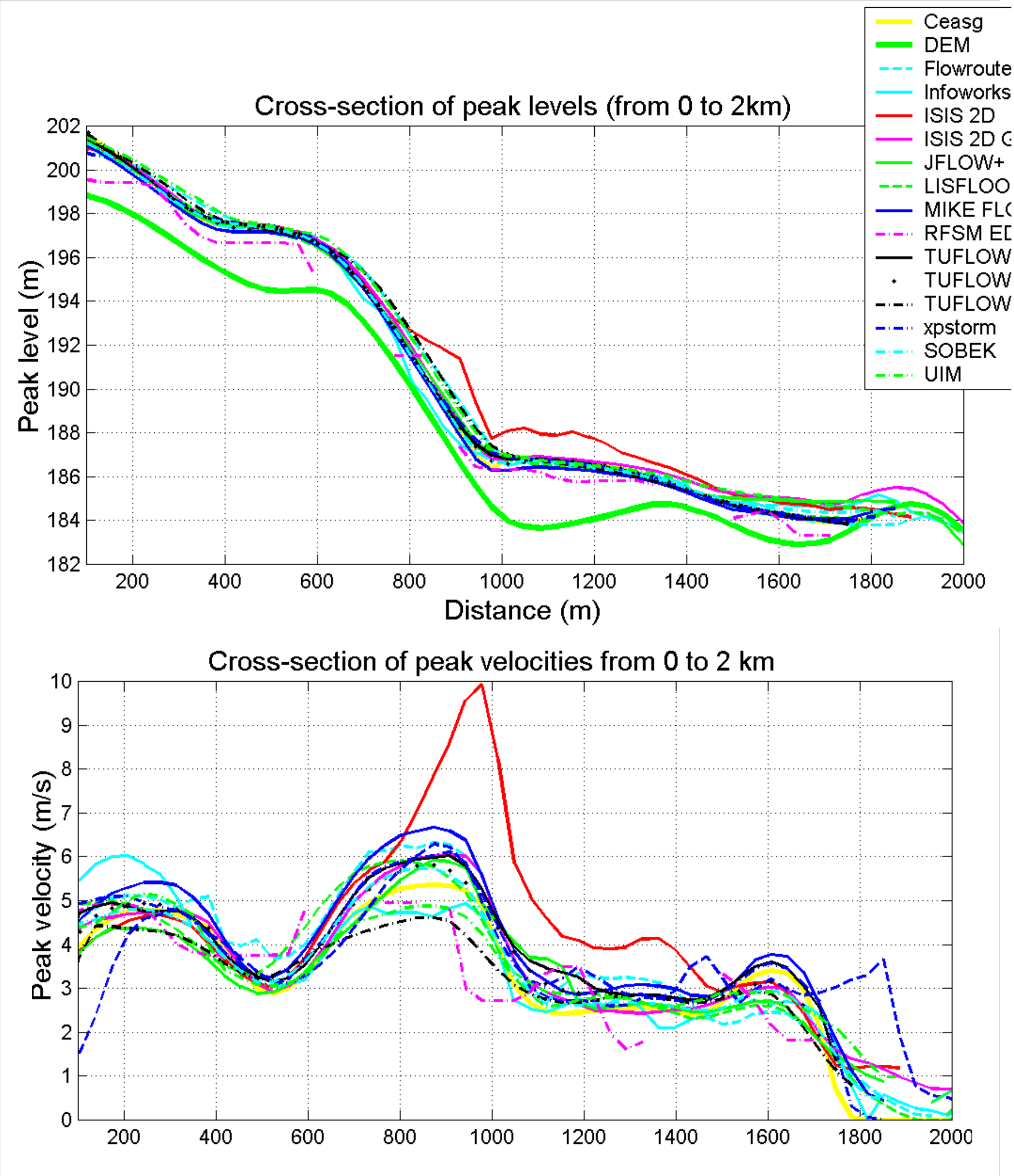


Figure 4.20 Cross-sections of peak levels and velocities along the valley centre line, (see Figure 4.18, 0–2km down from the location of the dambreak

Notes: The thick green line is the ground level (DEM).

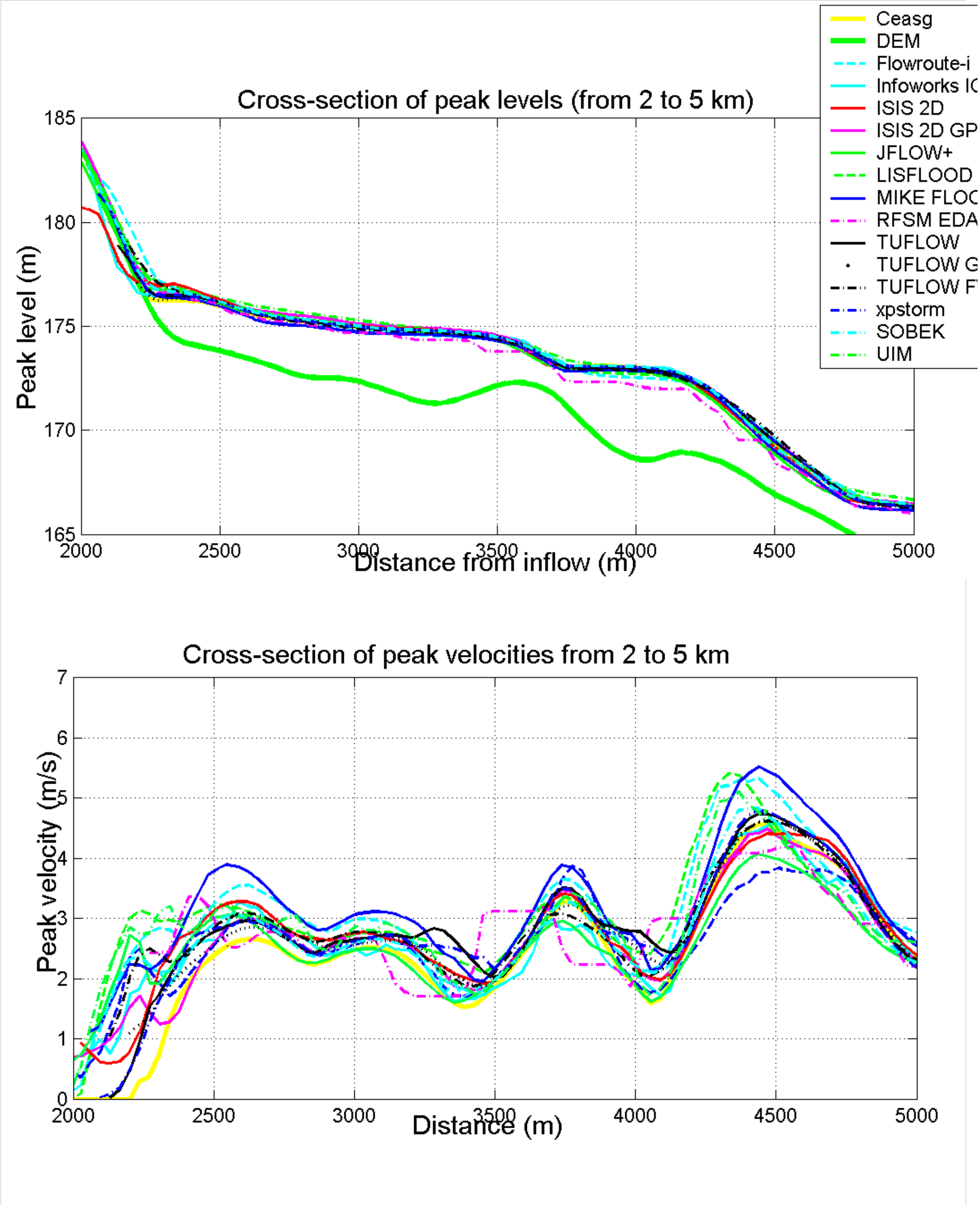


Figure 4.21 Cross-sections of peak levels and velocities along the valley centre line (see Figure 4.18, 2–5km down from the location of the dambreak

Notes: Time series output points 1 and 6 are 3240m and 3670m from the inflow respectively.

The thick green line is the ground level (DEM).

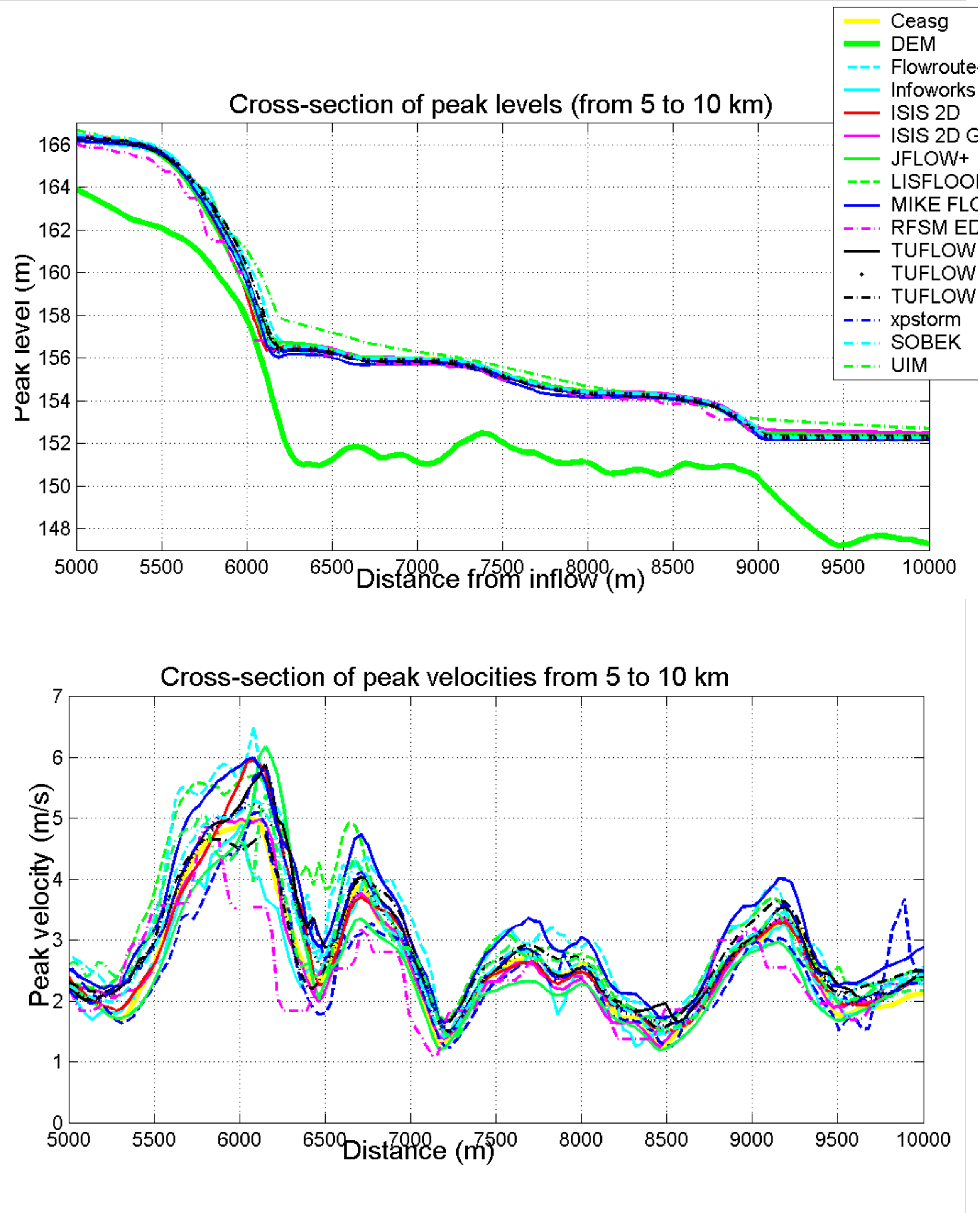


Figure 4.22 Cross-sections of peak levels and velocities along the valley centre line (see Figure 4.18, 5–10km down from the location of the dambreak

Notes: Time series output points 2, 3 and 7 are located 5290m, 7080m and 7330m from the inflow respectively.

The thick green line is the ground level (DEM).

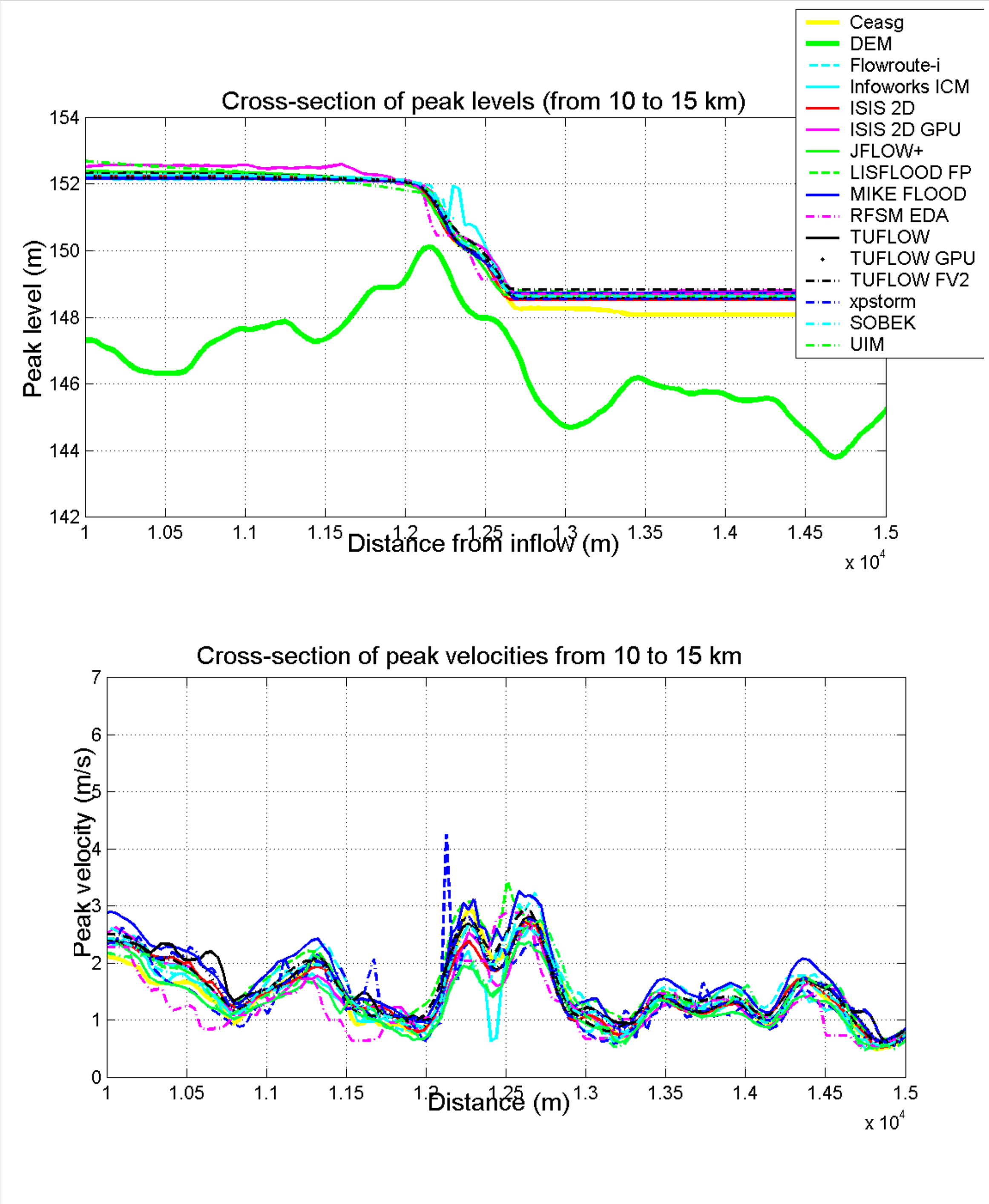


Figure 4.23 Cross-sections of peak levels and velocities along the valley centre line (see Figure 4.18, 10–15km down from the location of the dambreak

Notes: Time series output point 4 is located at 10,460m.

The thick green line is the ground level (DEM).

4.6.4 Summary and interpretation of results

Full SWE models

Arrival times and water levels

Predictions by the full models can be described in general terms as follows. Predictions of flood arrival times were consistent between most models within a maximum range of ~30min at point 5 (bottom of the valley). This is to be compared to a travel time of almost 3h from the location of the assumed dam failure. Peak water levels were consistent with each other within ~0.4m at most points (for example, 1, 3, 7), which at most represented ~10% of the predicted peak depth in the deeper areas of the flow (although differences are greater than this on the edges of the valley where the flood was shallower).

At point 5 (located in a ~2.5km^2 large pond at the downstream end of the valley where the water finally settles after filling any depressions located further upstream), final water levels were all within a 0.4m range. Differences there occur as the result of differences further upstream (amount of water that remains in ‘depressions’, which may be dependent on how the topography is accounted for within the different model grid structures).

Final water levels at other points were usually within a ~0.2m range.

Observations from the cross-section plots in Figures 4.20 to 4.23 are broadly consistent with those from the time series. In addition the peak depth contour plots suggest that agreement between models in the prediction of inundation extent is within the precision allowed by the grid resolution used (50m).

Velocities

The peak velocities predicted by the most full models were within a relatively wider range than peak depths, for example, 1.5–2.2m/s at point 4 and 1.2–1.6m/s at point 7, although again the contour plots confirm that discrepancies are generally within the precision permitted by the 50m grid resolution.

ISIS 2D

The ADI solver of ISIS 2D experienced difficulties in a large area of steep high momentum flow ~1000m from the dam (see Figure 4.20).

ANUGA and ISIS 2D GPU

Exceptions to the general behaviour described above include the large travel times predicted by ANUGA (almost 1.5h at point 5). The final water level predicted by ANUGA was also ~0.5m below those predicted by others at point 5. Evidence of numerical difficulties is observed in areas of very shallow flow (abnormally large velocities). This is visible in the contour plots in Figure 4.19 and the velocity cross-section in Figure 4.20 (from 1700m to 1900m).

A similar behaviour is observed to some extent in the ISIS 2D GPU results, with some spurious residual shallow flow and high velocities even after dewatering, visible in the time series for point 7. In addition abnormally high velocities are predicted in most shallow areas; see the contour plots Figure 4.20 (and the point concerning ISIS 2D GPU in Section 0).

3-term models (LISFLOOD-FP, RFSM-EDA)

The results are generally similar to those of the full SWE models, although with some relatively minor differences in the flood wave dynamics (see, for example, RFSM EDA at points 1 and 3). The flood wave front appears to arrive at point 5 earlier by ~0.5h with RFSM EDA.

The peak water level elevations are broadly consistent, although slightly outside the range of the SWE model predictions, resulting in some noticeable differences in the peak inundation extent predicted by RFSM EDA (and amplified by the coarser resolution used); see Figure 4.18.

The velocity predictions were at times in significant disagreement with the SWE models (see RFSM EDA at point 3 or in Figure 4.19, or the peak velocities of LISFLOOD-FP at 6500m in 22).

The predictions from LISFLOOD-FP were, in this category, those that best matched the results by the full SWE models.

2-term model (UIM)

The results are generally similar to those of the full SWE models, although with some differences in the flood wave dynamics (for example, point 7). The flood wave front appears to arrive at point 5 later by ~1h.

The peak water level elevations are broadly consistent, although slightly outside the range of the SWE model predictions (for example, between 6000 and 7000m where higher peaks are observed, probably due to model oscillations). UIM also exhibited some oscillatory patterns at points 2 and 6 during the receding phase of the flood (not represented here).

0-term models (ISIS Fast, RFSM Direct)

RFSM Direct and ISIS Fast do not predict any velocities, transient peak levels or travel time, only final levels which have little practical relevance in a dam failure scenario. It is acknowledged that the final levels predicted in this test are in agreement with the full models' predictions.

4.6.5 Miscellaneous model parameters

Table 4.6 Miscellaneous model parameters for Test 5

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 50m or 7600 elements)	(5) Time-stepping	(6) 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
InfoWorks ICM	2.5.2	Yes – GPU	7758 triangles	60s	9s
ISIS 2D	3.6 (ADI)	Partial [1]	50m	5s	58.5s
ISIS 2D GPU	1.17	Yes	50m	Adaptive	57s
ISIS Fast	3.6	No	50m	N/A	3.6s
JFLOW+	2.0	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 [1]	N/A	<1s
RFSM EDA	1.2	No	530 elements [1]	Adaptive typical 10–15s	13.8s
SOBEK	2.13	No	50m	10s	168s
TUFLOW	2012-05-AA Single precision	No	50m	Adaptive (5–18s)	26s
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	50m	Adaptive (2.4–3.3s)	9s [2]
TUFLOW FV [3]	2012.000b First order (and second order)	Yes – 12 CPU cores	7424 elements	Adaptive (~1s)	67s (150s)
UIM	2009.12	OMP	50m	0.5s	2670s

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 50m or 7600 elements)	(5) Time-stepping	(6) Run time
XPSTORM	2011 2010-10-AB-iDP-w32	No	50m	10s	52.3s

Notes: [1] See Appendix B.

[2] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[3] Run times: first order solution (second order solution)

Other information provided

Ceasg: 'The Ceasg simplified flow model is intended for use at significantly higher resolutions than 50m; within the model formulation are underlying assumptions that become weaker as the model resolution is reduced. While the model can technically be applied to very coarse grids, this can only be recommended for flow routing purposes where the vertical resolution of the available data is also coarse (for example, 1m vertical resolution). Wherever higher resolution data is available, it is strongly recommended that it is used. In line with this advice, the native 10m DTM has been used for this test'.

ISIS: 'The ADI solver provides sensible results for this test case, however sharp peaks in velocities indicates its lack of shock capturing capabilities in small areas with high topography gradients. For tests with higher predominance of transcritical flow TVD scheme should be used'.

ISIS 2D GPU: 'High velocities seen on the edges of the flood extent can be attributed to the very steep valley walls where velocities are calculated by dividing the flow calculated at the cell centre by the average cell depth (bed elevations are sampled at cell corners). The steep bed gradient of the cell causes the flow to be divided by a very small depth, resulting in large velocities where cells are wetting and drying on steep slopes'.

ISIS Fast: 'ISIS FAST only calculates the final state of the water elevation (maximum of sequential iterations), depending on the volume in the domain and the boundary conditions. No time series is generated. ISIS FAST includes a feature to determine probable flow paths, which when displayed together with the final results gives a sensible idea of the maximum flood extent. However this feature does not provide any calculated water depth for the flow paths. ISIS FAST gives a sensible idea of the final extent of the flood and a quick estimation of water levels, but is not suitable to analyse wave propagation. ISIS FAST can be used in a test like this specially for broad-scale screening analysis in order to identify critical areas or scenarios'.

ISIS Fast Dynamic: 'ISIS FAST Dynamic is under heavy development – due to the topographic characteristics of this test, results are not yet sensible'.

RFSM EDA: 'The shorter travel times observed with RFSM EDA are the 'result of using large grid size for flow on slopes'. Test 5 was also run with the specified grid resolution of 50m, and the results were visually indistinguishable from the other models

(Jamieson et al. 2012a). The large computational elements mean that water can travel too fast on slopes, as can be seen in these results. In common floodplain topography this does not occur'.

Authors' response: The topography used in Test 5 was derived from the topography of a real valley that is not unlike typical valleys where dams may be built.

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

TUFLOW GPU: Produces results consistent with TUFLOW, TUFLOW FV.

TUFLOW FV: 'Results consistent with other full 2D solvers. First order solution produces lower peak velocities'.

4.6.6 Conclusions from Test 5

All **full SWE models** predicted similar results in terms of travel times and peak flood levels, within a precision range that is likely to be adequate for a problem of this type and scale in a practical application. However, predictions of flood extent along the edges of inundation where depths are shallow are unlikely to be consistent between packages.

The differences observed in the velocity predictions by the full models suggest that predictions of velocity (or of any variable, such as hazard, that is a function of velocity) by any particular model are likely to agree to within an order of magnitude rather than a precise quantification, particularly in practical applications where more complex local flow patterns may be expected and may be inadequately modelled at a relatively coarse resolution.

The results from the ANUGA and ISIS 2D GPU models featured abnormally high velocities, particularly in areas of shallow flow. These were either due to numerical difficulties or to the approach used to generate results in gridded format from the raw output.

The simplified **3-term models** and UIM were broadly accurate when predicting peak flood levels, less so when predicting travel times, velocities, or any flow patterns in detail, for which the use of a full SWE model seems to be the most desirable for this class of flooding. LISFLOOD was found to give the best comparisons in this category.

ISIS Fast Dynamic was found to be inadequate and was therefore not run. RFSM Direct and ISIS Fast were inadequate in the prediction of anything other than a 'final' inundation extent.

4.7 Test 6: Dambreak

4.7.1 Test 6A: laboratory scale

Introduction

This dambreak test case (see Appendix A.6 for details) is the original benchmark test case available from the IMPACT project (Soares-Frazão and Zech 2002), for which measurements from a physical model at the Civil Engineering Laboratory of the Université Catholique de Louvain (UCL) are available. The physical dimensions are those of the laboratory model. The test involves a simple topography, a dam with a 1m wide opening, and a building downstream of the dam (see Figure 4.24). An initial condition is applied, with a uniform water level of 0.4m upstream from the dam, and 0.02m downstream.

Measured water levels and velocities were provided by UCL for six points (G1 to G6, except for velocities at G6). Some of the measurement data are missing for part of the time, particularly velocities.

The objective of the test is to assess the package's ability to simulate hydraulic jumps and wake zones behind buildings using high-resolution modelling.

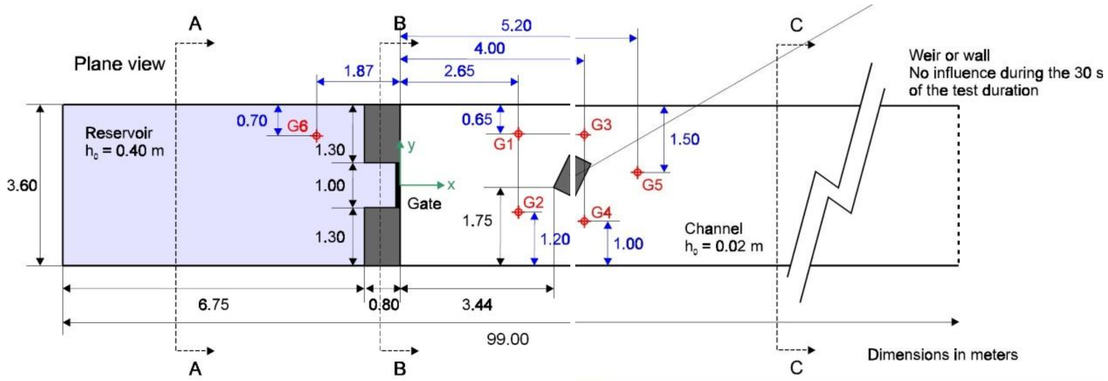
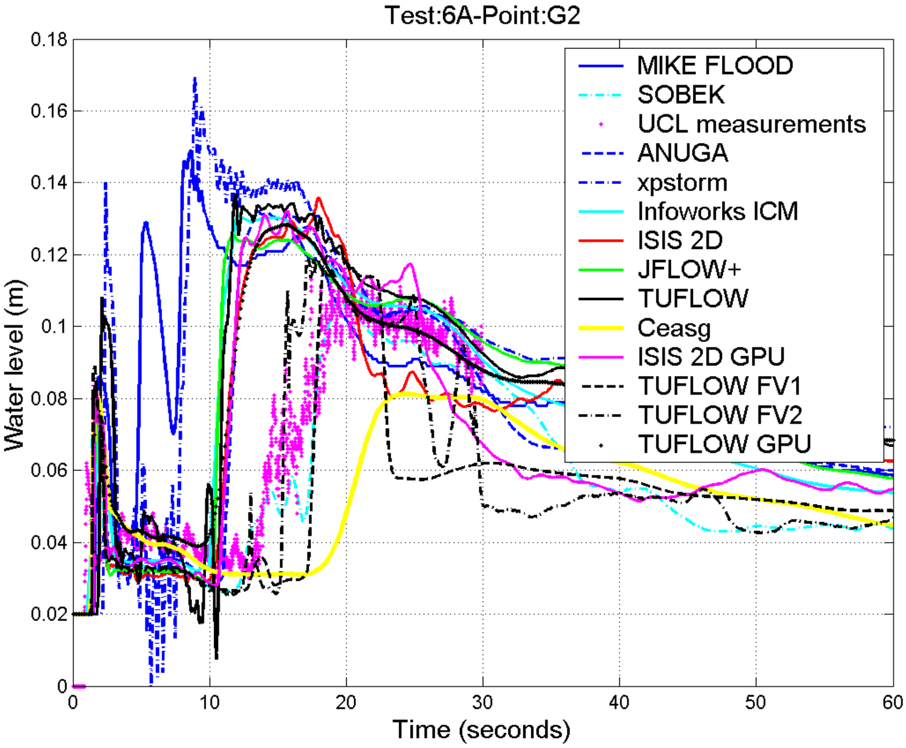
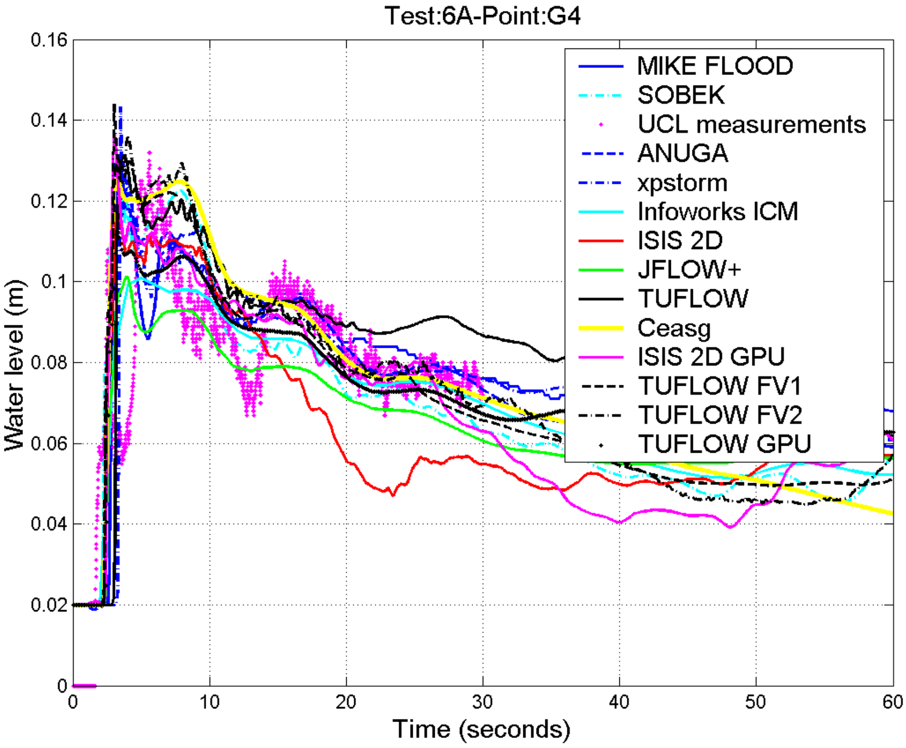
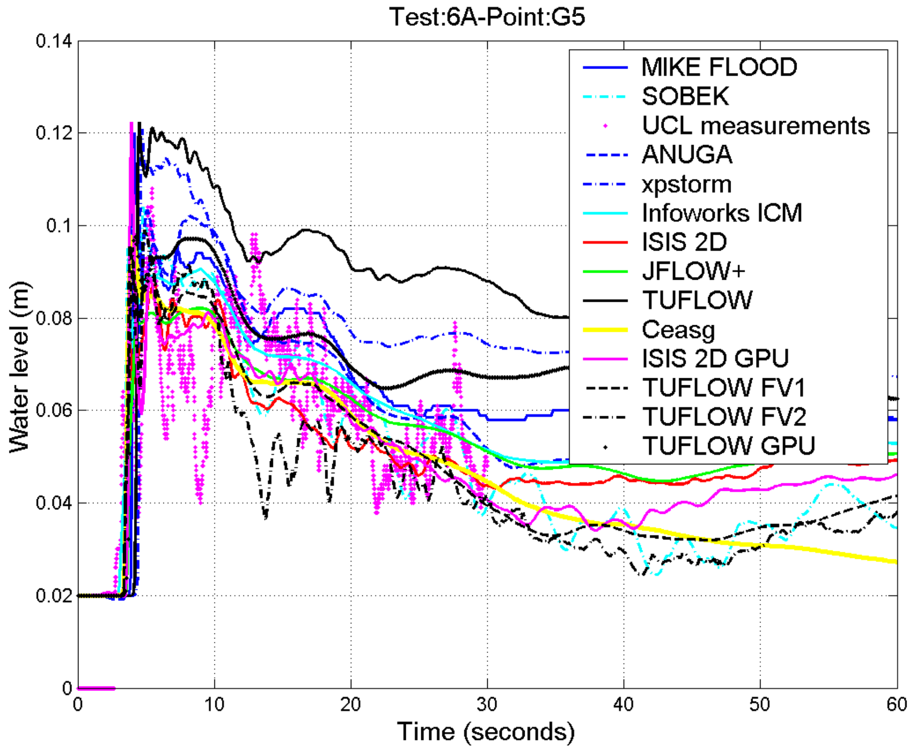


Figure 4.24 Set-up for Test 6A (adapted from Soares-Frazão and Zech 2002)

Water level and velocity time series







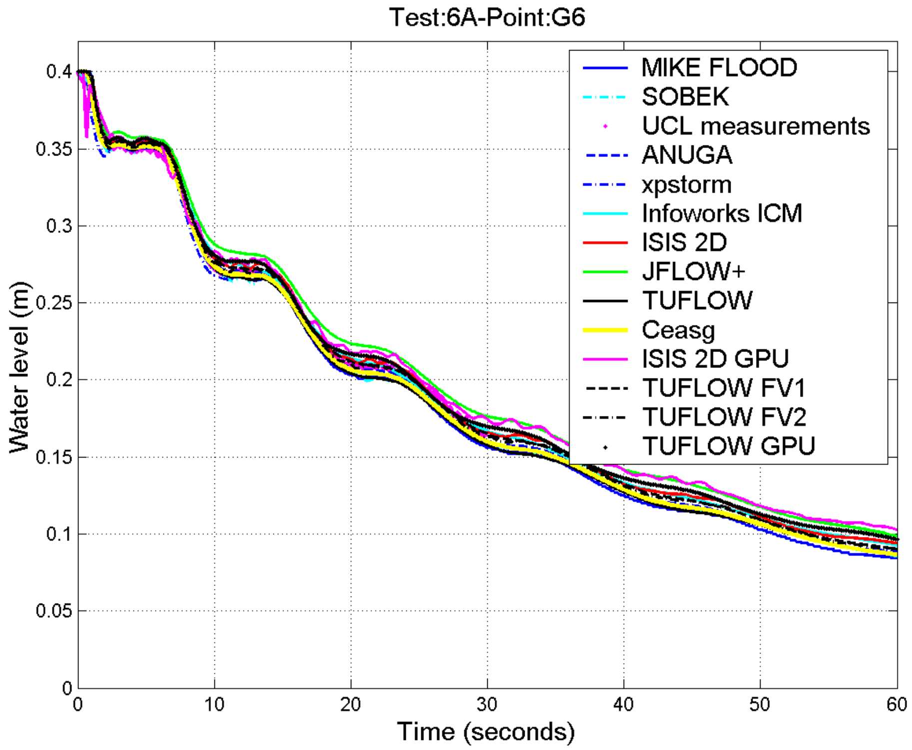
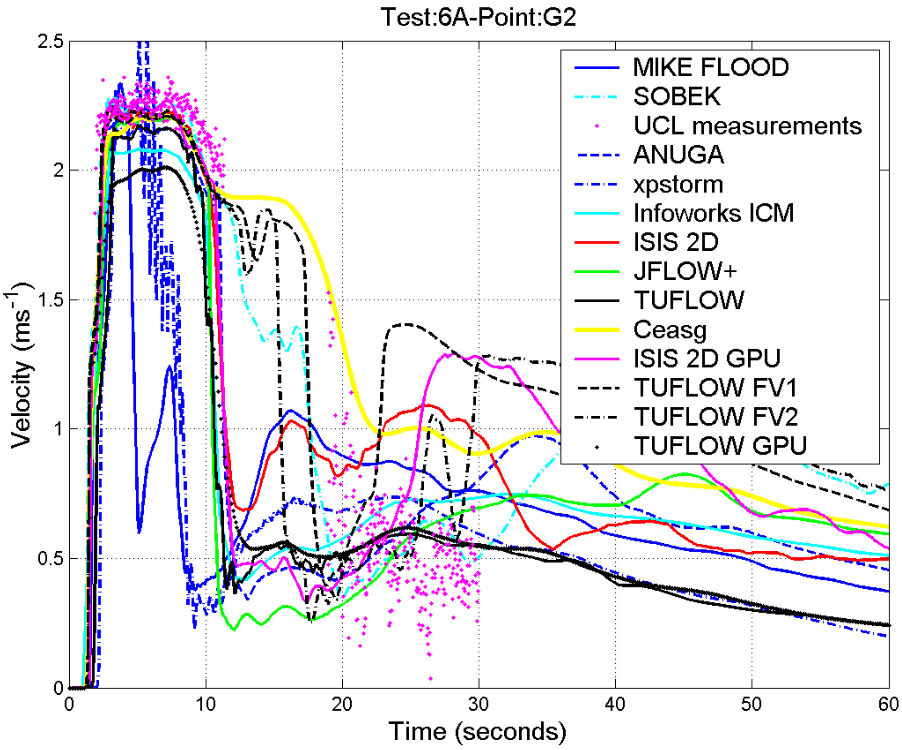


Figure 4.25 Water levels time series (results at a selection of points: G2, G4, G5 and G6)



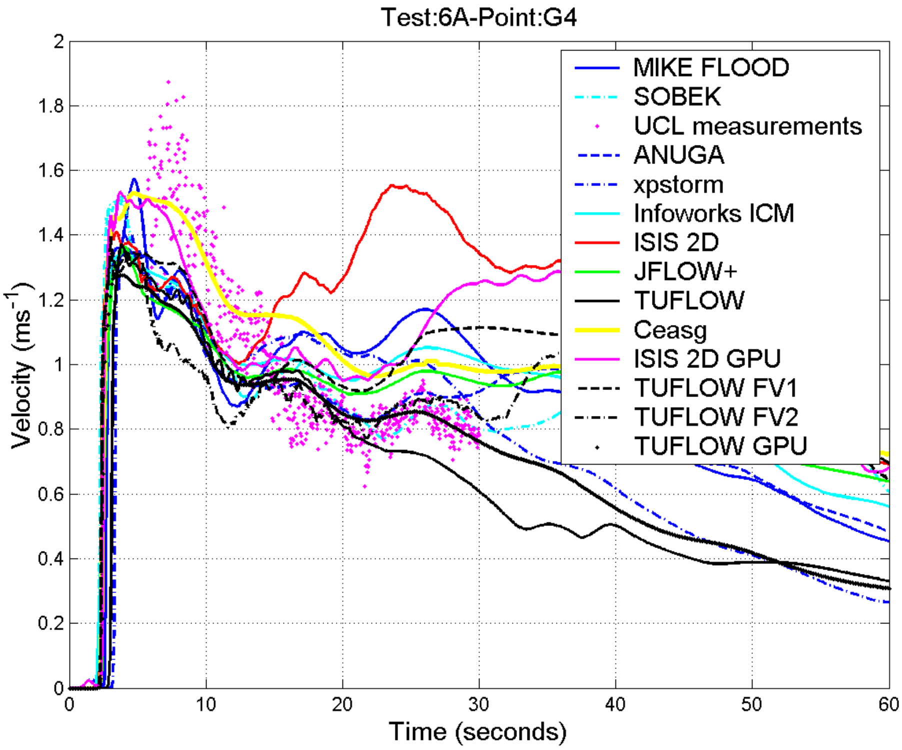


Figure 4.26 Velocities time series (results at a selection of points: G2 and G4)

Summary and interpretation of results

Full SWE models

Only full SWE models participated in Test 6A.

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

Comments on the initial 30s phase for which UCL measurements were available are as follows.

At point G6 upstream from the gate, water level predictions were in excellent agreement with UCL measurements (no velocity measurements were available at G6), reflecting the periodical behaviour of the flow through the gate with a period ~9s. Discrepancies in depth predictions at G6 had a relative magnitude of ~10% at most, suggesting that the flow through the gate was accurately modelled.

Consistent observations at other points cannot be made. Most models predicted water level and velocity variations within the range in which the UCL measurements oscillated, but the transcritical flow patterns caused by the water deceleration downstream from the gate and by the interaction with the building were not consistently and accurately predicted by any of the models. At best there was usually a discrepancy in the timing of transitions. However the shock capturing schemes clearly performed better in the modelling of these transitions, see for example, point G2 (with Ceasg predicting a less well-defined critical transition, and XPSTORM exhibited a markedly oscillatory behaviour[3]).

[3]This would be due to using an older version of the TUFLOW solver.

Miscellaneous model parameters

Table 4.7 Miscellaneous model parameters for Test 6A

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 0.1m or 36,000 elements)	(5) Time-stepping	(6) Run time	(7) Eddy viscosity (m^2/s) [1]
ANUGA	1.1beta_7501	No	37,046 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+	2.0	Yes – GPU	0.1m	Average 0.032s	2.9s	None
LISFLOOD-FP	Not tested					
MIKE FLOOD	2012	Yes – 8 CPUs	0.1m	0.025s	59s	0.01
SOBEK	2.13	No	0.1m	0.02s	390s	0
TUFLOW	2012-05-AA Single precision	No	0.1m	Adaptive (0.01–0.5s)	32s	Spatially and time varying [2]
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	0.1m	Adaptive (0.013–0.05s)	5s [3]	As for TUFLOW
TUFLOW FV [4]	2012.000b First order (and second order)	Yes – 12 CPU cores	31,254 elements	Adaptive (~0.005s)	45s (87s)	Spatially varying using S = 0.2 [5]
XPSTORM	2011 2010-10-AB-iDP-w32	No	0.1m	0.05s	42.9s	0.05 S + 0.05 C [6]

Notes: [1] ‘N/A’ in column (7) refers to the fact that the model does not account for Eddy viscosity.

[2] Eddy viscosity recalculated every time step using the Smagorinsky velocity based formulation with a coefficient of 0.5, plus a constant component of 0.05m^2/s. The majority of the model had peak values of 0.05–0.07m^2/s, with localised areas of large velocity gradients experiencing peak values up to 0.09m^2/s.

[3] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[4] Run times: first order solution (second order solution)

[5] 0.2 (Smagorinsky)

[6] 0.05 (Smagorinsky) + 0.05 (Constant)

Other information provided:

Flowroute-*i*™: 'At the time of submission, Test 6 was not carried out using Flowroute-*i*™ as shock capturing was not supported at this time. Implementation of a computationally efficient shock capturing routine is included within our development pathway for 2013'.

Ceasg: 'The Ceasg model faithfully reproduces the dynamic effects anticipated, including the formation of a hydraulic jump immediately in front of the building which migrates upstream as the outflow from the breached reservoir lessens. The results presented here have been generated at the resolution and roughness suggested; no additional sensitivity testing has been performed, but it is suggested that there is likely to be a high sensitivity to roughness and cell size. Many of the dynamic behaviours this test is designed to examine are likely to be heavily dependent on these parameters'.

TUFLOW: As for Test 5, the enhancements in the 2012-05-AA release for supercritical flows provide an improvement in the results compared with 2010. The 'Number Iterations == 4' setting was used to improve convergence.

TUFLOW GPU: The finite volume shock capturing is aptly demonstrated with the TUFLOW GPU results. Even better reproduction of the hydraulic jump and comparison with the flume test results in Test 6A are achieved using a 0.05m grid.

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

Conclusions from Test 6A

Test 6A did not demonstrate conclusively a superior ability on the part of any of the **full SWE models** to accurately predict hydraulic jumps and wake zones around buildings on the scale of physical model data. Ranges of variability, that is, peaks (which are important in flood management applications) were predicted rather than values of water levels at specific times. Shock capturing schemes, however, tended to perform better in this respect.

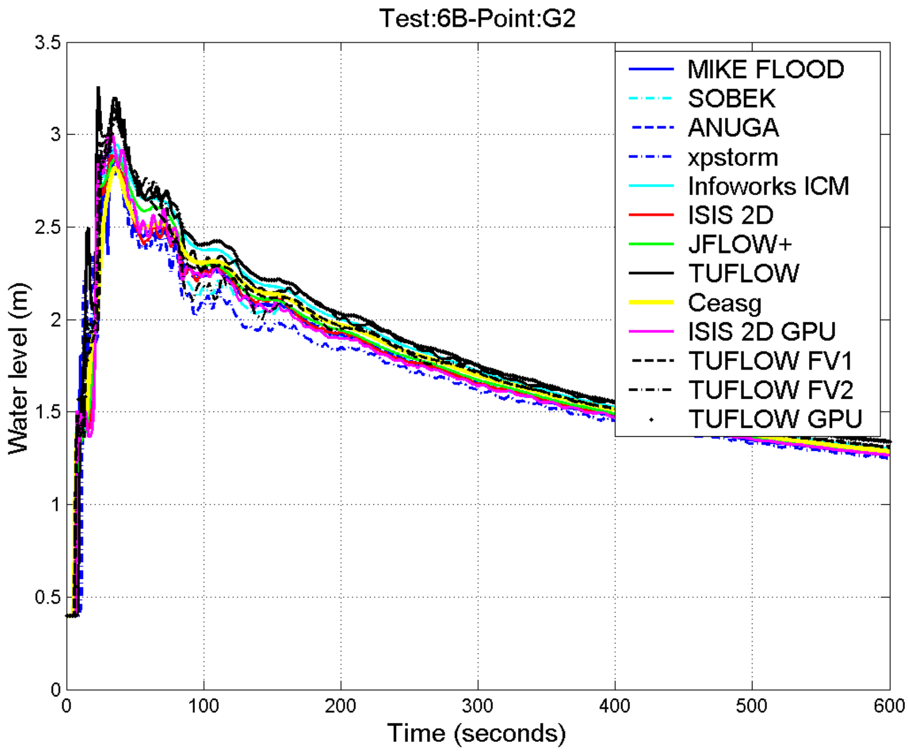
4.7.2 Test 6B: field scale

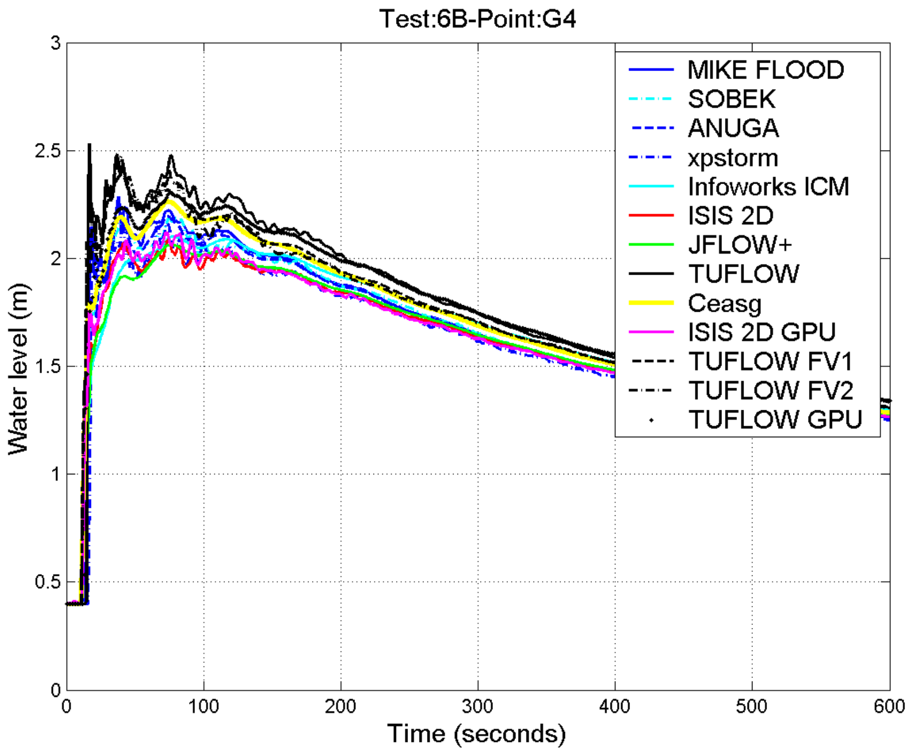
Introduction

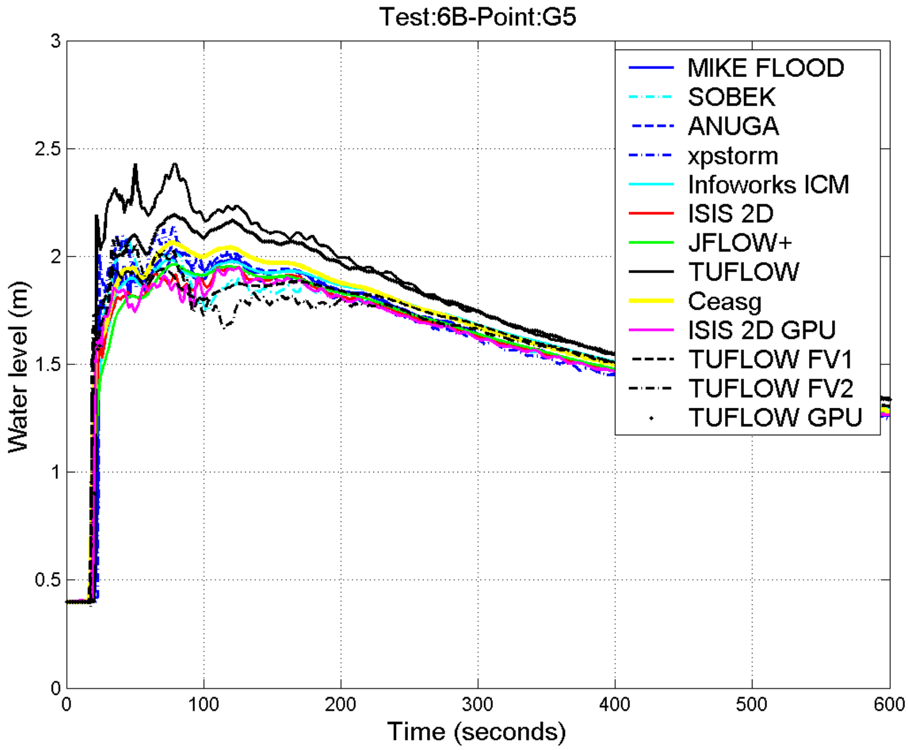
This dambreak test case (see Appendix A.6 for details) has been adapted from the original IMPACT test case (Test 6A), where all physical dimensions (including the initial water levels) have been multiplied by 20 to reflect realistic dimensions encountered in flood inundation modelling applications. Thus the canal is 72m wide, the building 16m by 8m, and the initial condition consists of a uniform water level of 8m upstream from the dam, and 0.4m downstream.

The objective of the test is to assess the package's ability to simulate hydraulic jumps and wake zones behind buildings at the field scale using high-resolution (2m) modelling.

Results: water level and velocity time series







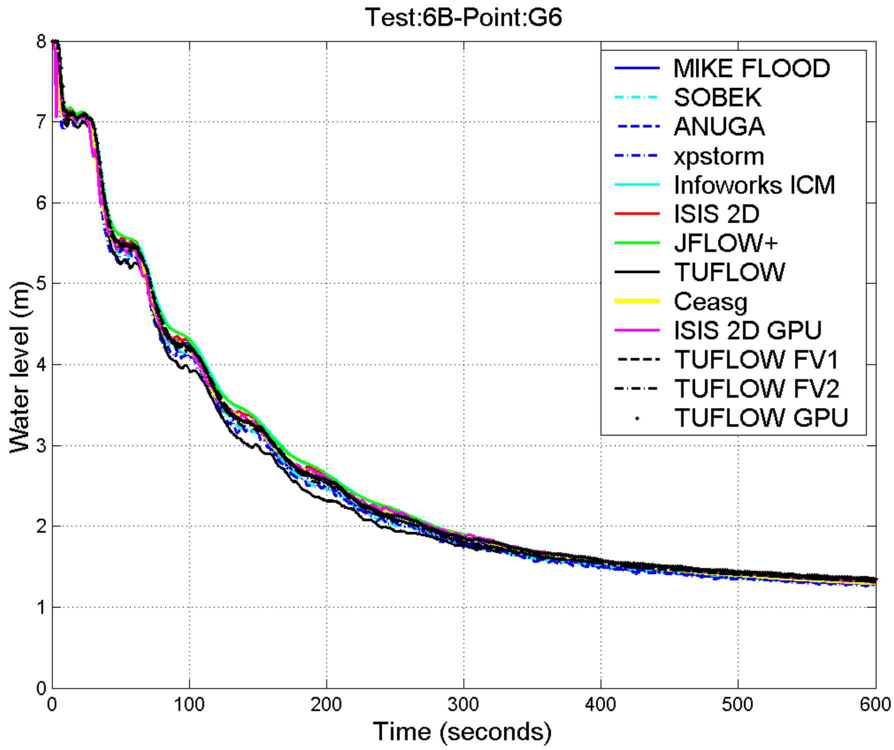
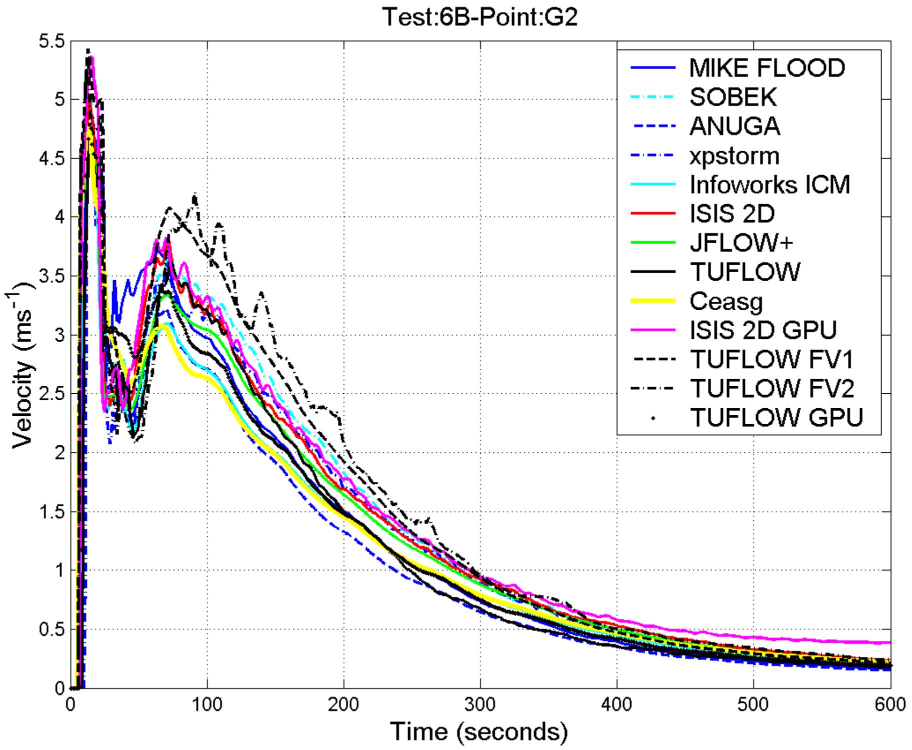


Figure 4.27 Water levels time series (results at a selection of points: G2, G4, G5 and G6)



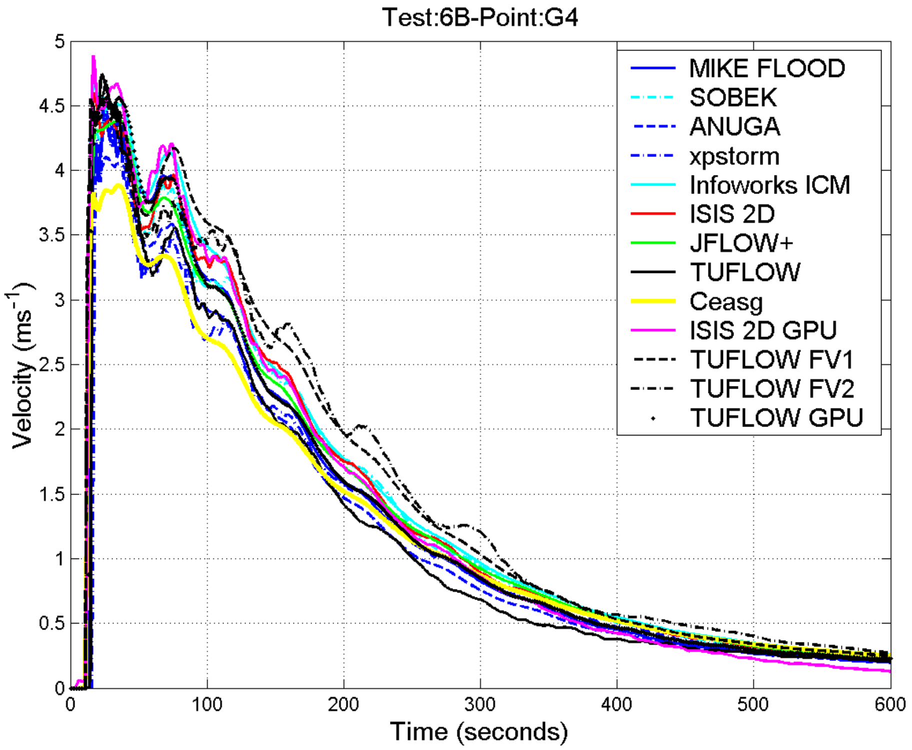


Figure 4.28 Velocities time series (results at a selection of points: G2 and G4)

Results: peak water level and velocity grids

NB: ANUGA grids were provided but could not be processed by the software used by the authors.

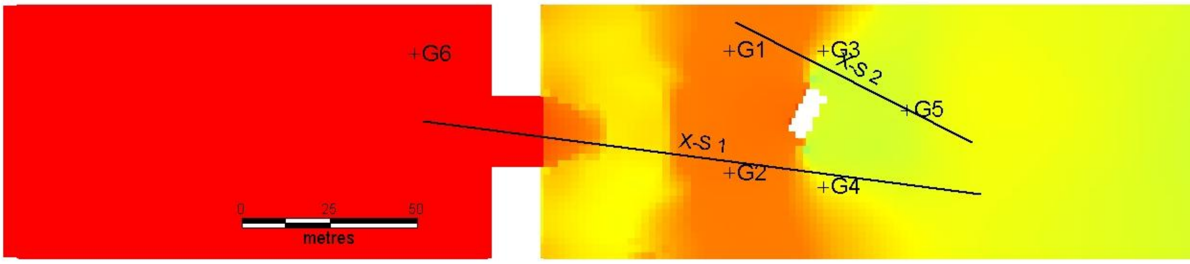


Figure 4.29 Plan view showing the hydraulic jump and the locations of the cross-sections (from a peak water level grid)

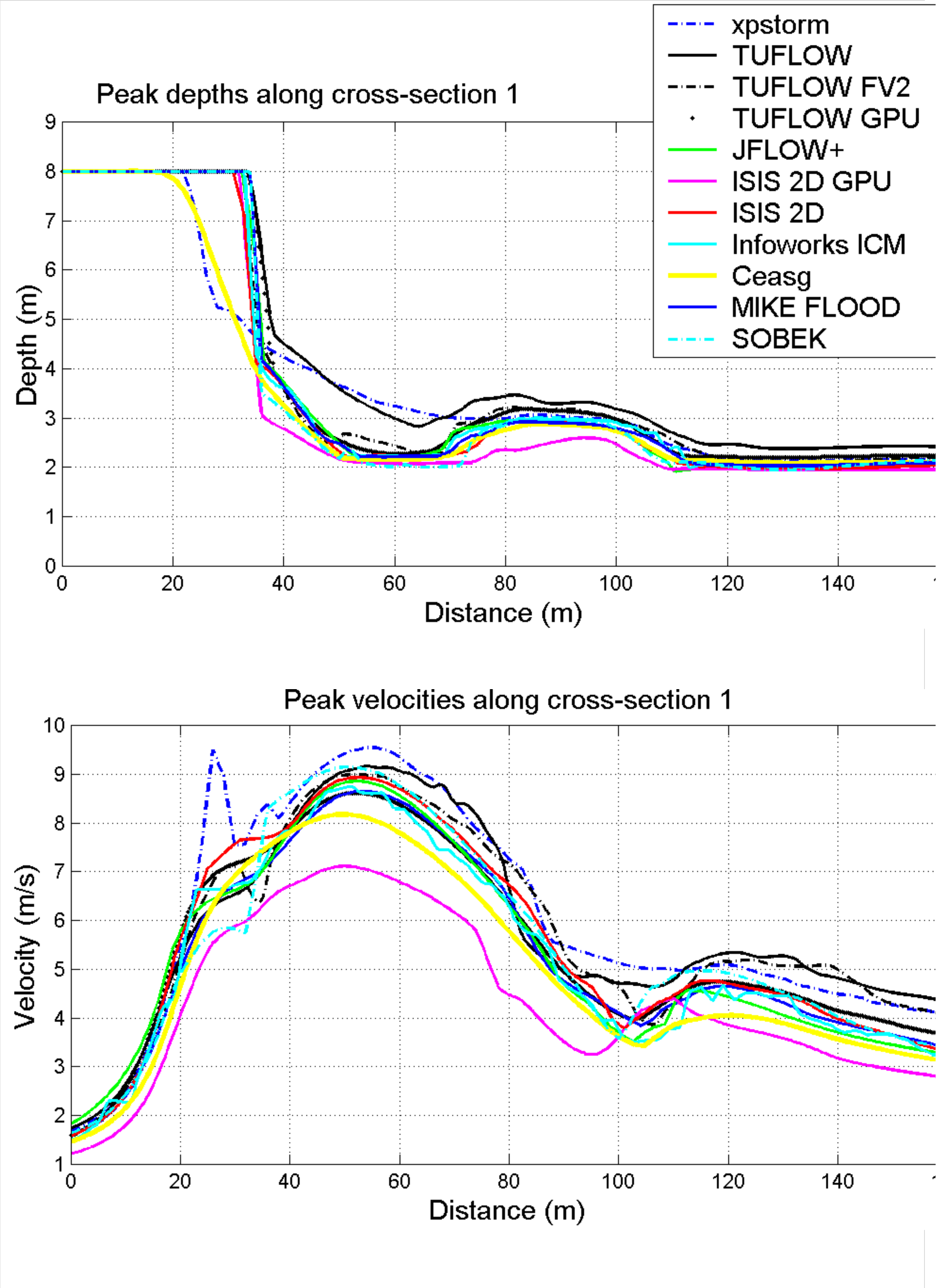


Figure 4.30 **Peak water level elevations and velocities along cross-section 1**

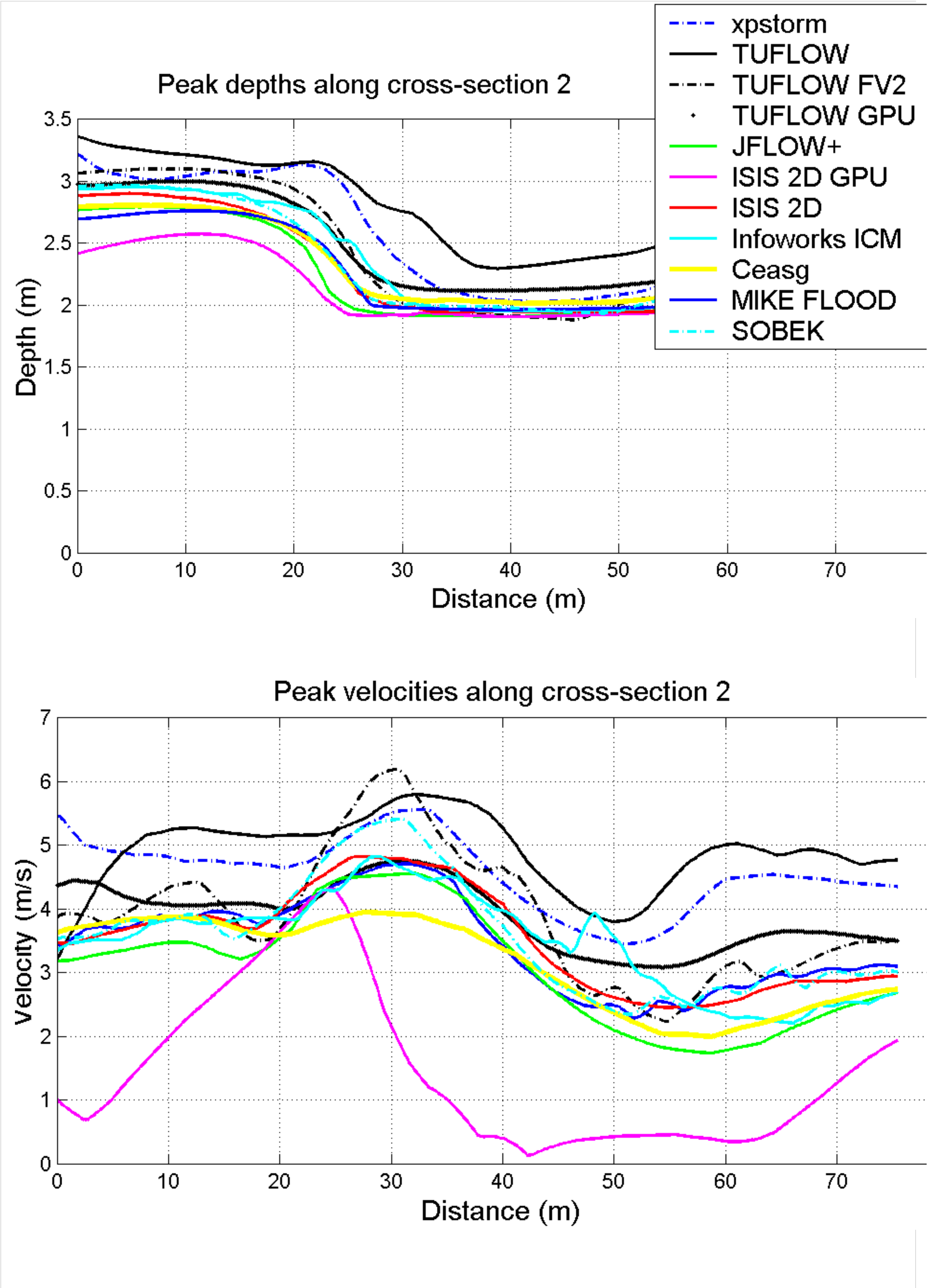


Figure 4.31 Peak water level elevations and velocities along cross-section 2

Summary and interpretation of results

Full SWE models

Only full SWE models participated in Test 6B.

As in Test 6A, all models agreed (within a 5–10% range) in the prediction of the water level decrease upstream from the constriction (point G6) after the removal of the dam, with a periodical behaviour similar to that observed in Test 6A.

At points downstream from the gate, model predictions were generally consistent with each other, with predictions of peak depths being within 15–20% of each other, or within a 50cm wide range (see Figure 4.27). A similar comment can be made regarding peak velocities (Figure 4.28). However, some degree of oscillatory behaviour, particularly in the high momentum region downstream from the gate opening means that the cross-sectional values from the peak D and peak V grids are often higher with TUFLOW and XPSTORM than with other models (Figures 4.30 and 4.31).

ISIS 2D GPU

ISIS 2D GPU has much lower peak velocities in parts of space domain (for example, along cross-section 2). This is not corroborated by any similar observations in the time series at the output points.

Miscellaneous model parameters

Table 4.8 Miscellaneous model parameters for Test 6B

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 2m or 36,000 elements)	(5) Time-stepping	(6) Run time	(7) Eddy viscosity (m^2/s) [1]
ANUGA	1.1beta_7501	No	36,219 elements	Adaptive	1390s	N/A
Ceasg	1.12	No – GPU	2m	0.1s	14s	N/A
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+	2.0	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
TUFLOW	2012-05-AA Single precision	No	2m	Adaptive (0.1–3.3s)	38s	Spatially and time varying [2]

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 2m or 36,000 elements)	(5) Time-stepping	(6) Run time	(7) Eddy viscosity (m^2/s) [1]
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	2m	Adaptive (0.06–0.25s)	12s [3]	Same as TUFLOW
TUFLOW FV [4]	2012.000b First order (and second order)	Yes – 12 CPU cores	31,254 elements	Adaptive (~0.035s)	109s (195s)	Spatially varying using S=0.2 [5]
XPSTORM	2011 2010-10-AB-iDP-w32	No	2m	0.2s	61.7s	0.5 S + 0.1 C [6]

Notes:

[1] 'N/A' in column (7) refers to the fact that the model does not account for Eddy viscosity.

[2] Eddy viscosity recalculated every time step using the Smagorinsky velocity based formulation with a coefficient of 0.5, plus a constant component of 0.05m^2/s. The majority of the model had peak values of 0.05–0.07m^2/s with localised areas of large velocity gradients experiencing peak values up to 0.09m^2/s.

[3] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW 'Classic').

[4] Run times: first order solution (second order solution)

[5] 0.2 (Smagorinsky)

[6] 0.05 (Smagorinsky) + 0.05 (Constant)

Other information provided

Ceasg: 'It is suggested that there is likely to be a fair sensitivity of the results to roughness. At 2m resolution, the representation of the building on a fixed regular grid will only be approximate; both cut-cell and nested grid variants of the Ceasg flow model are available, which would both provide a better description of the building within the domain. As these features are not being tested elsewhere in this series of benchmarks, neither has been included in this test'.

Flowroute-*i*™: 'At the time of submission, Test 6 was not carried out using Flowroute-*i*™ as shock capturing was not supported at this time. Implementation of a computationally efficient shock capturing routine is included within our development pathway for 2013'.

ISIS: 'ADI scheme is not suitable for this case. TVD scheme with its shock capturing capability is able to simulate realistically the hydraulic jump in front of the building and the wake zone behind it for both the laboratory and the real-scaled model'.

ISIS 2D GPU: ‘ISIS 2D GPU simulates properly a model driven by shock wave propagation and wake zone development where supercritical conditions are predominant. The shock capturing scheme is able to simulate realistically the hydraulic jump in front of the building and the wake zone behind it for both the laboratory and the real-world scale models’.

LISFLOOD-FP: ‘Not tested due to the occurrence of supercritical flow’.

TUFLOW: As for Test 5, the enhancements in the 2012-05-AA release for supercritical flows provide an improvement in the results compared with 2010. The ‘Number Iterations == 4’ setting was used to improve convergence.

TUFLOW GPU: The finite volume shock capturing is aptly demonstrated with the TUFLOW GPU results.

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

Conclusions from Test 6B

All **full SWE models** predicted similar results in terms of peak depths and peak velocities, with a precision likely to be adequate for a problem of this type and scale in a practical application. Shock capturing properties appear to be important in the prediction of peak values of velocity and depths, and critical transitions. The predictions by ISIS 2D GPU feature unrealistically low velocities in some areas.

4.8 Test 7: River and floodplain linking

4.8.1 Introduction

This river and floodplain modelling test case (see Appendix A.7 for complete details and maps) consists of a ~7km long by ~0.75 to ~1.75km wide floodplain (composed of three distinct areas, floodplains 1, 2 and 3). In the test, the river Severn that flows through the site is modelled for a total distance of ~20km. Boundary conditions are a hypothetical inflow hydrograph and a downstream rating curve for the Severn.

The objective of the test is to assess the package’s ability to simulate fluvial flooding in a relatively large river, with floodplain flooding taking place as the result of river bank overtopping. The following capabilities are also tested:

- the ability to link a river model component and a 2D floodplain model component, with volume transfer occurring by embankment/bank overtopping and through culverts and other pathways
- the ability to build the river component using 1D cross-sections
- the ability to process floodplain topography features supplied as 3D breaklines to complement the DEM[4]

[4] The breaklines provided were derived from the 1m DEM and were a ‘vector’ representation of important crest lines in the topography (including embankments). If participants were not able to implement the breaklines they were still expected to extract these crest elevations directly from the DEM.

4.8.2 Results: water levels and velocities in the river channel

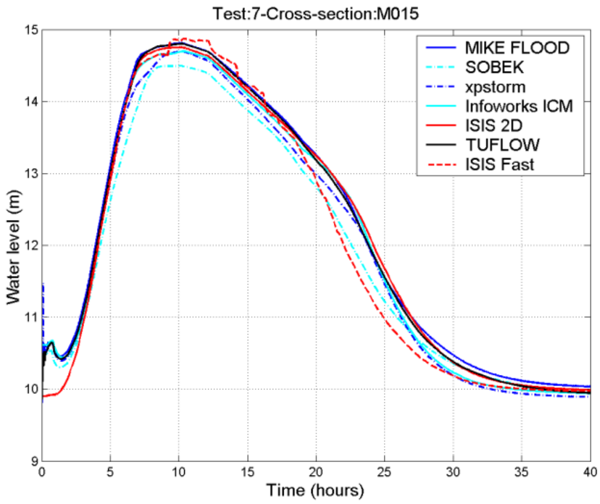
Water transfers between the river and the floodplains are governed by water level differences. It is therefore important to compare river water levels predicted by the models. 1D velocities are not taken into account in 1D river / 2D floodplain volume transfer calculations (which usually rely on water level differences) and are presented only as a means to help understanding differences in the predicted levels[5].

River bank elevations varied between ~13m at the top end of floodplain1 (near cross-section M024) to ~11.5m at the bottom end of floodplain 3 (just upstream from M044).

Water was able to flow into the southern end of floodplain 1 for any river level above 10.0m through the 10m wide opening at M030. However, most of the flooding of floodplain 1 happened by overtopping of the embankments protecting it.

Floodplain 2 was flooded by embankment overtopping only.

Water was able to flow through the Pool Brook culvert (at M033) into floodplain 3 at all times, but a level of ~10.5m or higher was required for any significant flooding to happen. Much of the flow into floodplain 3 also happened by overtopping of the river banks south of the village of Upton.



[5] In the case of SOBEK, the velocities plotted at cross-sections M025 and M035 are the resultants of the two velocity components calculated by the fully 2D model in this part of the river. Although SOBEK has the capability of linking 1D and 2D models both horizontally and vertically, in this test the developers adopted a fully 2D approach using a uniform square grid. The authors have been informed by Deltares of recent developments including the implementation of curvilinear grids for rivers.

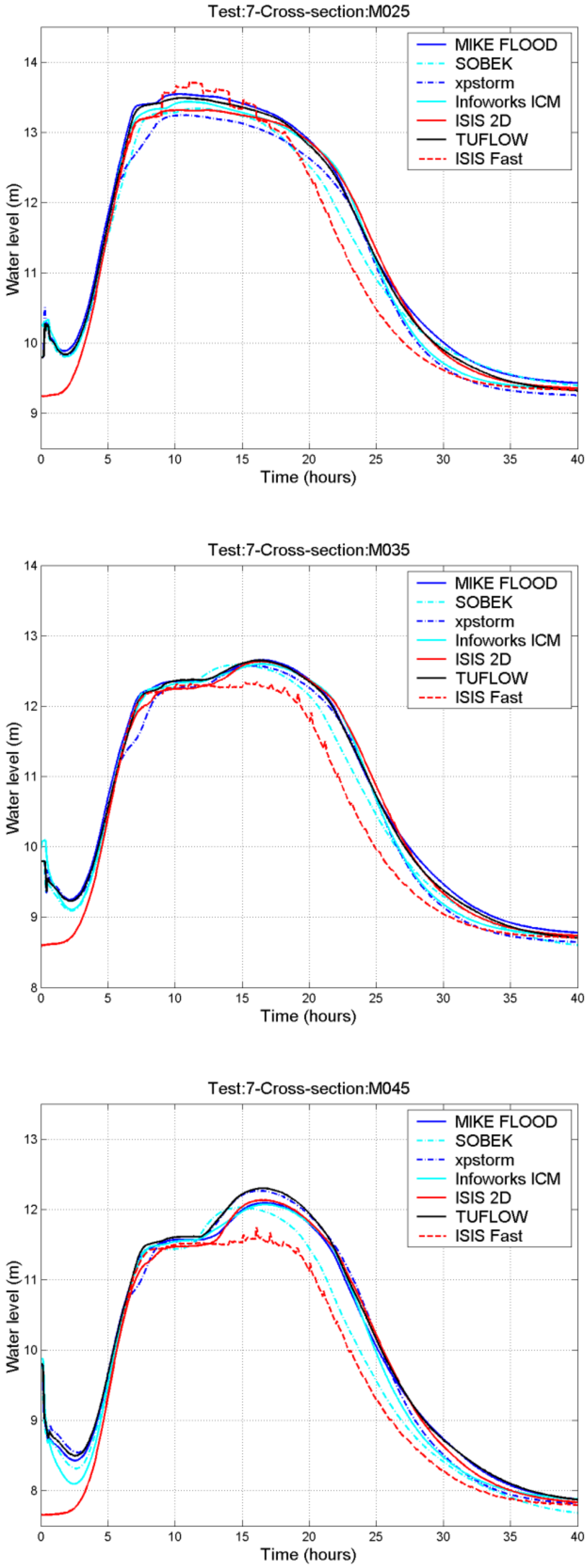


Figure 4.32 Water levels at river cross-sections M015, 25, 35, 45

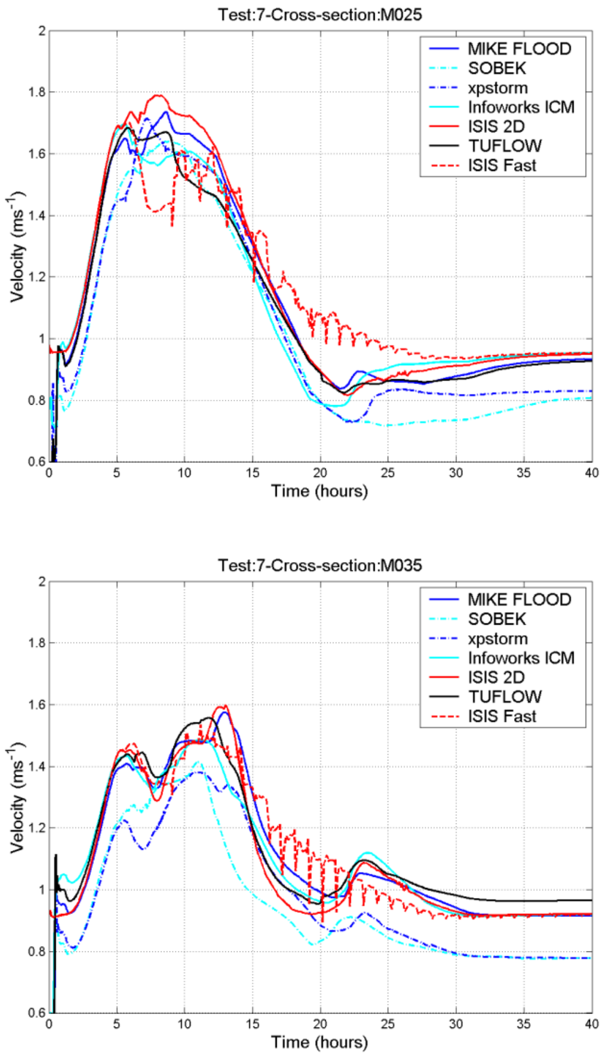


Figure 4.33 Velocities at river cross-sections M025, 35

The following observations can be made from Figures 4.32 and 4.33.

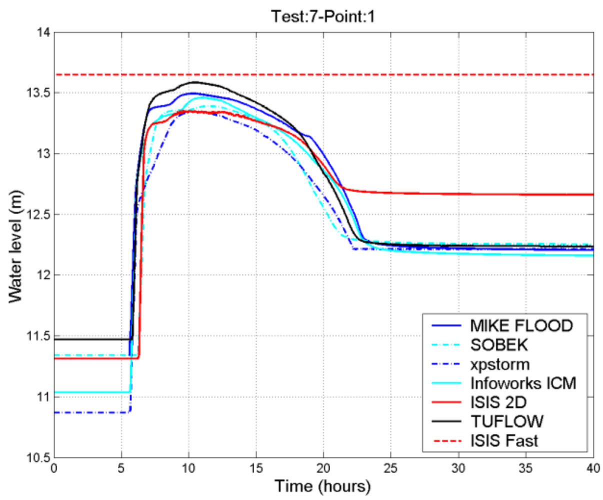
M015 is located more than 3km upstream from the start of floodplain inundation and the predictions of river level at this location are not affected by floodplain flooding in a significant manner. At the other three cross-sections, the water level rise comes to a visible halt when significant overtopping of the river banks starts to occur (around t = 7h), stays almost constant for ~2 to ~5h and rises again by ~0.1 to ~0.6m when most floodplains have been filled. Close inspection of the graphs reveal that river levels reach the relevant bankfull levels (not all visible on graphs above) at slightly different times depending on which model was used, resulting in differences in the timing of flooding within the floodplains.

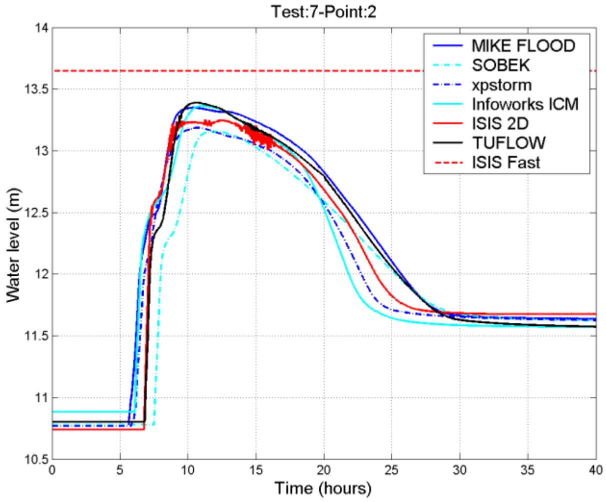
Peak water levels predicted in the river were within a ~0.3m range, except those by ISIS Fast. The curves show that ISIS Fast and ISIS 2D (as expected as they both rely on ISIS 1D for river level predictions) made identical predictions until floodplain flow started to occur, but significantly different ones thereafter.

The differences in peak levels observed can be broadly explained by the different schemes for linking the 1D and 2D models and different model constructions. Exchange processes between river and floodplain are complex and this is reflected in the models. Small differences upstream affect local inundation processes, which in turn affect river levels and inundation processes further downstream. A ‘cascading’ effect operates, which makes it unlikely that models will return identical results.

4.8.3 Results: water levels and velocities on the floodplains

NB As mentioned in Section 4.8.6 below, the water levels predicted by ISIS FAST in Test 7 are an estimate of the ‘peak’ water levels, as is the case whenever ISIS Fast is used in ‘linked mode’. These peak levels are represented below as single horizontal lines spanning the entire time domain.





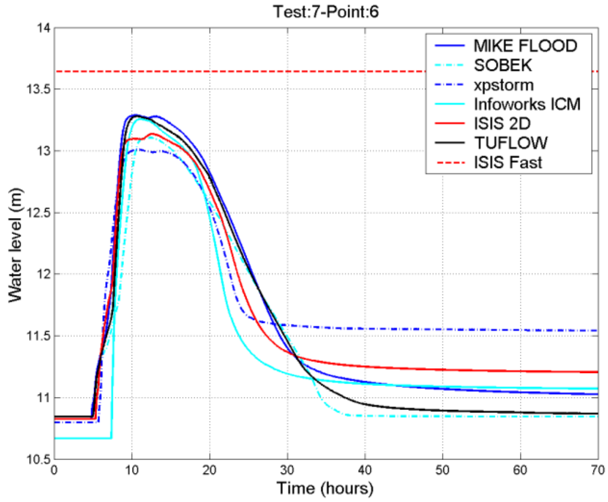
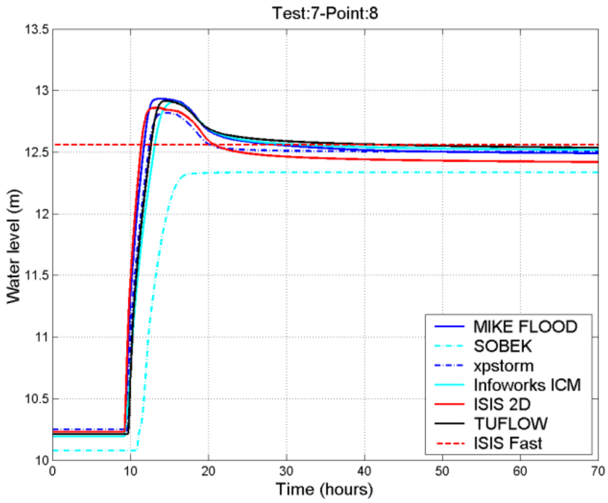


Figure 4.34 Water levels time series for floodplain 1



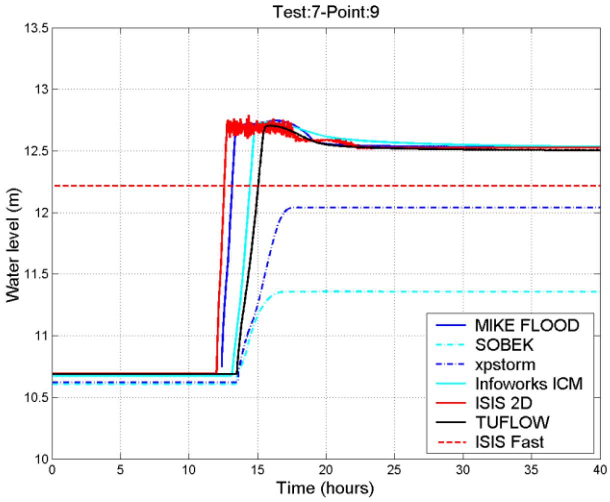
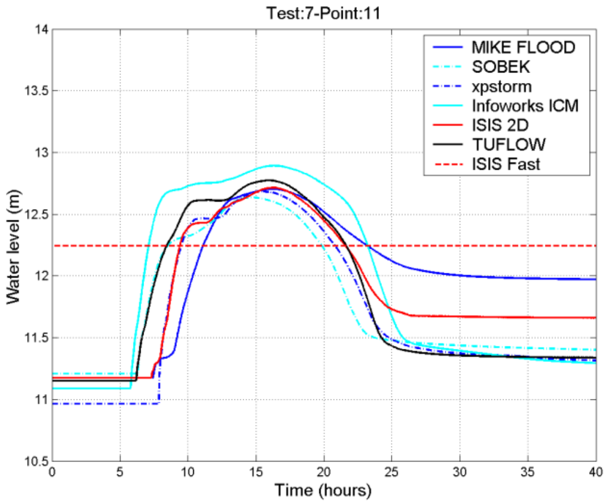


Figure 4.35 Water levels time series for floodplain 2



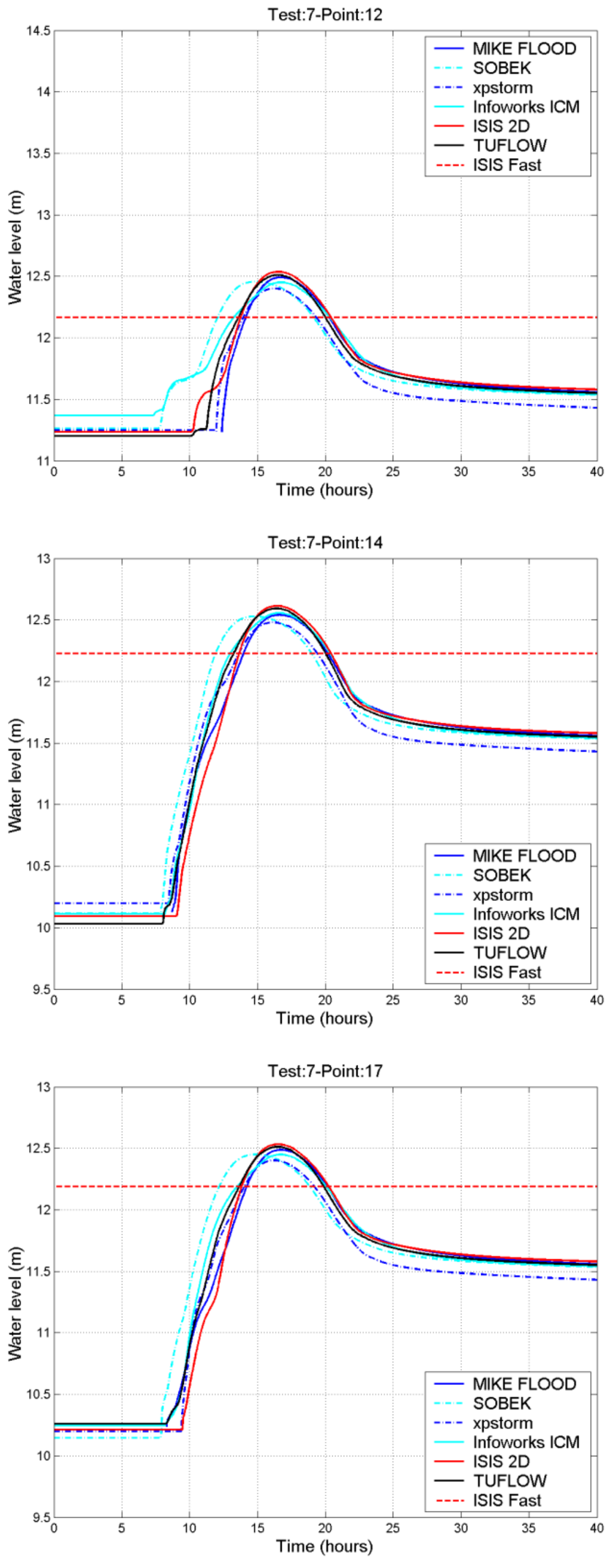


Figure 4.36 Water levels time series for floodplain 3

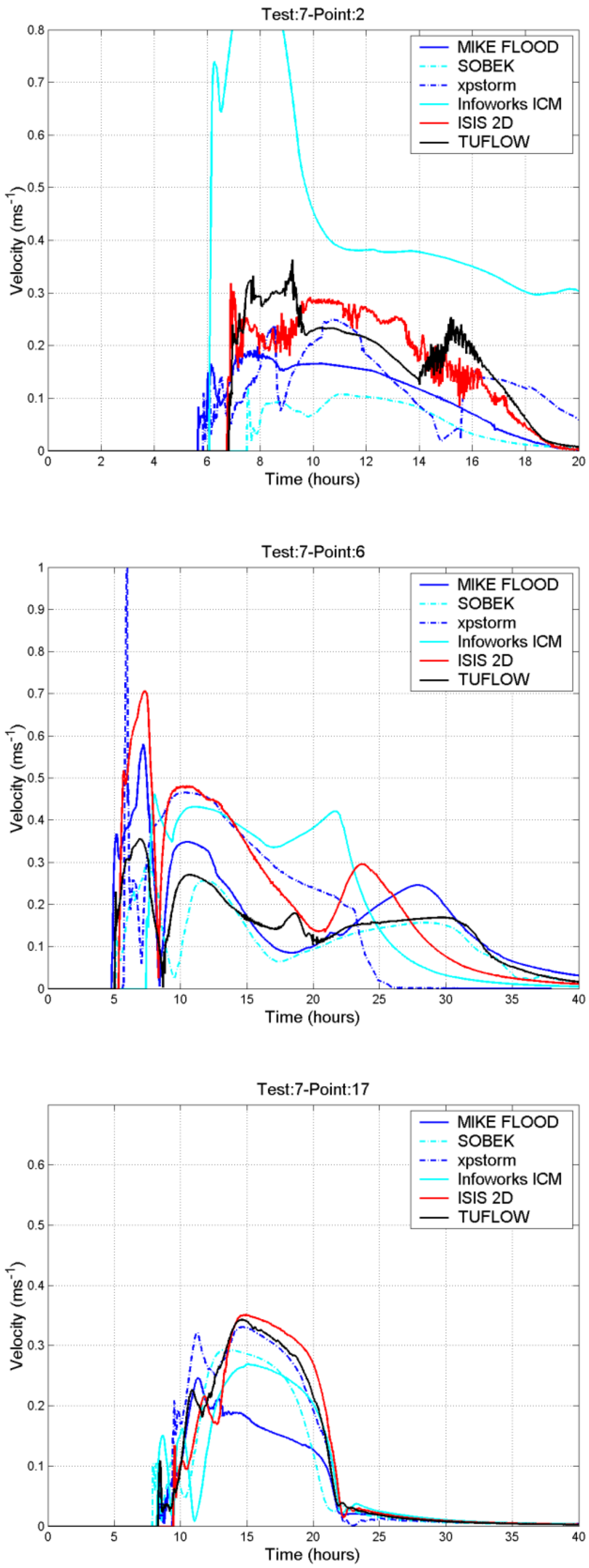


Figure 4.37 Velocities time series (all floodplains)

4.8.4 Results: output in gridded format

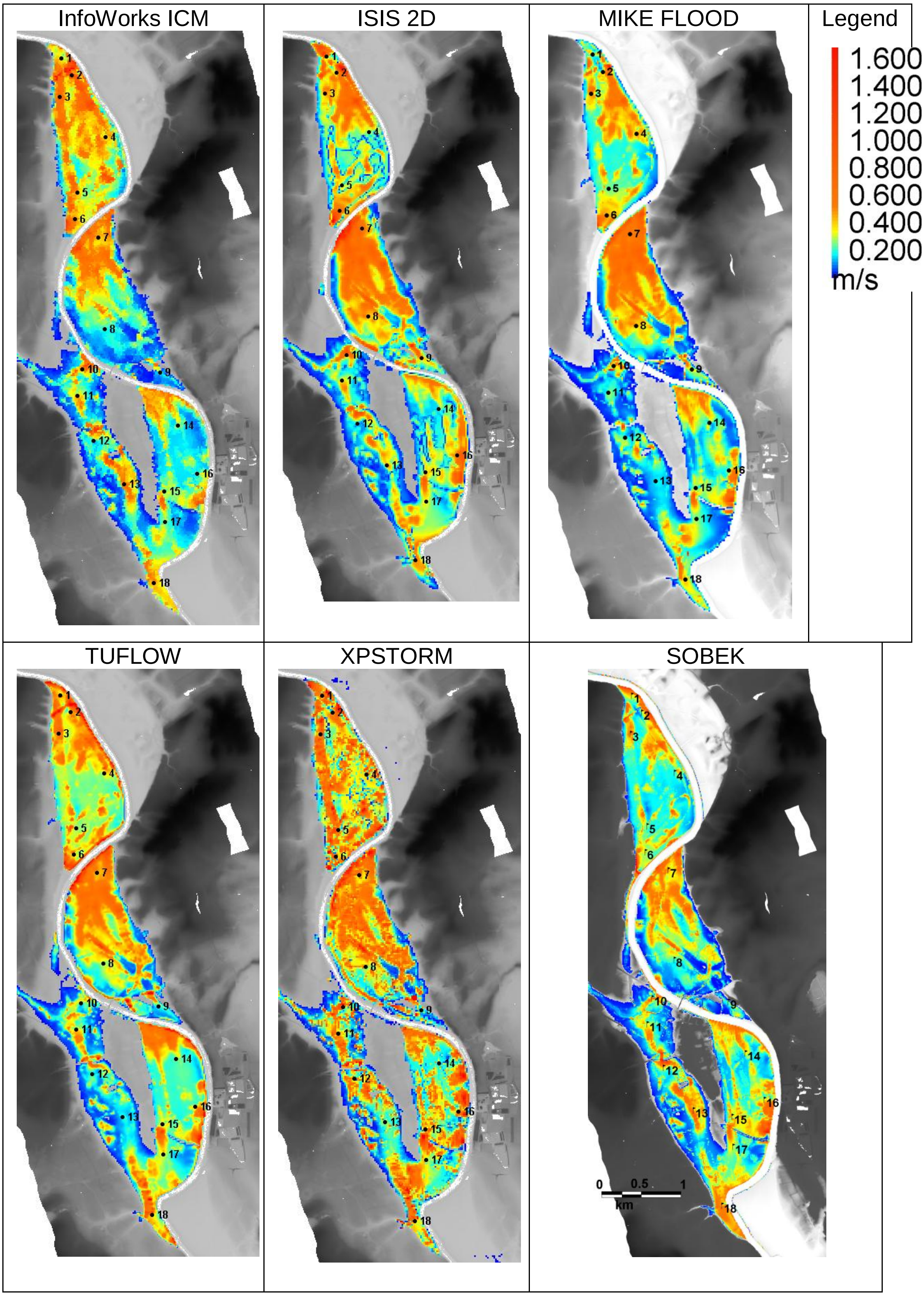


Figure 4.38 Peak velocities predicted in Test 7

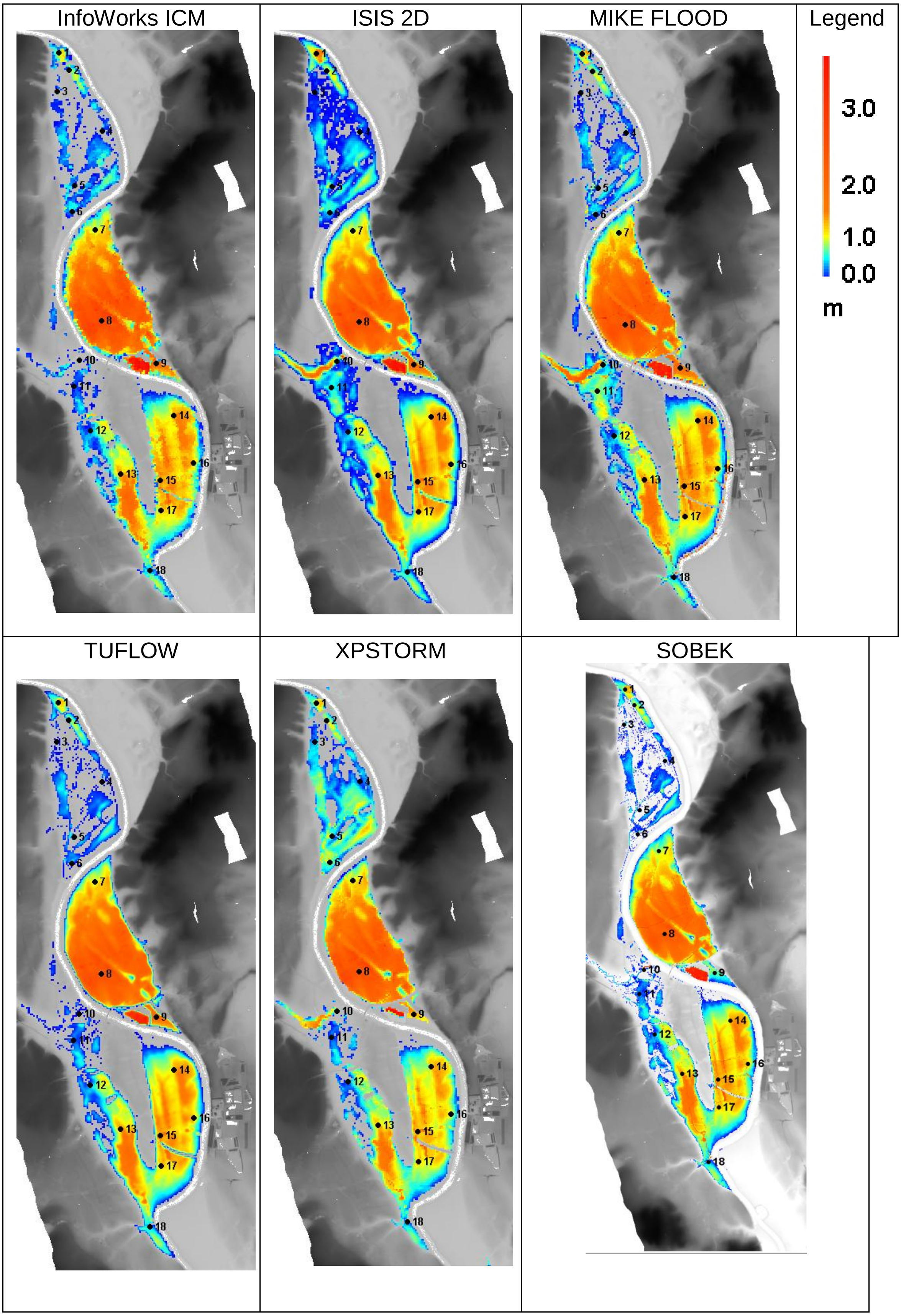


Figure 4.39 Final depths predicted in Test 7

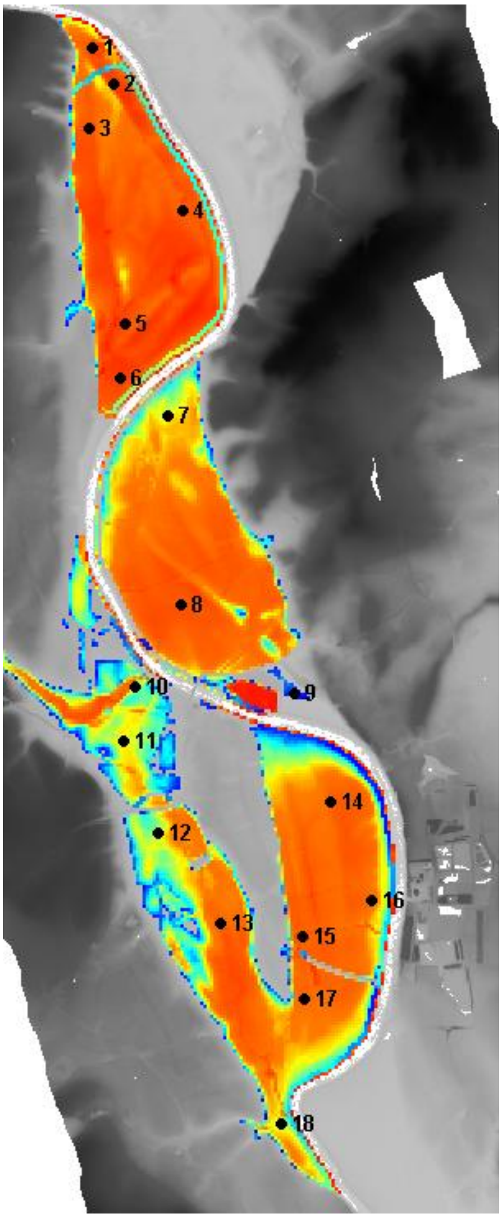


Figure 4.40 Peak depths predicted by ISIS Fast in Test 7

4.8.5 Summary and interpretation of results

The reader is first referred to comments on the predictions of flow in the main Severn channel, made in Section 4.8.2, as many of the differences observed in the prediction of channel flow are useful in understanding differences in the prediction of floodplain flow.

With the exception of ISIS Fast, only full SWE models were applied to Test 7.

Full SWE models

Floodplain 1

Point 1 (see Figure 4.34)

Point 1 lies in a low depression outside the perimeter of the embankment surrounding most of floodplain 1. Predicted peak levels and arrival times are found to be consistent with the 1D predictions at river cross-sections nearby. The final level after 'dewatering' is expected to be equal to ~12.13m, that is, the level of the lowest point along the river bank breakline provided as part of the Test 7 data set. All models predicted this reasonably well except ISIS 2D (0.5m too high), suggesting the possibility that the data provided were not included with sufficient detail in the ISIS 2D model.

Points 2 to 6 (see Figure 4.34)

On the rest of the floodplain (points 2 to 6), the peak levels predicted are all consistent with the presence of a single almost horizontal water body (with a ~5cm level difference at most between point 2 at the north end and point 6 at the south end, depending on the model) at mean elevation ~13.20 ± 0.1m, which generally match the water elevations predicted in the river channel. This is generally higher than the embankment elevations (~13.1m at north end to ~12.8m at south end of floodplain), resulting in a high level of water transfer by embankment overtopping. Some siginificant discrepancies in the timing of the start of inundation are observed (up to 2h at point 2), reflecting:

- differences in river levels
- differences in model approaches used to predict overtopping (which may include crucial parameters such as discharge coefficients and so on
- the implementation of the embankment crest elevations
- modelling of the 10m opening near cross-section M030

It is also clear from Figure 4.34 (point 6) that flooding was significantly delayed at this location in the InfoWorks ICM model, suggesting that the opening in the embankment near this point was not modelled(or not adequately).[6]

Dewatering at points 2,3,4,5,6:

With all models except ISIS, the floodplain eventually dries out (through the opening at M030), but water remains in some depressions (such as at point 6).

Floodplain 2

Points 7 and 8 (see Figure 4.35)

Observations in floodplain 2 differ from those for floodplain 1 in that calculated embankment overtopping depths were generally smaller (this can be estimated from the predicted river levels), resulting in larger discrepancies between models in the prediction of overtopping discharges and of the duration during which overtopping happened.

It can be observed in the graphs for points 7 (not shown here) and 8 that every model predicted identical levels at these two points from the time of the peak onwards, reflecting the fact that both points were part of a single water body. All models except SOBEK predicted the floodplain level to rise above the embankment elevations and become controlled by river levels. According to the SOBEK model, the floodplain level stopped rising when overtopping stopped, before reaching the river level or the lowest point along the embankment crest (at elevation ~12.50m).

[6] Since the testing period, an option to implement linear coupling between 2D and 1D was implemented in a new version of InfoWorks ICM, which can give a better representation of the connection at this location.

The final water level (after the recession) in all simulations, except the SOBEK simulation (for the reason given above) is predicted correctly as being equal to ~12.5m (the lowest point along embankment).

It is emphasised that the different behaviour in the SOBEK results above should not be interpreted as a shortcoming in the SOBEK model or in the numerical solver itself. However, it is possible that calculated river/floodplain transfer discharges were very different even between the InfoWorks ICM, ISIS, MIKE FLOOD and TUFLOW models, even if this did not result in differences in floodplain peak levels.

Point 9 (see Figure 4.35)

Flooding could only occur at this location if the river level around cross-section M035 rose to above ~12.49m (a low point along the embankment to the south). This was only the case by a small amount (~0.08 to ~0.13m depending on the model). Observations are similar to those at points 7 and 8 in that most models predicted peak level to become controlled by the river level. Exceptions to this were SOBEK (as above) and XPSTORM. The final level after dewatering was correctly predicted by all models (except, understandably, SOBEK and XPSTORM).

Floodplain 3

Points 10 and 11 (see Figure 4.36)

These points lie in the area to the west of Upton-upon-Severn where flood levels are expected to be similar to those in the river levels with a rapid response due to the very large culvert (modelled) allowing the Pool Brook (not modelled) to flow into the Severn. However, it is observed that the flood is predicted to reach points 10 and 11 with considerable discrepancies in timing (up to 3h) depending on the model considered with SOBEK, TUFLOW and InfoWorks ICM predicting an earlier arrival than ISIS 2D, XPSTORM and MIKE FLOOD. This shows that a variety of modelling approaches exist to model such structures, and to represent a link between it and the river on one side, the floodplain on the other side, and denotes a significant lack of consistency in the results obtained.

Points 12 to 17 (see Figure 4.36)

In this area the floodplain is not defended and the banks are natural, albeit with a slight natural slope downward from the river bank towards the floodplain interior. The observations made at all these points are very similar, and the curves show that they are all part of a single body of water during most of the flood. Peak levels on the floodplain are controlled by peak levels in the river (larger overtopping depths occurring over long distances and durations, allowing the full floodplain capacity to be occupied by water). There were differences however in arrival times within a range of up to ~2.5hours, with SOBEK prediction of peaks arriving earlier than others. SOBEK and InfoWorks ICM also predicted a much earlier initial rise at point 12, most probably due to the approach used to model openings through the road embankments to the north, allowing the flood to arrive earlier than in other models through this route.

The final elevation of ~11.5m, due to a low point in the river bank crest elevation, is predicted by all models within ~0.05m.

All floodplains

Velocities (NB Only the graphs for points 2, 6, and 17 are shown in Figure 4.37)

There are very significant differences in the predicted velocities as can be observed in all velocity plots, and in the peak velocity mapping These differences can be explained from two different effects.

At the beginning of the flood, immediately after overtopping of the embankment or river banks, sharp peaks can be observed as the flow finds its way along floodplain slopes. The magnitude of this peak is heavily dependent on:

- predicted overtopping discharges[7]
- the rate of change in time of these discharges
- the ability of the models to handle the predictions of highly transient flows (XPSTORM in particular predicted a sharp peak at several points)

The magnitude of this peak value is therefore unlikely to be consistently predicted beteween models, as confirmed by Figure 4.38.

At later stages a quasi-steady flow lasting several hours often occurs, as a small head difference exists between the north and south end of the floodplains. As commented, discrepancies exist between models (for various reasons detailed above) in the magnitude of these slopes, resulting in discrepancies in the calculated velocities.

The above comments suggest that velocity predictions are unlikely to be accurate in river / floodplain models such as the one in this test. Peak velocity mapping is therefore likely to be only indicative for this type of problem.

ISIS Fast

Due to the simplified representation of floodplain hydraulics in ISIS Fast, the interaction between the floodplain flow and the river flow is predicted to happen in a discontinuous manner (this is visible for example on the velocity plots for cross-sections M025 and M035), resulting in significantly different peak levels in both the river and the floodplain, by up to ~0.5m, compared with the full SWE models.

4.8.6 Miscellaneous model parameters

Table 4.9 Miscellaneous model parameters for Test 7

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 20m or 16,700 elements)	(5) Time-stepping	(6) Run time
InfoWorks ICM	2.5.2	Yes – GPU	29,521 triangles	1s	38.5min
ISIS	3.6 (ADI)	Partial [1]	20m	4s	6.8min
ISIS Fast	3.6	No	20m	N/A	0.116min

[7] This is for example the case at point 2, where the graph shows a large InfoWorks ICM velocity relative to the other software tested. The tested version of InfoWorks ICM did not support the addition of 3D breaklines; as a result the embankment upstream of this point was not sufficiently picked up by the 2D mesh. Later versions of InfoWorks ICM support the addition of breaklines with irregular profiles which would improve results at this point.

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 20m or 16,700 elements)	(5) Time-stepping	(6) Run time
MIKE FLOOD	2012	Yes – 8 CPUs	20m	12s	3.82min
SOBEK	2.13	No	10m	10s	194.9min
TUFLOW	2012-05-AA Single precision	No	20m	15s	3.33min
XPSTORM	2011 2010-10-AB-iDP-w32	No	20m	10s	9.0min

Notes: 1 See Appendix B.

Other information provided

SOBEK: '2D modelling of river with 20m grid is too coarse. 2D modelling of river with 10m grid is more appropriate'. The model was built and run at a resolution of 10m instead of the specified 20m.

ISIS Fast: 'When ISIS FAST is in 'linked mode' (for example, ISIS FAST dynamically linked to ISIS 1D), then the reported water levels are the maximum values from the 'link time steps' and are thus estimates of the maximum water levels (for example, Test 7). When it is used with no linking, then the reported levels are the final water levels'.

TUFLOW: 'The enhancements made for the 2012-05 release have improved the velocity outputs and have allowed the 2D time step to be increased from 10s to 15s with improved stability and less mass error (-0.06% 2010/10s time step vs. -0.04% for 2012/15s)'.

NB There was room for the modellers' own initiative in Test 7 on how to model a number of features. All information provided by the participants on the modelling approaches used is included in Appendix C.

4.8.7 Conclusions from Test 7

All packages participating in Test 7 have demonstrated their ability to implement linked 1D river / 2D floodplain modelling.[8] This functionality is not yet supported in the current versions of ANUGA, Ceasg, Flowroute-*i*™, JFLOW+, RFSM, TUFLOW FV, TUFLOW-GPU and UIM (LISFLOOD-FP was not run due to lack of staff resources).

The test has identified a relatively high level of inconsistency in the results produced by the various models. The discrepancies observed between models reflect the physics of a fluvial flood event of this type.

[8] In the case of SOBEK, while a 1D–2D link is also supported, Deltares supplied results from a model where the river was part of the 2D mesh, its preferred approach for this type of problem.

- River and floodplain dynamics are complex. Exchanges of water affect river levels which in turn affect exchanges downstream, even upstream in subcritical river flows, resulting in complicated 'cascading' propagation of any differences arising in the model predictions.
- These exchanges depend critically on river bank or embankment overtopping discharges, and on the flow through structures.
- Peak velocities on floodplains depend on overtopping discharges, the flow through structures and the rate at which these change in time.

Accurate modelling of these exchange processes is therefore crucial to the accurate prediction of flood hazard on floodplains where linked 1D–2D models is used. This includes the need to accurately implement the geometry of critical structures such as embankments, or even natural river banks (where any inaccuracy in the geometry must be small compared with typical overtopping depths, which are often as small as ~0.1m).

Although the floodplain topography and dimensions of structures were specified, participants used different modelling approaches and parameters to model overtopping (these were not specified and consistent modelling techniques with appropriate guidance on parameterisation do not exist at the present time). In addition there is evidence that the participants were not always able to implement the correct structure dimensions or the correct elevations along river banks and embankments. Errors concerning these were often comparable with, if not larger than, overtopping depths and therefore had very significant effects in the prediction of flood flow patterns.

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

4.9.1 Introduction

The modelled area (see Appendix A.8 for details) is approximately 0.4km by 0.96km and is shown in Figure 4.41. The flood is assumed to arise from two sources:

- a uniformly distributed rainfall event (peaking at 400mm/h over a time base of 3min), applied to the modelled area

a point source at the location represented in Figure 4.41 occurring over a time base of ~15min, with a peak at 5m^3/s occurring ~35min after the rainfall event

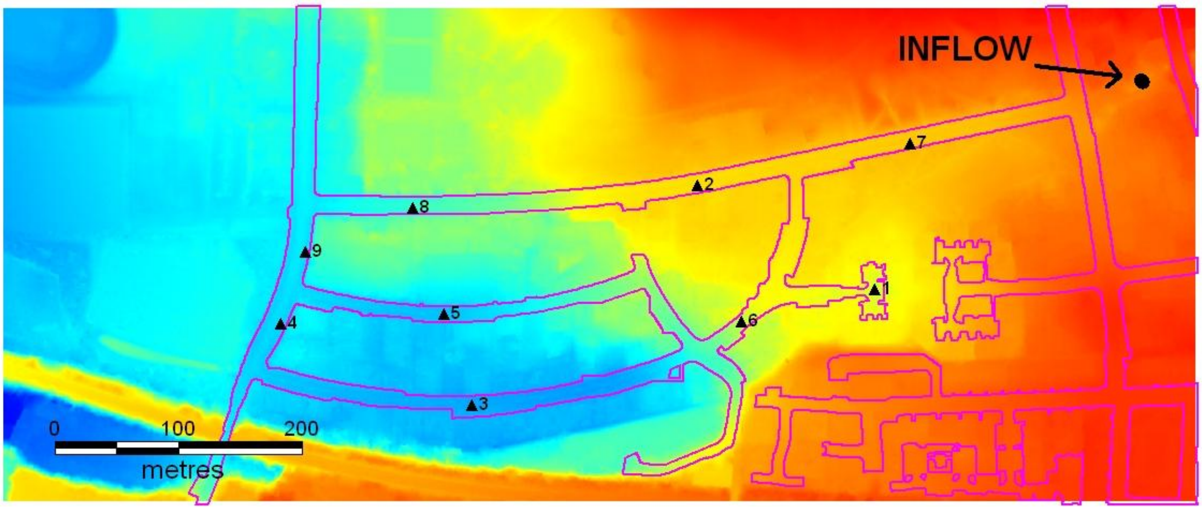


Figure 4.41 DEM used, with the location of the point source

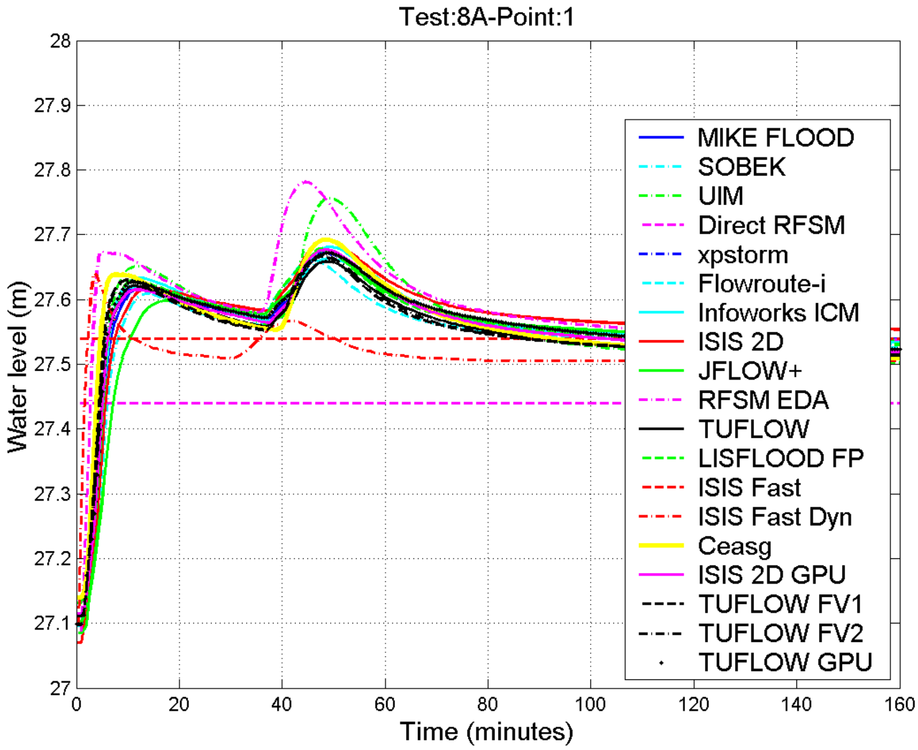
Notes: Purple lines: outline of roads and pavements

Triangles: output point locations

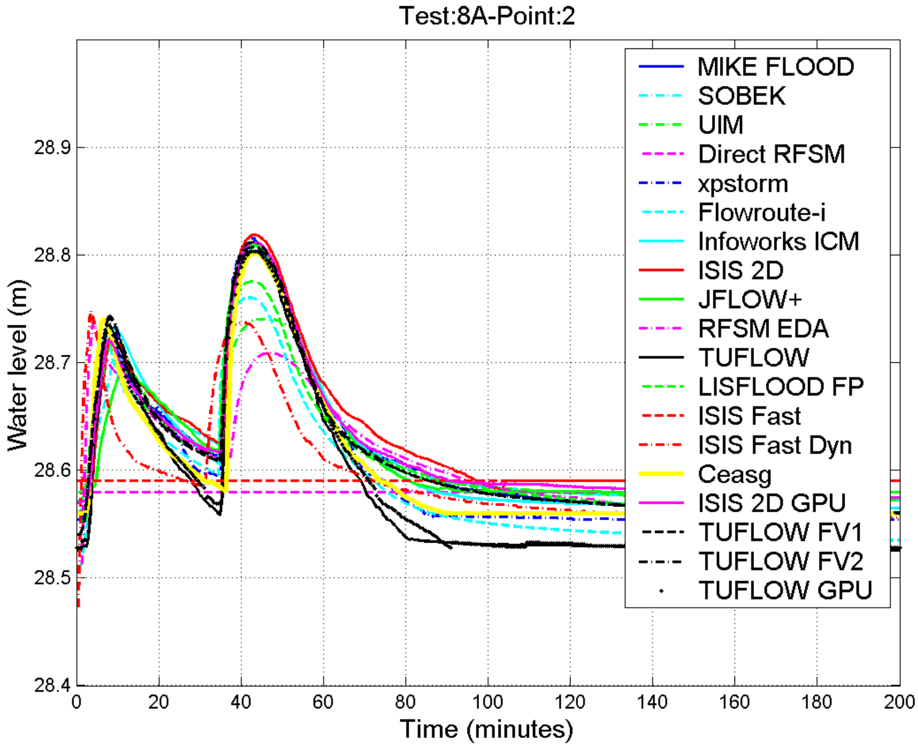
This tests the package's capability to simulate shallow inundation originating from a point source and from rainfall applied directly to the model grid, at relatively high resolution.

4.9.2 Results: water level and velocity time series

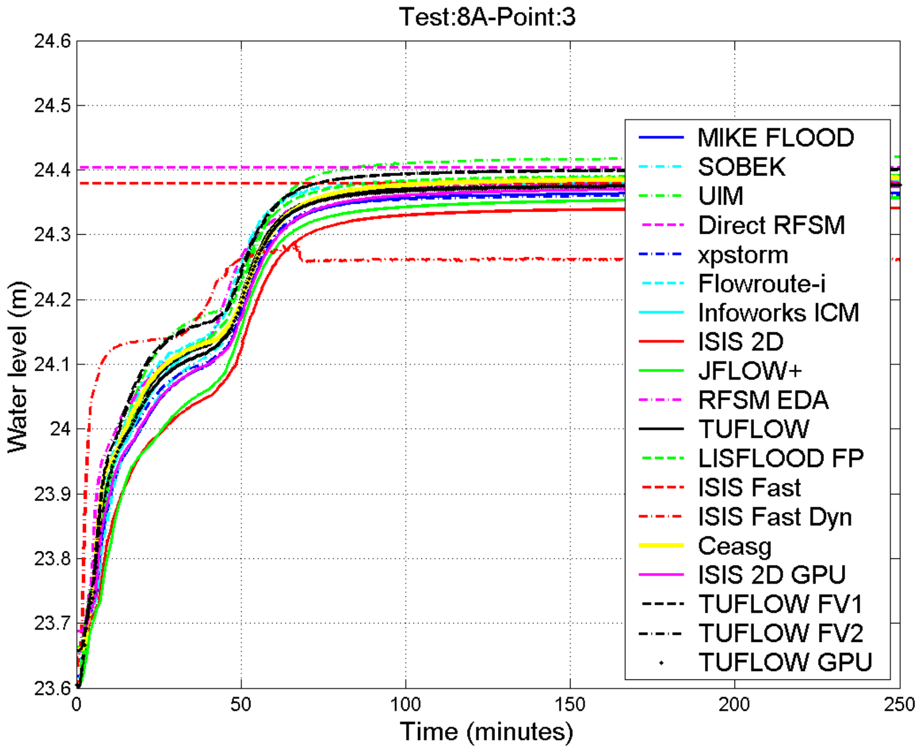
NB Direct RFSM and ISIS Fast predict a 'final water level'. The final water levels predicted are represented as horizontal lines spanning the entire time domain.



Test:8A-Point:1
Water level (m)
Time (minutes)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



Test:8A-Point:2
Water level (m)
Time (minutes)
MIKE FLOOD
SOBEK
UIM
Direct RFSM
xpstorm
Flowroute-i
Infoworks ICM
ISIS 2D
JFLOW+
RFSM EDA
TUFLOW
LISFLOOD FP
ISIS Fast
ISIS Fast Dyn
Ceasg
ISIS 2D GPU
TUFLOW FV1
TUFLOW FV2
TUFLOW GPU



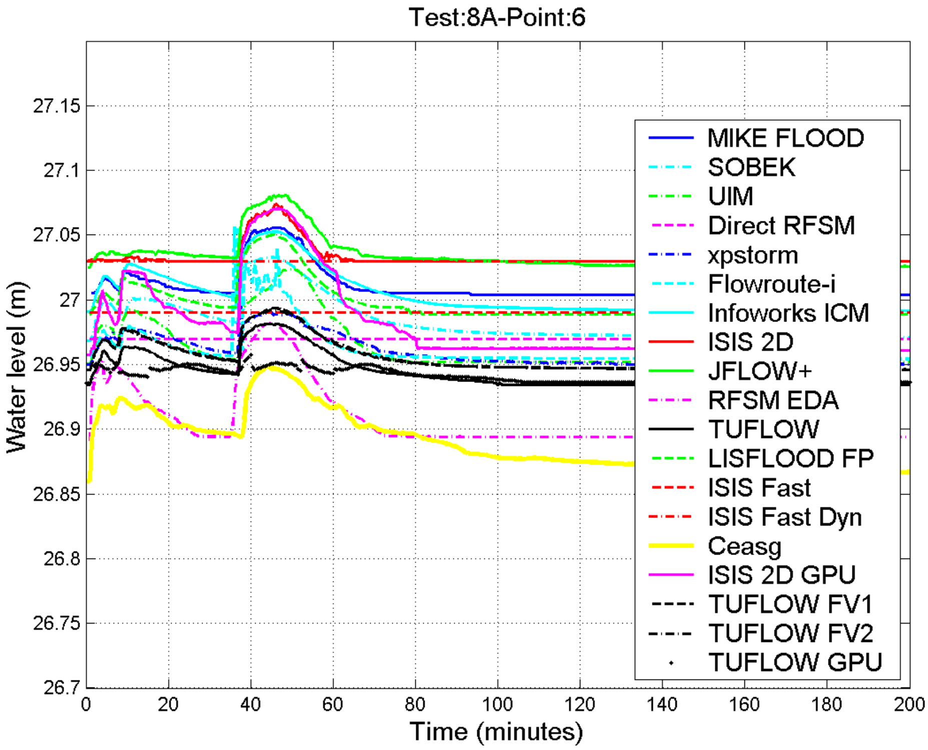


Figure 4.42 Water levels time series at points 1, 2, 3 and 6

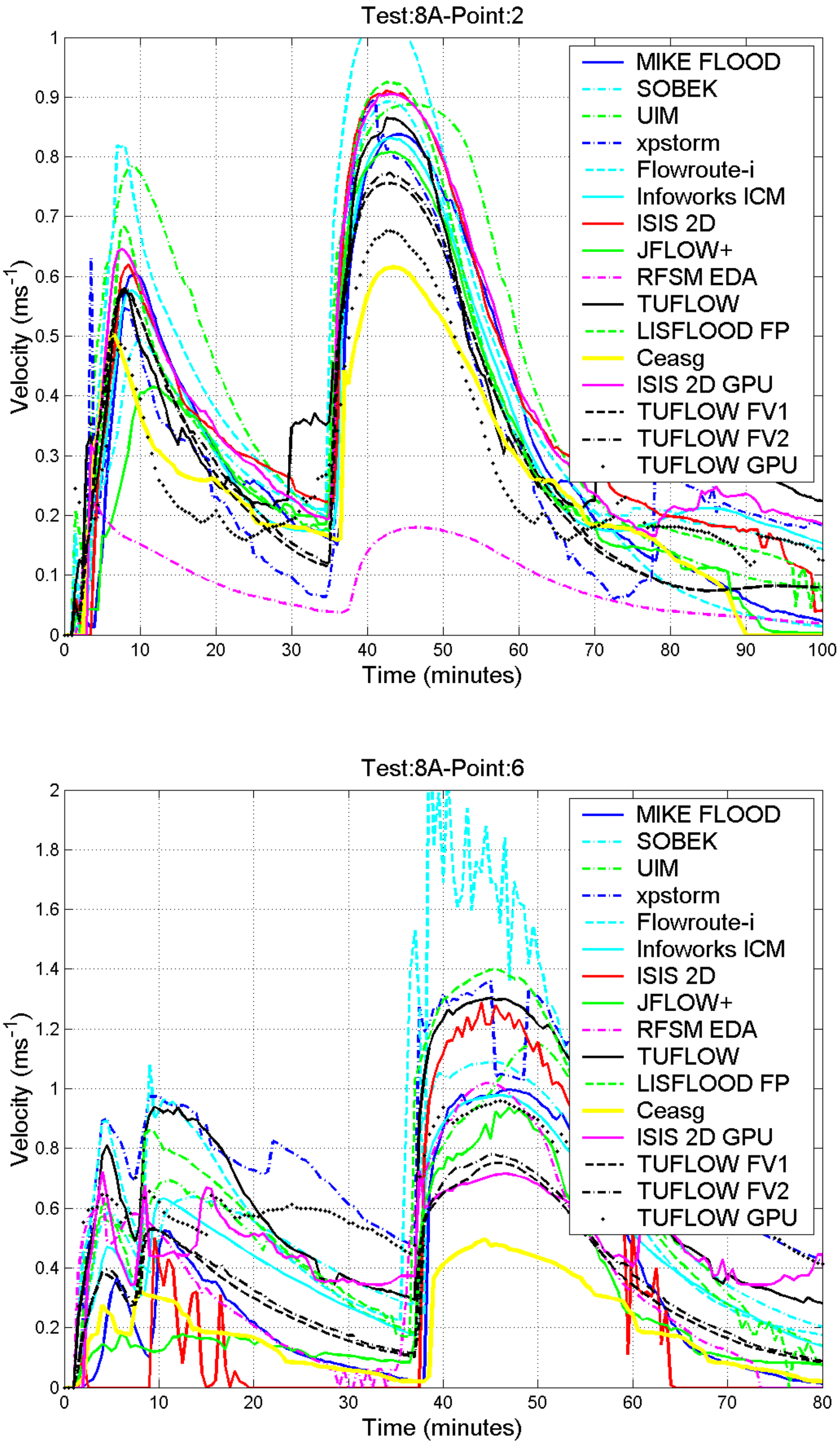


Figure 4.43 Velocities time series at points 2 and 6

Results: output in raster format

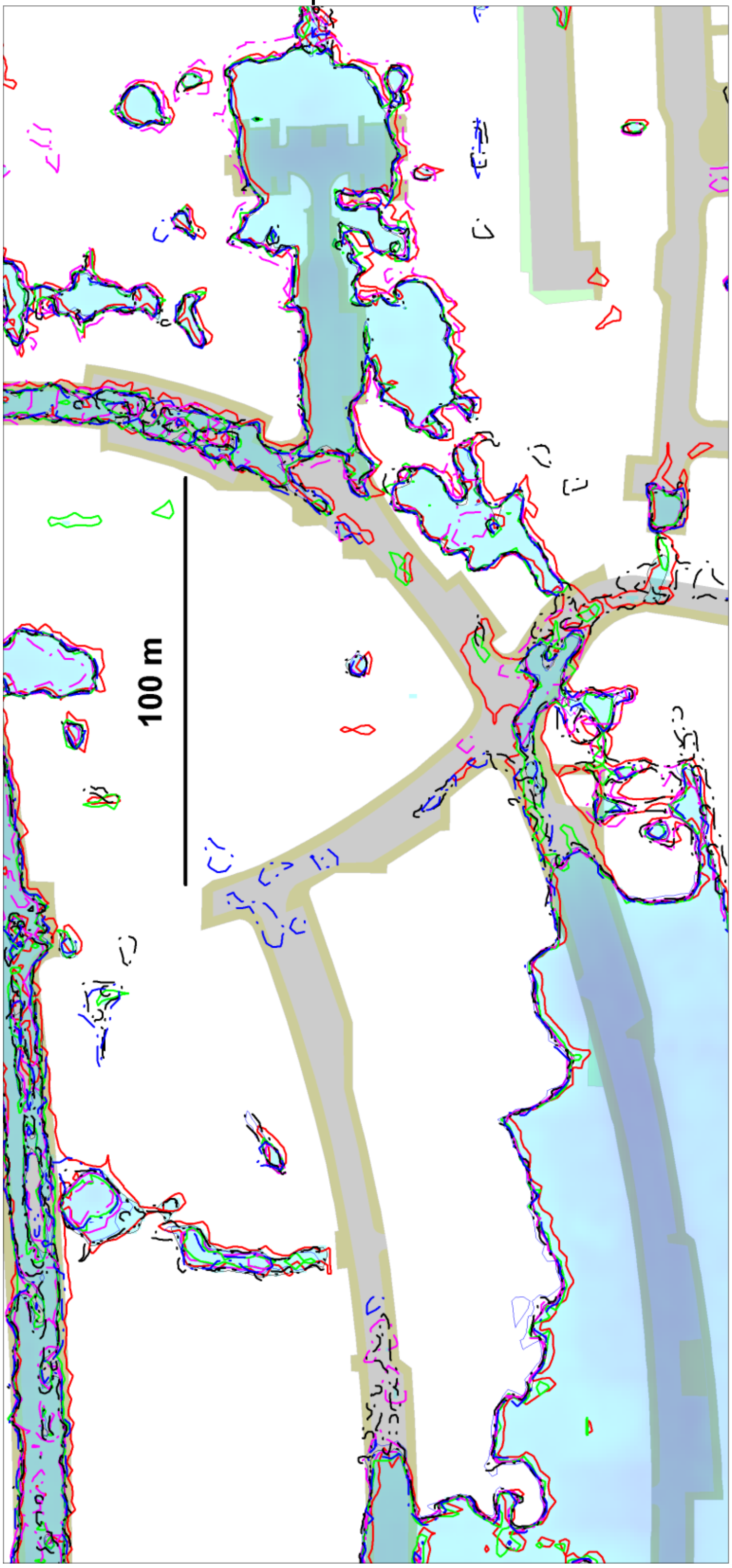


Figure 4.44 20cm contours of peak depth

Notes: Colours consistent with other figures

4.9.3 Results: summary and interpretation

Topography

Local variability in DEM elevations (provided at a 0.5m resolution), combined with the prescribed model resolution of 2m, meant that there were significant discrepancies between models in the local dry ground elevations considered at the output points. This is visible in Figures 4.42 and 4.43). Differences typically within a 0.05–0.1m range were observed. At certain points, for example, point 6 (shown), 8 and 9, these differences were of the same magnitude or even larger than typical peak depths predicted.

Such topography-related discrepancies affect model results in various ways and more so in areas of very shallow flow. A conclusion from Test 8A (and 8B) is that a resolution of 2m is likely to be insufficient in a case of high-resolution urban flood modelling.

Full SWE models

Water levels

Almost all predictions by the full models exhibited a 'double-peaked' shape due to the very intense rainfall occurring between t = 1min and t = 4min, and the point inflow peaking at t ~38min. Due to the short travel times, the timings of these peaks are mostly in agreement between models, within a few minutes. However at point 3 (downstream pond) large time lags (up to ~20–25min) in relation to the travel times of typically ~30min are observed as the levels are rising when the pond is fed by residual shallow flows (especially those due to the rainfall event). Other observations are as follows.

- At point 1, peak depths over 0.5m were predicted. All SWE models agree in the prediction of this within a range smaller than ~5% of the depth.
- At points 2, 4, 7 maximum depths did not exceed ~0.35m. However, all full models agreed in the prediction of the peak levels within ~0.04m at most (this range was also usually smaller in the case of the second peak).
- The final levels predicted at point 3 (downstream pond) were all within a ~0.07m range for a ~0.8m depth).
- The ISIS results show significant oscillations in areas of shallow flow (mainly points 6, 8 and 9).

Velocities

Velocity predictions showed significant discrepancies among the full SWE models within a range typically up to ~100% (in the peak values predicted). This affected particularly areas of shallow flow (points 6, 8 and 9) where topography effects were significant. The differences were smaller at locations 2, 3, 4 and 7 (although still up to ~30–40% range; see, for example, point 2).

A number of factors explain these differences:

- topography effects
- differences in the treatment of very shallow flows
- differences in the modelling of direct rainfall

- various degrees of numerical difficulties in the prediction of supercritical flows in some areas (for example, with Flowroute-*i*™)

3-term models (LISFLOOD-FP, RFSM EDA)

Water levels and velocities

The manner by which transient processes are predicted by this class of model distinguished them from the full SWE predictions, although this is more evident with RFSM EDA than with LISFLOOD (see points 1 and 2). Predictions of velocities are frequently found to be significantly different, especially in areas of high water velocity; see, for example, RFSM EDA at point 2.

2-term model (UIM, ISIS Fast Dynamic)

Similarly to the 3-term models, UIM made predictions of transient processes that distinguished themselves the full SWE predictions (see, for example, points 1 and 2). Predictions of velocities are frequently found to be different. While the predictions were generally closer to the full SWE or 3-term model, the run time was a lot larger.

ISIS Fast Dynamic appears to predict significantly shorter travel times than others (for example, point 3) and gives an approximate representation of transient floodplain flow processes (point 1). There is an unexpected ~0.1m difference in the final level at point 3, which is significant as it is set within a very large ‘pond’ where most of the water settles and therefore a 0.1m water level difference represents a large volume of water.

Velocity predictions by ISIS Fast Dynamic were not provided; see the comment in Section 4.9.4.

0-term models (RFSM Direct and ISIS Fast)

Predictions of final water level are generally in agreement with others, although some noticeable differences occurred due to the use of a coarser resolution, for example RFSM Direct at point 1.

4.9.4 Miscellaneous model parameters

Table 4.10 Miscellaneous model parameters for Test 8A

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 2m or 97,000 elements)	(5) Time-stepping	(6) Run time
Ceasg	1.12	Yes – GPU	2m	0.5s	84s
Flowroute-*i*™	3.2.0	Yes – 4 CPUs	2m	Adaptive	122s
InfoWorks ICM	2.5.2	Yes – GPU	99,615s	30s	66s
ISIS 2D	3.6 (ADI)	Partial [1]	2m	1.0s	560s
ISIS 2D GPU	1.17	Yes	2m	Adaptive	327s

ISIS Fast	3.6	No	2m	N/A	1s
ISIS Fast Dynamic	3.6	Partial	2m	0.5s	90s
JFLOW+	2.0	Yes – GPU	2m	Average 0.31s	66s
LISFLOOD-FP	5.7.2	Yes	2m	Adaptive	268.2s
MIKE FLOOD	2012	Yes – 8 CPUs	2m	1.5s	367s
RFSM Direct	3.5.4	No	1111 Impact Zones Based on a 10m grid	N/A	<1s
RFSM EDA	1.2	No	1786 elements [1]	Adaptive typically 1s	156s
SOBEK	2.13	No	2m	10s	1494s
TUFLOW	2012-05-AA Double precision	No	2m	1.5s	477s
TUFLOW GPU	2012-05-AA	Yes – 448 GPU cores	2m	Adaptive (0.2–0.3s)	84s [2]
TUFLOW FV [3]	2012.000b First order (and second order)	Yes – 12 CPU cores	2m	Adaptive (~0.33s)	410s (612s)
UIM	2009.10	OMP	2m	0.05s	18470s
XPSTORM	2011 2010-10-AB-iDP-w32	No	2m	1s	562.3s

Notes: [1] See Appendix B.

[2] These simulation times for TUFLOW GPU are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW ‘Classic’).

[3] Run times: first order solution (second order solution)

Miscellaneous information available

Ceasg: ‘The nature of the DTM means that the results of the Ceasg model (as all models) will be highly sensitive to the resampling technique used. These sensitivities will be most pronounced on well-defined flow routes, where there is are relatively large differences in elevation over short distances, for example, the road network where there are verges and pavements on either side of each carriageway. Such differences may lead to different results between models, or between different runs of the same model using different resampling techniques'.

ISIS 2D: 'In this test case both the TVD and ADI model were run. Run times and results obtained with the TVD solver improve significantly the results previously reported in 2010 and 2011. However the results obtained with the ADI solver seem to be accurate and stable with the added value of a much lower runtime required for the model. In terms of flood extent the results are sensible and also show improvement when compared with the previous report. The local effects of supercritical flow over the steep road do not seem to have significant impact in the overall flood extent; as a consequence TVD results do not provide relevant improvement when compared to ADI'.

ISIS Fast Dynamic: 'Velocities calculated by ISIS FAST Dynamic are not sensible for this type of test due to the simplicity of the routing mechanism. Discrepancies can be found in the timings due to the mechanism used by ISIS Fast to route the flow. In general, ISIS FAST Dynamic provides sensible results for water depths, as well as a good estimation for flood extents and flood propagation'.

LISFLOOD-FP: 'This is not the standard version of LISFLOOD-ACC from the previous tests but the Sampson et al. (2012) version with a simple routing scheme for the very shallow flows and the acceleration formulation for flows with depths above 5 mm (see also de Almeida et al. 2012). This test model was built by Chris Sampson'.

RFSM EDA: 'Because of the sub-element representation the Impact Zones encompass a large range in ground elevations around each test point. Therefore the levels can at times be seen to rise from and fall to a lower level than other models'.

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

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

4.9.5 Conclusions from Test 8A

Most **SWE models** predicted similar results in terms of peak water levels within a range of a few centimetres. Such differences are insignificant in problems where the predicted depths are several times larger, but in urban flood problems, they may affect flow predictions as flow depths are often very shallow in such problems.

Significant differences due to the different approaches used to process the topography suggest that a 2m grid may be insufficiently fine for high resolution modelling of shallow urban flows, particularly if accurate velocity predictions are expected. However, it should not be concluded at this stage that grid refinement (to resolutions finer than 2m) is necessarily a way forward as this is likely to have counterproductive effects in terms of computational (in)efficiency and therefore the ability to run multi-simulations, quantify uncertainties, perform risk studies, calibrate models and so on.

Fast shallow flows in some areas were predicted at the expense of numerical oscillations (for example, ISIS 2D, Flowroute-*i*™).

The **3-term models** (RFSM-EDA, LISFLOOD) and **UIM** predicted the transient processes (flood waves, peak levels) with an acceptable level of accuracy, although LISFLOOD was in this respect more in line with the full SWE models. RFSM EDA predicted orders of magnitude of velocities similar to those predicted by the SWE models, but not precise values. The same was generally observed with **ISIS Fast**

Dynamic, although without any velocity predictions, and much shorter travel times than others (this last point was also observed with RFSM EDA). **RFSM Direct and ISIS Fast** predicted a 'final' state broadly in line with others.

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

4.10.1 Introduction

This test (see Appendix A.8 for details) is based on the same site, DEM and modelled area as in Test 8A. A culverted watercourse of circular section is assumed to run through the site, with a single manhole at the location indicated in Figure 4.45. An inflow boundary condition is applied at the upstream end of the pipe, with a surcharge expected to occur at the manhole. The flow from the above surcharge spreads across the surface of the DEM.

Participants were expected to take into account the presence of a large number of buildings in the modelled area and to apply a land-cover dependent roughness value with two categories:

- roads and pavements
- any other land cover

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

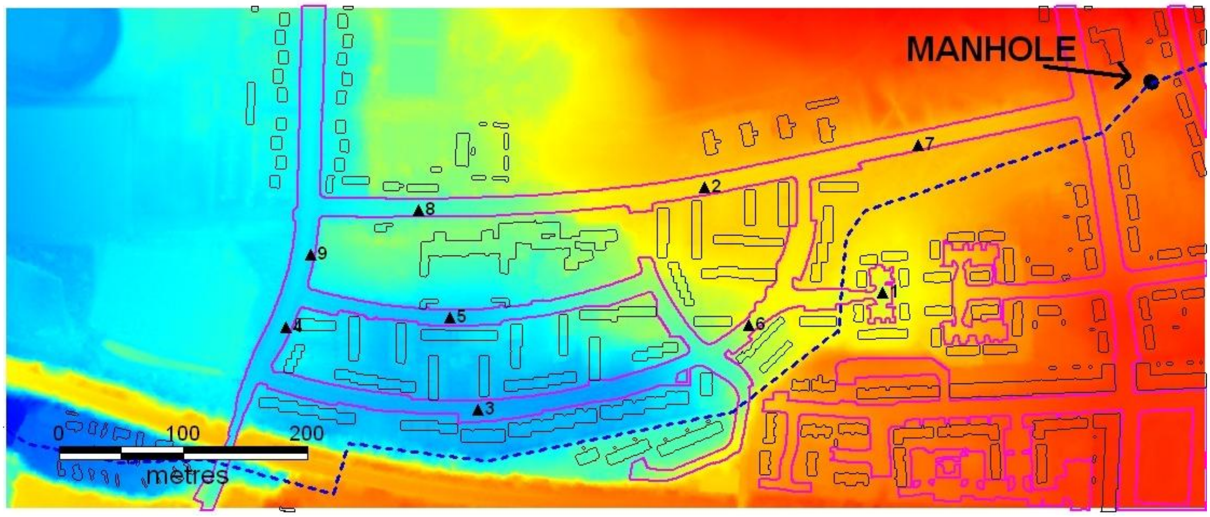


Figure 4.45 DEM used, with the location of the manhole

Notes: The course of the pipe is irrelevant to the modelling.

Triangles: output point locations

4.10.2 Results

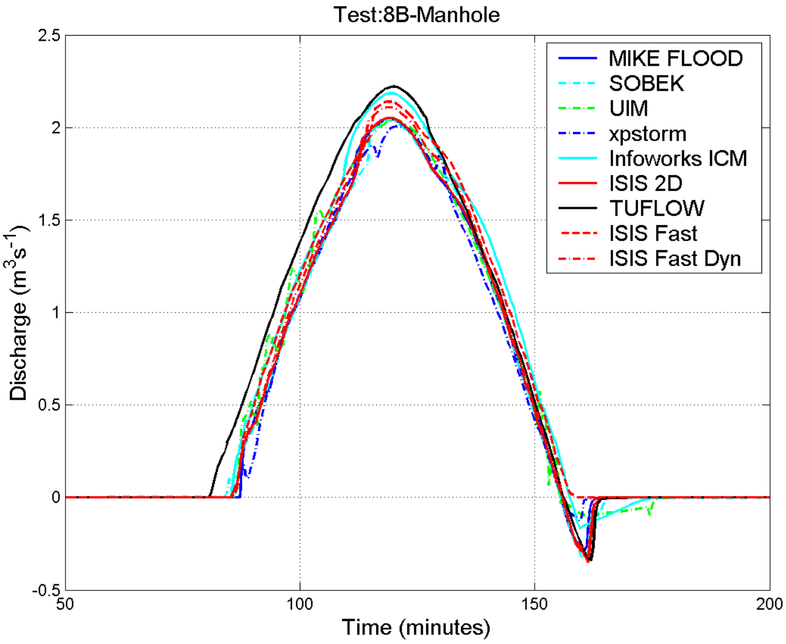


Figure 4.46 Manhole discharge

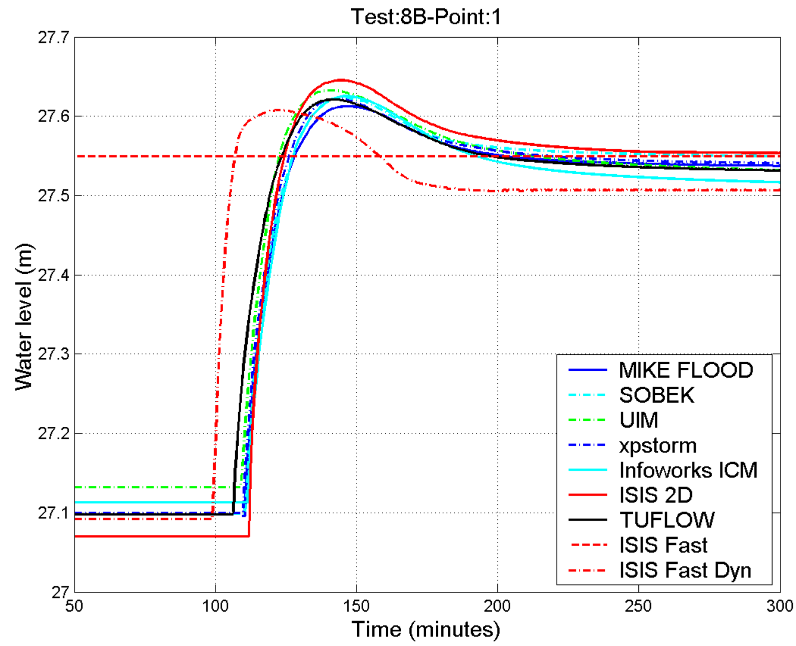
The manhole flow predictions were generally very similar to each other, although with total volumes differing within a ~15% range, as shown in Table 4.11.

Table 4.11 Predicted total volumes of manhole flow

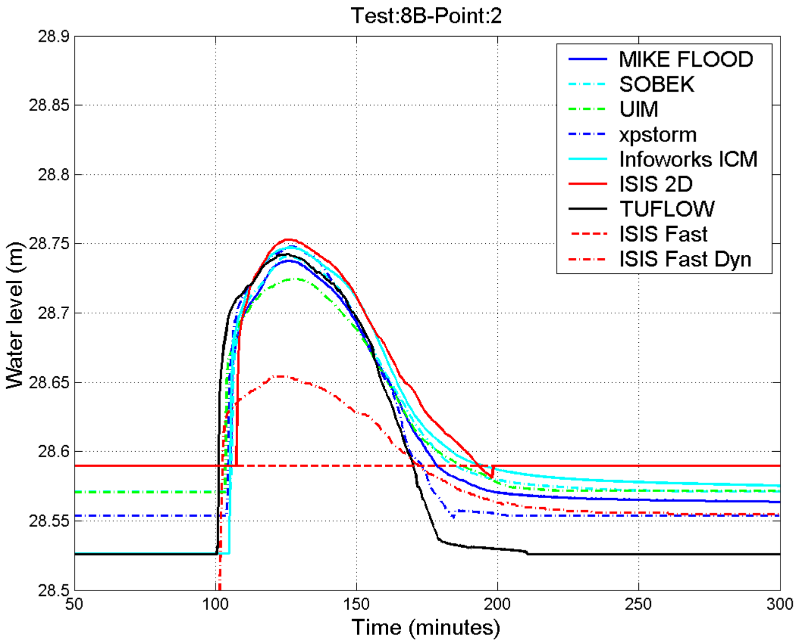
Package	Volume (m^3)
TUFLOW	5840
InfoWorks	5653
ISIS Fast	5569
ISIS Fast Dynamic	5234
UIM	5227
ISIS 2D	5058
MIKE FLOOD	5033
SOBEK	4987
XPSTORM	4954

Water levels and velocities

NB ISIS Fast is a 'final water level' model. The final water level predicted is represented as a horizontal line spanning the entire time domain.



Test:8B-Point:1
27.7
27.6
27.5
27.4
27.3
27.2
27.1
27
Water level (m)
50
100
150
200
250
300
Time (minutes)
MIKE FLOOD
SOBEK
UIM
xpstorm
Infoworks ICM
ISIS 2D
TUFLOW
ISIS Fast
ISIS Fast Dyn



Test:8B-Point:2
28.9
28.85
28.8
28.75
28.7
28.65
28.6
28.55
28.5
Water level (m)
50
100
150
200
250
300
Time (minutes)
MIKE FLOOD
SOBEK
UIM
xpstorm
Infoworks ICM
ISIS 2D
TUFLOW
ISIS Fast
ISIS Fast Dyn

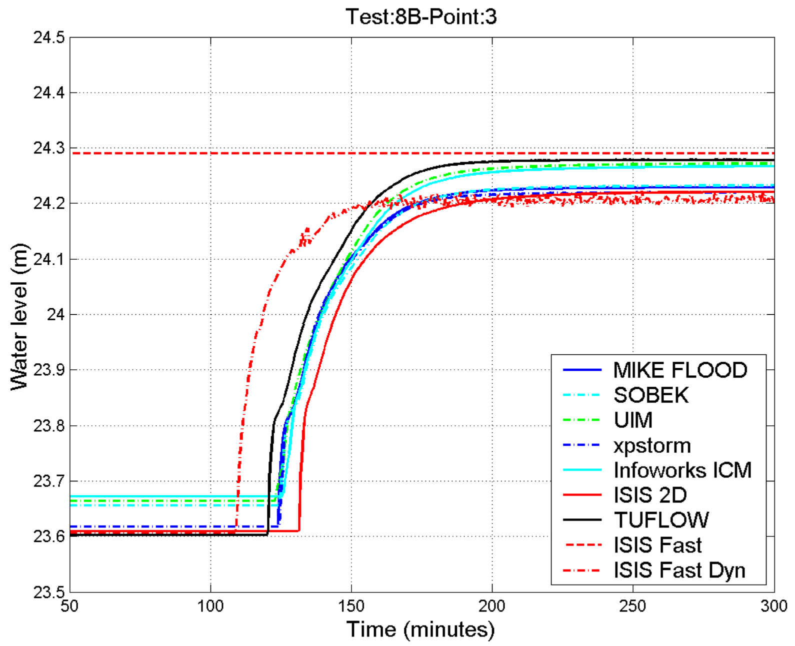


Figure 4.47 Water levels time series (results at 1, 2 and 3)

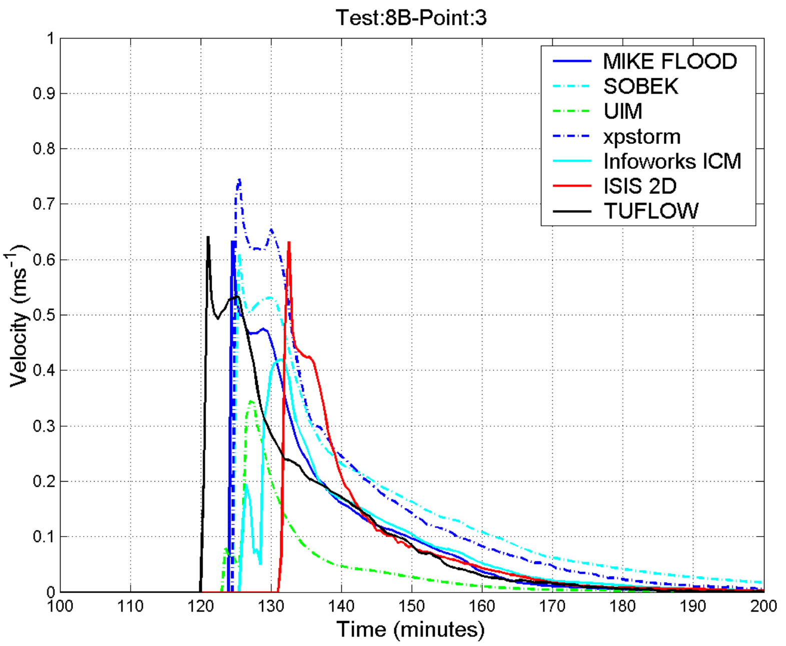


Figure 4.48 Velocities time series (results at point 3)

4.10.3 Results: summary and interpretation

Full SWE models

Water levels

Very similar comments to those made for the Test 8A results can be made with, in addition, the effects of differences in the prediction of the manhole outflow.

Transient peak water levels were generally in good agreement, with small differences when compared to predicted depths, except, as in Test 8A, at point 6, 8 and 9 (not shown) where topography-related effects were large. For example, at point 1 all SWE models agreed in the prediction of the peak levels within a range smaller than ~6% of the depth (see also point 2).

The final levels predicted at point 3 (downstream pond) were all within a ~0.08m range for a ~0.7m depth. The small differences observed may be partly due to differences in the computed manhole outflow (see Section 4.10.2).

Velocities

There are considerably larger differences in the predictions of velocities, up to 50% or more (for example, point 3).

Simplified models

The predictions by UIM are generally in agreement with the full SWE models.

As in Test 8A, ISIS Fast Dynamic has reduced travel times (points 1, 3) and differences in the prediction of transient peaks (for example, point 2) compared with the full models (and no velocity predictions).

ISIS Fast predicted generally correct final levels.

4.10.4 Miscellaneous model parameters

Table 4.12 Miscellaneous model parameters for Test 8B

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 2m or 97,000 elements)	(5) Time-stepping	(6) Run time
InfoWorks ICM	2.5.2	Yes – GPU	98,789 triangles	30s	34s
ISIS 2D	3.6 (ADI)	Partial [1]	2m	1s	234.8s
ISIS Fast	3.6	No	N/A	N/A	5s
ISIS Fast Dynamic	3.6	Partial	2m	0.5s	72s
MIKE FLOOD	2012	Yes – 8 CPUs	2m	1s	135s
SOBEK	2.13	No	2m	5s	1134s
TUFLOW	2012-05-AA Double precision	No	2m	1.5s	176s

(1) Name	(2) Version	(3) Multi-processing	(4) Resolution (expected: 2m or 97,000 elements)	(5) Time-stepping	(6) Run time
UIM	2009.10	No	2m	Adaptive 0.039–10s Average 0.055s	44600s
XPSTORM	2011 2010-10-AB-iDP-w32	No	2m	1s	360s

Notes: [1] See Appendix B.

Other information provided

ISIS 2D: 'The 2D domain was dynamically linked to the surcharged pipe. From the outflow hydrograph can be observed that some water flows back to the pipe, thus reducing the volume in the area. The outflow volume obtained with the linked model is 5075m^3'.

'In this test case both the TVD and ADI model were run. Run times and results obtained with the TVD solver improve significantly the results previously reported in 2010 and 2011. Nonetheless, the results obtained with the ADI solver were satisfactory and stable with the added value of a much lower runtime required for the model. The local effects of supercritical flow over the steep road do not seem to have significant impact in the overall flood extent; as a consequence TVD results do not provide relevant improvement when compared to ADI'.

ISIS Fast Dynamic: see Test 8A

SOBEK: 'The top of the manhole as instructed, lies at elevation 31.46m. This is 'in a kind of pond (or area surrounding by higher grounds). The water level in this pond has to rise above 31.86 m, before the water flowing out of the surcharging culvert can flow out of this pond and inundate other parts of the modelled 2D landscape. Due to this pond, we observed that the actual maximum surcharging-culvert-discharge is smaller than in a situation, where there is not such pond in the 2D landscape'.

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

4.10.5 Conclusions from Test 8B

The packages taking part in Test 8B have demonstrated their ability to link a 1D pipe model to a 2D overland flow (through a manhole). This functionality is, however, not supported in the current versions of ANUGA, Ceasg, Flowroute-*i*™, ISIS 2D GPU, LISFLOOD, RFSM, TUFLOW FV and TUFLOW GPU.

Conclusions similar to those in Test 8A can be made regarding the accuracy of the 2D flow predictions (see Section 4.9.5).

4.11 Run times

Computational times (Table 4.13) vary within up to four orders of magnitude in each test. This is explained by:

- the choice of time step (this is partly imposed by the numerical approach, although simulations may have been run with time steps shorter than necessary)
- the number of iterations performed at each time step
- the efficiency of the numerical algorithm
- the use (or not) of multi-processing
- any ‘overhead’ computational costs (pre- and post-processing of data; data transfers and so on)
- hardware specification

Details on hardware used and any multi-processing implemented are given in Section 3.4. As peripheral processes (pre- and post-processing, data transfers) have a relatively large impact on run times when model dimensions are small (in both time and space), making it difficult to interpret run times, Table 4.13 contains only run times from the ‘heavier’ tests. However, the information available to the authors does not allow them to fully explain the discrepancies observed in the table.

Many simulations were run on multiple cores. While this generally has the advantage of resulting in shorter run times, it also has the disadvantage of making it difficult to run multiple simulations in parallel (as is frequently done in engineering practice). The run times reported in Table 4.13 should therefore be considered in light of the information on hardware and multiprocessing in Section 3.4.

In many applications there are advantages in using packages that are not parallelised and yet achieve run times comparable with those of parallelised codes. Simulation times achieved using one CPU core only (no CPU or GPU parallelisation) are marked by an asterisk and grey shading in Table 4.13.

In addition, there may be even larger differences between models in terms of the total time to undertake modelling (including set-up time, trial runs and so on) than in terms of the run time of the ‘production run’. This is likely to be a further advantage of simplified models (ISIS Fast, RFSM) in situations where these make acceptably accurate predictions.

The tests were run in 2009 in the case of ANUGA, UIM, SOBEK and RFSM Direct. Consequently these three packages have not benefitted from any recent hardware advances in the same way as others.

Table 4.13 Summary of run times for all tests and packages

	Test 2 (s)	Test 4 (s)	Test 5 (s)	Test 6B (s)	Test 7 (min)	Test 8A (s)
ANUGA *	1130	3650	4160	1390		
Ceasg	15	72	569	14		84
Flowroute-*i*™	6	21	9			122
InfoWorks ICM	11	44	9	34	38.5	66
ISIS 2D *	22	82	58.5	559.1	6.8	560
ISIS 2D GPU	22	25	57	19		327
ISIS Fast Dynamic *	2					90
ISIS Fast *			3.6		0.12	1
JFLOW+	10	17.6	22	6		66
LISFLOOD-FP	7.2	21	28.2			268.2
MIKE FLOOD	9.6	32.1	28.3	54.9	3.82	367
RFSM (Direct)*	1		<1			<1
RFSM – EDA *	11	13	13.8			156
SOBEK *	100	1014	168	1010	194.9	1494
TUFLOW *	7.3	47	26	38	3.33	477
TUFLOW GPU	16	25	9	5		84
TUFLOW FV [1]	26 (41)	142 (481)	67 (150)	109 (195)		410 (612)
UIM *	712	17000	2670			18470
XPSTORM *	12	84	52.3	61.7	9	562.3

Notes: Empty cells: test not run

* Run times achieved using one CPU core only (no CPU or GPU parallelisation).

[1] First order solution (second order solution)

5. Improvements to the benchmarking tests

In light of the experience gained from the benchmarking exercise presented in this report, this section reviews the fitness-for-purpose of the existing benchmark test cases against the background of changing Environment Agency needs and flood inundation modelling capability. Recommendations for future updates of the benchmark test cases are also made.

5.1 Improvements to the existing benchmarking tests

5.1.1 Test 1 Flooding a disconnected water body

Test 1 is trivial and undertaken successfully by all modelling packages participating in the exercise. The modelling package capability tested is similar to that of Test 2.

It is recommended that Test 1 is removed from the set of benchmark test cases.

5.1.2 Test 2 Filling of floodplain depressions

Test 2 successfully distinguishes between momentum-conservative modelling packages and simplified models where full momentum conservation has been sacrificed to achieve greater computational efficiency.

It is recommended that Test 2 should be retained.

5.1.3 Test 3 Momentum conservation over a small obstruction

Test 3 successfully identifies modelling packages that conserve momentum.

It is recommended that test 3 should be retained.

5.1.4 Test 4 Speed of flood propagation over an extended floodplain

Test 4 is considered to be a good test of the ability of modelling packages to simulate flood propagation over a flat floodplain and therefore should be retained. There is a minor ambiguity in the specification of the boundary condition which causes problems for some modelling packages.

It is recommended that Test 4 is retained, but with the specification of the boundary condition improved.

5.1.5 Test 5 Valley flooding (due to dam failure)

Test 5 is a good test of the capability of modelling packages to simulate valley flooding at full scale.

It is recommended that Test 5 should be retained.

5.1.6 Test 6A Dambreak, laboratory scale with UCL (Belgium) laboratory measurements

The flood modelling packages being benchmarked are designed to make predictions at the field scale to enable practical flood risk management decision making. This results in computer model predictions and physical model measurements that compare well at one location and badly at others. In addition, there is no consistency in the comparison between modelling package performance. This makes it impossible to draw any conclusions regarding the modelling packages suitability for support decision making by the Environment Agency.

The main reason for retaining this test is that is the only one where modelling package performance is assess using real data. However, this benefit is outweighed by the points above and it is recommended that Test 6A should be removed.

5.1.7 Test 6B Dambreak, field scale

Test 6A is a good test of the capability of modelling packages to simulate complex high velocity flows immediately downstream of a dam, separating the performance of packages that employ shock capturing numerical schemes from these that do not. The geometry is currently provided in the form of a DEM, which can be improved by changing the format to GIS polygons.

It is recommended that this test is retained, but that the format of the data provided is altered.

5.1.8 Test 7 River and floodplain linking

In principle this is a good practical test which demonstrates a modelling package's ability to link a 1D model river model to a 2D floodplain model, and to simulate water transfer over banks / flood defences and through 1D structures. In practice, however, participants do not always follow the instructions sufficiently closely. This results in differences in predictions occurring due to a misapplication of the data rather than differences in techniques employed by the modelling packages.

It is recommended that Test 7 is retained but that an attempt is made to improve the setup instructions and to make it clear to participants that their results will be rejected if the instructions are not followed.

5.1.9 Test 8A Rainfall and point source surface flow in urban area and 8B Surface flow from a surcharging sewer in urban areas

Test 8A is successful at identifying modelling packages capable of simulating direct rainfall onto an urban catchment and simulating shallow flow over a complex urban topography. However, further consideration needs to be given to the grid resolution used for the test (currently 2m) and to how important features such as road gullies are included in the simulation. The related Test 8B is successful at demonstrating a modelling package's capability to link a 1D sewer model to a 2D surface model, but otherwise is a repeat of Test 8A.

It is recommended that Tests 8A and 8B are replaced by a single Test 8 made up of a rainfall boundary condition as in Test 8A and a surcharging sewer boundary condition as in Test 8B, but with a time lag between the rainfall input and the sewer surcharging.

5.2 Potential additional benchmark tests

Participants in the benchmarking exercise suggested a number of possible improvements and extensions to the set of test cases available. These would address some of the perceived shortcomings of the existing set.

5.2.1 Testing the ability of modelling packages to undertake simulations involving high computational demands

At present the most computationally demanding test is Test 8 (97,000 elements) for which simulations are completed typically in 1–10 minutes. For modelling packages that employ high performance computing (for example, parallelisation on GPU), Test 8 is not sufficiently computationally demanding to demonstrate the benefits of this high performance computing approach because too large a share of the computational effort is spent dealing with peripheral processes(pre- and post-processing, transfer of data and so on) which are not parallelised.

There are two possible solutions to this, either the grid resolution for Test 8 is significantly refined (that is, 0.5m) or a new test is introduced. The new test would be require a DEM of a very large area (for example, 1000km^2 or more), possibly subjected to catastrophic coastal flooding such as an extreme storm surge (see the example image in Figure 5.1 and Table 5.1).

Figure 5.1 Example from the Fens, UK, of DEM for possible new test with high computational demand

Table 5.1 Relationship between resolution and number of elements

Area (km^2)	Resolution (m)	Number of elements
1000	100	100,000
1000	50	400,000
1000	10	10,000,000

5.2.2 Testing modelling packages ability to support broad-scale modelling and support uncertainty analysis.

The benefits of ‘fast’ simulation models such as the RFSM or ISIS Fast are not currently demonstrated using the current benchmark tests. These models are designed to assess flood risk at a national scale or to provide multiple realisations of a single event to permit uncertainty analysis. This could be addressed using the same data set suggested above but assuming the coastline to be defended, with hundreds of possible defence breach locations specified, combining this with a number of possible sea levels/surge durations and breach size could generate the need for 10,000 or more simulations. The required output could be in the form of a statistical distribution of peak flood levels at selected points on the floodplain. Modellers would be free to use their own judgement in defining the grid resolution. A ‘reference’ run using a modelling packaged based on the shallow water equations with a high resolution grid (100m or finer) could also be undertaken. Although this would take many days of computing effort, its output would provide a benchmarking data set against which the fast models could be compared.

5.2.3 Potential new urban flooding data set

Following the Australian floods in 2007 and 2011, the Water Research Laboratory, University of New South Wales, Sydney, undertook a field data collation and physical modelling exercise to provide validation data for 2D hydrodynamic modelling in the urban area. The data set chosen was that of the June 2007 flood in Merewether. The data set was expanded by means of a scale physical model, suitably validated against available flood peak water levels in the flooded urban area. The site is attractive and suitable as a test site due to severity of the flooding hazard during the June 2007 storm, the influence of buildings as obstructions to flow, the dendritic and somewhat constrained nature of the overflow path and availability of key data sets.

It is recommended that further work is undertaken to ascertain whether or not it would be possible for the Environment Agency to access and evaluate these data.

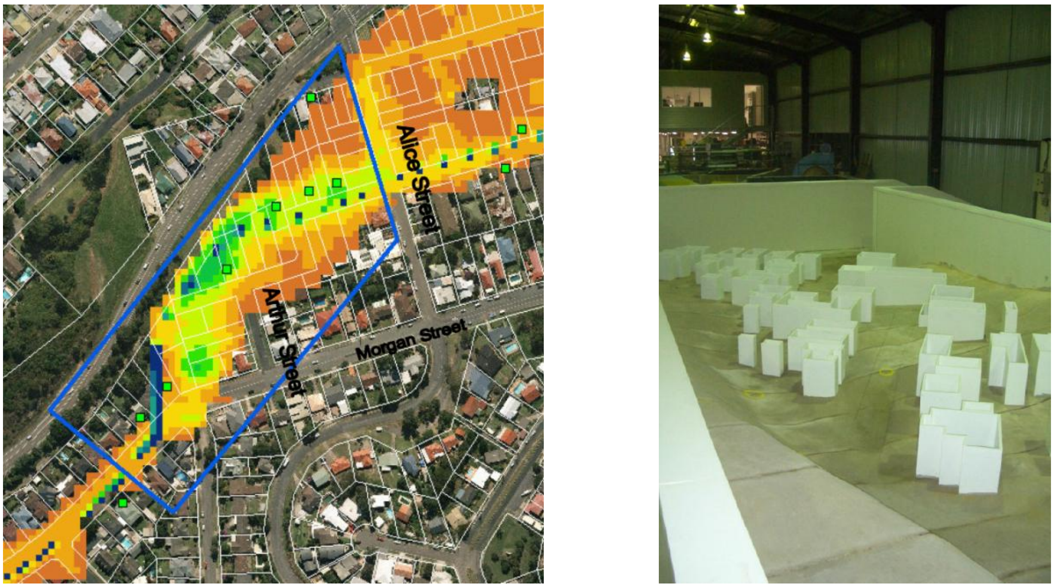


Figure 5.2 New Australian urban flooding data set

5.3 Miscellaneous comments

The number of modelling packages participating in the exercise means that the presentation style of the current report has reached its limits. A sufficient number of simulations have now been undertaken for each benchmark test case to consider a move to a web-based format where an envelope encapsulating the simulations achieved by all packages is made available against which developers can present their results. Were such an approach to be adopted it would be necessary to insist that developers also complete a methodology disclosure template against which they would be required to make public information on their packages underlying equations, numerical approaches and so on.

5.4 Conclusions

Overall the majority of the benchmark test cases remain fit-for-purpose. However the following alterations are recommended prior to embarking on a further round of 2D flood modelling package benchmarking.

- Tests 1 and 6A should be removed, the specification of the boundary conditions for Test 4 should be improved to avoid misinterpretation, the setup instructions for Test 7 should be improved, and Tests 8A and 8B should be combined into a single test with consideration given to adding more detail on the storm water drainage system.

- Consideration should be given to including three additional benchmark test cases to account for developments in 2D flood inundation modelling since the original test cases were created. These include the testing of packages developed to utilise GPU technology, developments in simplified methods for uncertainty analysis, and utilization of the data now available from the Water Research Laboratory, University of New South Wales, Sydney, Australia.

6. Conclusions

6.1 Packages based on the shallow water equations

As can be seen from Table 4.1, the full shallow water equation packages (ANUGA, Ceasg, Flowroute-*i*™, InfoWorks ICM, ISIS 2D, ISIS 2D GPU, JFLOW+, MIKE FLOOD, SOBEK, TUFLOW, TUFLOW GPU, TUFLOW FV and XPSTORM) have been applied to all the test cases, with the following exceptions.

- Packages not supporting 1D–2D linking at the time of testing were not applied to Tests 7 or 8B (ANUGA, Ceasg,[9] Flowroute-*i*™, ISIS 2D GPU, JFLOW+, TUFLOW GPU and TUFLOW FV).
- Tests 6A/6B were not run using Flowroute-*i*™ because of the occurrence of rapidly varying supercritical flows.

The detailed discussion of the predictions from each test in Section 4 leads to the general conclusion that the packages have produced comparable predictions of water level and velocity across the full range of tests and are applicable across the full range of Environment Agency flood risk modelling requirements. However, the following caveats apply to this general conclusion.

- The modelling of rapidly varying or supercritical hydrodynamic processes such as those encountered in Tests 3, 5, 6 (flows due to dambreak and so on) is technically delicate and many models are occasionally subject to numerical oscillations, particularly those that lack shock capturing capability (Flowroute-*i*™ in Tests 3, 6, not run, and 8A, ISIS 2D with ADI in test 5, XPSTORM in Tests 6B and 7, and so on) though not only (ANUGA, InfoWorks ICM, and ISIS2D GPU in Test 5 and so on). This results in higher peak water level and velocity predictions than those obtained by the other shallow water equation packages. Using predictions that contain oscillations to create peak velocity or peak water level maps may result in higher values for extremes compared with solutions that do not contain oscillations. This could be significant in mapping maximum flood hazard.
- An issue with the mapping of peak velocities with ANUGA and ISIS 2D GPU requires investigation (highlighted by Tests 5 and 6B).
- For predictions of dambreak at the laboratory scale (Test 6A), there is reasonable agreement between predictions and measured orders of magnitudes of water depth and velocities, although not of the variations in time of these. However, the codes based on shock capturing numerical schemes (or those at least accommodate supercritical flows) perform better overall. When applied to the dambreak simulation at the field scale (Test 6B), the variation in predictions is much less significant. For such simulations it is prudent to use packages that employ a shock capturing numerical scheme (or at least handle supercritical flows).
- For 1D river to 2D floodplain linking (Test 7), close agreement is obtained for water level and velocity predictions in the river channel. However, significant variations in the timing of inundation, water level and velocity occur on the floodplains, reflected both in the time series output and the contour plots of peak velocities. These are due to variations in the way

[9] Although this would in principle have been possible through the Open-MI.

each package predicts the flood volume exchanged between the main channel and the floodplain, for which there is no consistent approach used in practice at the present time. This calculation is also very sensitive to the representation of river bank levels in the calculation of volume exchange. Further research into this aspect of model linking is required.

- For rainfall and point source generated surface flow in urban areas (Test 8A), the manner in which the underlying floodplain topography is represented has a significant influence on water level and velocity predictions. This would suggest that grid refinement (to <2m) may be desirable (and may also improve the accuracy of velocity predictions) in some cases. However, it is important to point out that this is likely to have counterproductive effects in terms of computational efficiency and therefore the ability to run multi-simulations, quantify uncertainties, perform risk studies, calibrate models and so on.

A direct comparison of the computational efficiency of each package is not possible due to differences in the hardware used, the time increments chosen by the modellers and various peripheral computational costs not directly related to the 2D flow modelling. However, the run times reported are considered acceptable for use on Environment Agency applications at the scale tested here. However, their computational requirements make their use impractical for regional and national flood risk assessment over large areas and for uncertainty analysis requiring multiple runs with varying parameter values.

It is possible to obtain predictions over large areas by using shallow water equation models with a very coarse grid resolution. However, the averaging of parameters necessary to achieve this means the quality of the predictions obtained are unlikely to be better than those one would get from a simplified modelling approach.

6.2 Packages based on simplified (3-term) equations and UIM (2-term model)

The three packages relying on a simplified form of the SWE neglecting advective acceleration have also been applied to most of the test cases, with some exceptions:

- Tests 7 or 8B as the models did not support 1D-2D linking at the time of testing[10]
- Tests 6A and 6B because of the occurrence of rapidly varying supercritical flows

The general conclusion for these three packages is that they generally produced predictions of water levels and inundation dynamics (velocities) comparable with those of the full SWE models at least in situations characterised by low momentum and/or slowly varying flow conditions. The caveats to these general conclusions are as follows.

- The results with UIM featured occasional oscillations (Tests 3 and 5). Due to its explicit numerical formulation, the model had to be run with very short time steps, leading to significantly longer run times than other models. Flood travel times were also longer than with the full SWE models in Test 5.

[10] Test 7 would have been an appropriate test of LISFLOOD-FP but it was not tested because of lack of staff resources.

- The coarser resolution used with RFSM EDA meant that the model did not predict local flow patterns as well as others. Also, flood travel times were often significantly shorter than with the full SWE models (Tests 2 and 5)
- The numerical formulation of LISFLOOD-FP also resulted in difficulties in areas of supercritial flow (Test 5).

Consequently, the packages based on the ‘3-term’ formulation of the SWE (advective acceleration neglected) and UIM (all acceleration terms neglected) are suitable to support decision making where inundation extent and maximum depth are required (that is, catchment flood management planning and flood risk assessment) and even provide a relatively accurate assessment of velocities.

They are, however, less suitable in situations involving highly unsteady and/or supercritical flows, hydrodynamic shocks and so on. Their predictions of travel times, wherever this is required (disaster planning and so on) should be considered cautiously. They are not suitable to predict highly unsteady complex flows in the immediate downstream vicinity of a catastrophic event (for example, dambreak).

It is recommended that this class of model be used cautiously where accurate velocity predictions are required, that is, strategic assessment for flood risk assessment, flood hazard mapping, contingency planning and reservoir inundation mapping.

There were some benefits in terms of reduced computational effort in applying RFSM EDA or LISFLOOD-FP compared with the full shallow water equation models for the tests reported here.

6.3 Packages based on simplified (2-term) equations and on volume spreading (0-term)

ISIS Fast Dynamic was only applied to Tests 1, 2 and 8. The broad conclusion is that the model is able to calculate a reasonably accurate final inundation extent in situations involving very low momentum flow. It also provides an approximate assessment of the order of magnitude of transient flood depths. It does not at the present time predict flood wave travel times or velocity magnitudes accurately. It has some benefits in terms of computational costs, although this was not always demonstrated (for example, Test 8A where some full SWE models were reported to be faster).

The ‘flood spreading’ algorithms (ISIS Fast and RFSM Direct) produced approximate predictions of ‘final’ inundation distributions, with clear benefits in terms of computational cost compared with other models. However, their use is limited to some large-scale applications where final water levels only are required (although ISIS Fast can be used in dynamic linked mode to produce an assessment of peak levels; see Test 7), and dynamic effects are insignificant and/or not of interest (that is, as can be the case in national and regional flood risk assessment, and catchment flood management planning).

Table 6.1 Suitable packages for Environment Agency applications

Application	Predictions required	Suitable packages identified in study
Large Scale[1] Flood Risk Mapping	Inundation extent	Usable predictions could be obtained using **all packages** discussed above, although the computational efficiency of some simplified models is an advantage.
Catchment Flood Management Plan Flood Risk Assessment Detailed Flood Mapping	Inundation extent Maximum depth	Appropriate predictions will be obtained using **packages based on the shallow water equations or simplified equations**. The need for detail mitigates against the use of RFSM Direct or ISIS Fast.
Strategic Flood Risk Assessment Flood Hazard Mapping Contingency Planning for Real Time Flood Risk Management Reservoir Inundation Mapping	Inundation extent Maximum depth Maximum velocity	The most suitable **packages** for this task are those **based on the shallow water equations**. If subcritical to supercritical or supercritical to sub-critical flow transitions exist, there may be benefit in using codes based on shock capturing numerical schemes (see Table 3.1).

Notes: [1] Large scale can extend to catchments of thousands of km^2

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List of abbreviations

ADI	alternating direction implicit
CPU	central processing unit
DEM	digital elevation model
DTM	digital terrain model
GPU	graphic processing unit
MDSF2	Modelling and Decision Support Framework 2
NaFRA	National Flood Risk Assessment
NLSWE	non-linear shallow water equation
RFSM	Rapid Flood Spreading Method
SWE	shallow water equation
TVD	total variation diminishing
WLBC	water elevation boundary condition

Appendix A: Test specifications

A.1 Test 1: Flooding a disconnected water body

A1.1 Modelling performance tested

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

A1.2 Description

This test consists of a sloping topography with a depression as illustrated in Figure A.1. The modelled domain is a perfect 700m × 100m rectangle. A varying water level, see Figure A.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 10.35m. 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 become horizontal at the same elevation as the sill, 10.25m.

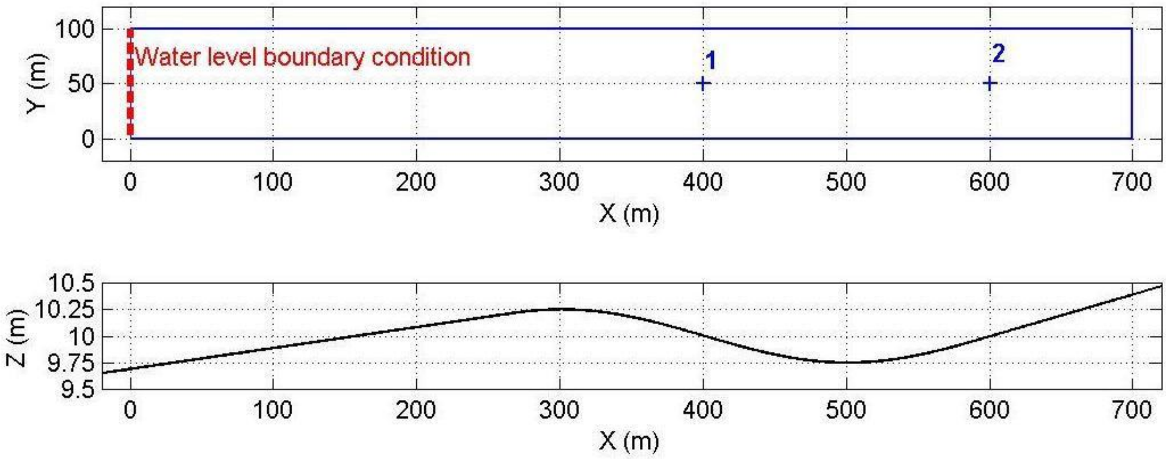

Figure A.1 Plan and profile of the DEM use in Test 1

Notes: The area modelled is a perfect rectangle extending from X = 0 to X = 700m and from Y = 0 to Y = 100m as represented.

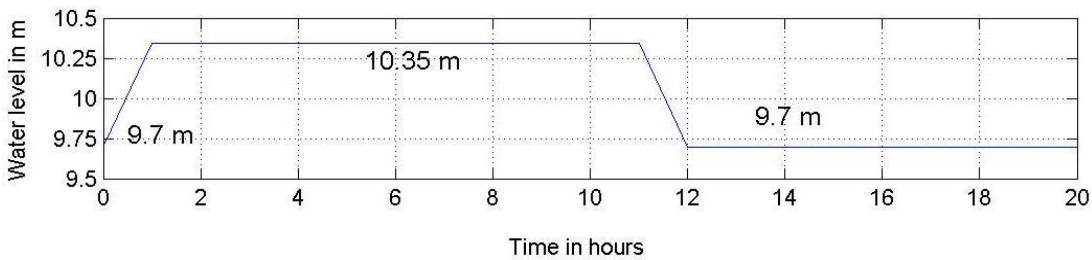

Figure A.2 Water level hydrograph used as boundary condition

Notes: Table provided as part of data set (see Section A.1.6)

A1.3 Boundary and initial conditions

Varying water level along the dashed red line in Figure A.1; table provided as part of data set.

All other boundaries are closed.

Initial condition: Water level elevation = 9.7m.

A1.4 Parameter values

Manning's *n*: 0.03 (uniform)

Model grid resolution: 10m (or 700 nodes in the area modelled)

Time of end: the model is to be run until time t = 20h

A1.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Water level vs. time (output frequency 60s), at two locations in the pond as shown in Figure A.1 and provided as part of the data set

A1.6 Data set content

Description	File name
Georeferenced Raster ASCII DEM at resolution 2m	Test1DEM.asc
Upstream boundary condition table (water level vs. time)	Test1BC.csv
Location of output points	Test1Output.csv

A1.7 Additional comments

Participants are asked to provide model results **at least** for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.2 Test 2: Filling of floodplain depressions

A2.1 Modelling performance tested

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

A2.2 Description

The area modelled, shown in Figure A.3, is a perfect 2000 m × 2000m square and consists of a 4 × 4 matrix of ~0.5m deep depressions with smooth topographic transitions. The DEM was obtained by multiplying sinusoids in the north to south and west to east directions, and the depressions are all identical in shape. An underlying average slope of 1:1500 exists in the north to south direction, and of 1:3000 in the west to east direction, with a ~2m drop in elevation along the north–west to south–east diagonal.

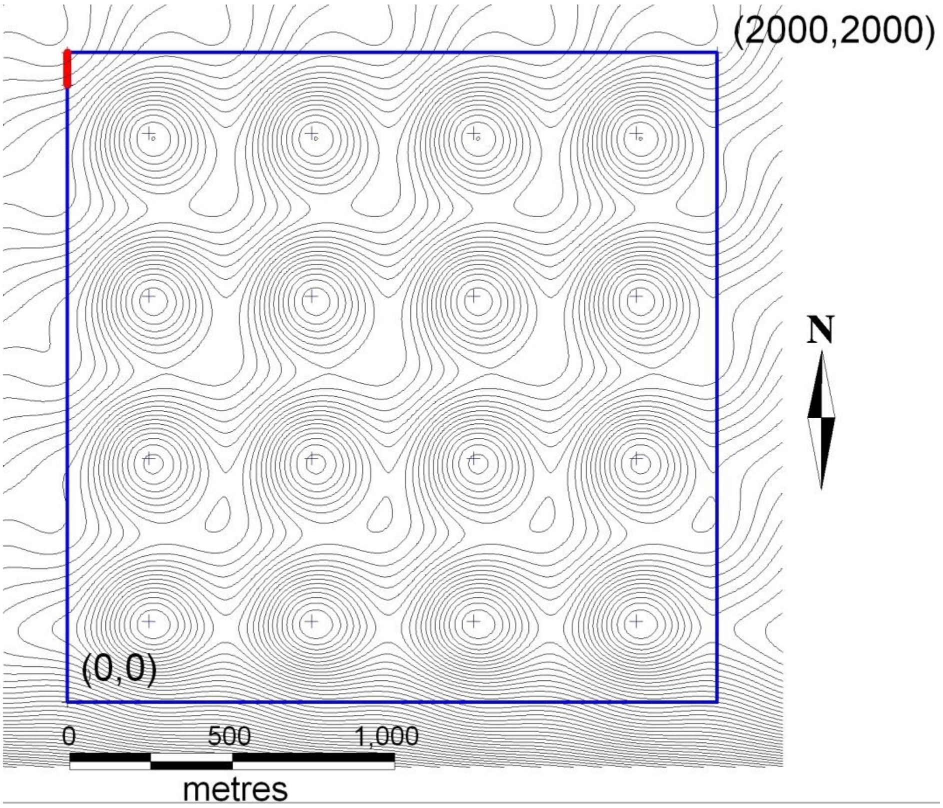

Figure A.3 Map of the DEM showing the location of the upstream boundary condition (red line), ground elevation contour lines every 0.05m, and output point locations (crosses)

The inflow boundary condition is applied along a 100m line running south from the north-western corner of the modelled domain (see Figure A.3).

A flood hydrograph with a peak flow of $20m^3/s$ and time base of ~85min is used. The model is run for 2 days (48h) to allow the inundation to settle to its final state.

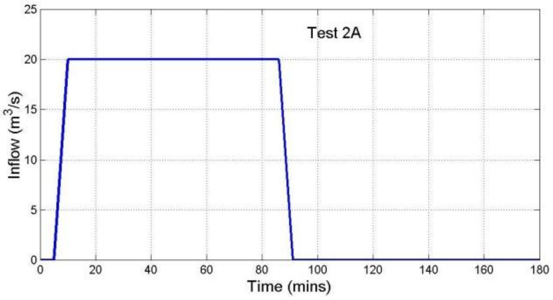

Figure A.4 Inflow hydrograph used as upstream boundary condition in Test 2

A2.3 Boundary and initial conditions

Inflow along the red line in Figure A.3; location and tables provided as part of data set.

All other boundaries are closed.

Initial condition: Dry bed.

A2.4 Parameter values

Manning's *n*: 0.03 (uniform)

Model grid resolution: 20m (or ~10,000 nodes in the area modelled)

Time of end: model is to be run until time t = 48h

A2.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Total water volume on the floodplain at the end of the simulation

Numerical prediction of **water level** vs. time at the centre of each depression (coordinates provided as part of data set)

Output frequency: 300s

A2.6 Data set content

Description	File name
Georeferenced Raster ASCII DEM at resolution 2m	Test2DEM.asc
Upstream boundary condition table (inflow vs. time)	Test2_BC.csv
Outline of modelled area (shapefiles)	Test2ActiveArea_region
Location of upstream boundary condition (shapefile)	Test2BC_polyline
Location of output points	Test2Output.csv

A2.7 Additional comments

Linear interpolation should be used to interpolate inflow values.

Participants are asked to provide model results **at least** for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.3 Test 3: Momentum conservation over a small obstruction

A3.1 Modelling performance tested

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

A3.2 Description

This test consists of a sloping topography with two depressions separated by an obstruction as illustrated in Figure A.5. The dimensions of the domain are 300m longitudinally (X) × 100m transversally (Y). A varying inflow discharge, see Figure A.6, is applied as an upstream boundary condition at the left-hand end, causing a flood wave to travel down the 1:200 slope. While the total inflow volume is just sufficient to fill the left-hand side depression at X = 150m, some of this volume is expected to overtop the obstruction because of momentum conservation and settle in the depression on the right-hand side at X = 250m. The model is run until time t = 900s (15min) to allow the water to settle.

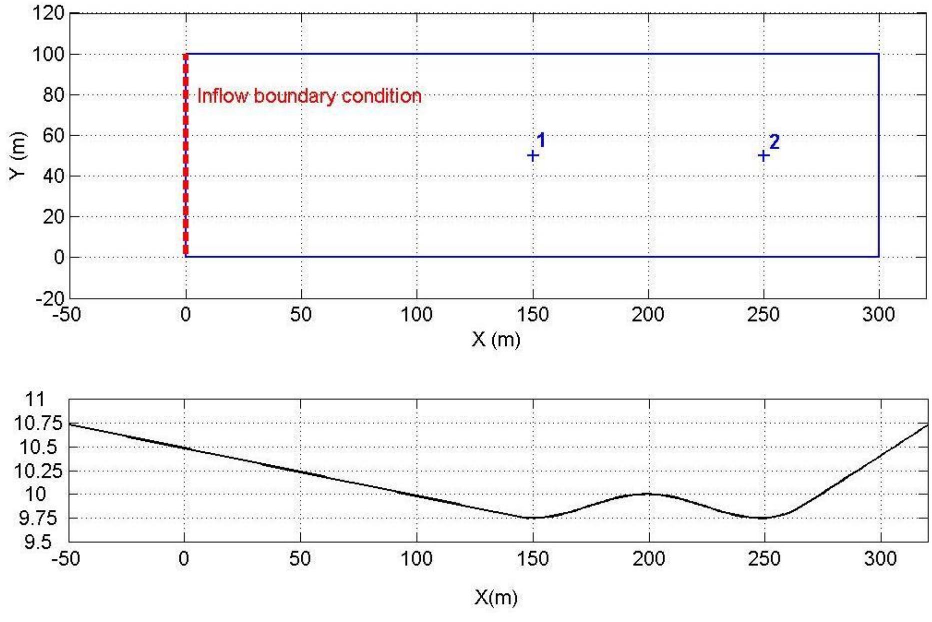

Figure A.5 Plan and profile of the DEM use in Test 3

Notes: The area modelled is a perfect rectangle extending from X = 0 to X =3 00m and from Y = 0 to Y = 100m as represented.

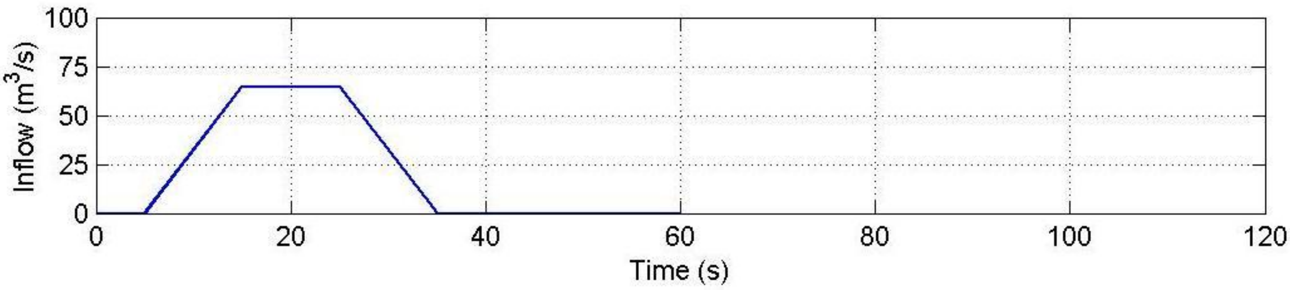

Figure A.6 Inflow hydrograph used as upstream boundary condition

A3.3 Boundary and initial conditions

Inflow boundary condition along the dashed red line in Figure A.5; table provided as part of data set

All other boundaries are closed.

Initial condition: Dry bed

A3.4 Parameter values

Manning's *n*: 0.01 (uniform)

Model grid resolution: 5m (or ~1200 nodes in the area modelled)

Time of end: the model is to be run until time t = 15min

A3.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Numerical predictions of **velocity** and **water level** vs. time (output frequency 2s) at location 1 (centre of the first depression) defined below

Numerical predictions of **water level** vs. time (output frequency 2s) at location 2 (centre of the second depression) as defined below:

Location	X	Y
1	150	50
2	250	50

A3.6 Data set content

Description	File name
Georeferenced Raster ASCII DEM at resolution 2m	Test3DEM.asc
Upstream boundary condition table (discharge vs. time)	Test3BC.csv

A3.6 Additional comments

Linear interpolation should be used to interpolate inflow values.

It is pointed out that results may be significantly affected by the effective modelled domain width in cases where this is not exactly 100m. Participants are reminded to ensure that the effective domain width is 100m (in this test only, an alternative is to multiply the inflow discharge by the appropriate ratio if the effective width is not 100m).

Participants are asked to provide model results **at least** for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.4 Test 4: Speed of flood propagation over an extended floodplain

A4.1 Modelling performance tested

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

A4.2 Description

This test is designed to simulate the rate of flood wave propagation over a 1000m × 2000m floodplain following a defence failure, Figure A.7. The floodplain surface is horizontal, at elevation 0m. One inflow boundary condition will be used, simulating the failure of an embankment by breaching or overtopping, with a peak flow of 20m^3/s and time base of ~ 6h. The boundary condition is applied along a 20m line in the middle of the western side of the floodplain.

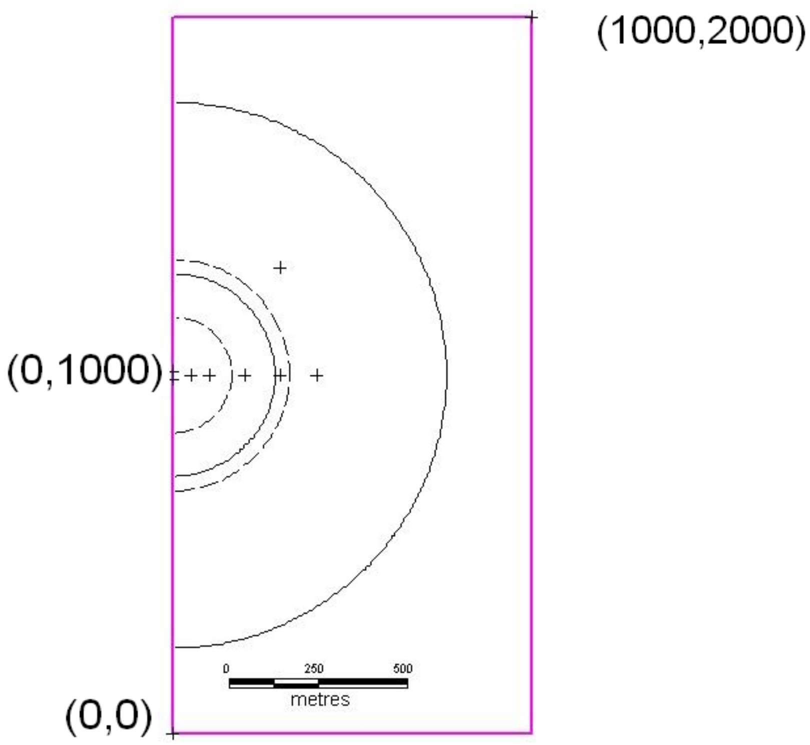

Figure A.7 Modelled domain, showing the location of the 20m inflow, six output points, and possible 10cm and 20cm contour lines at time 1h (dashed) and 3h (solid)

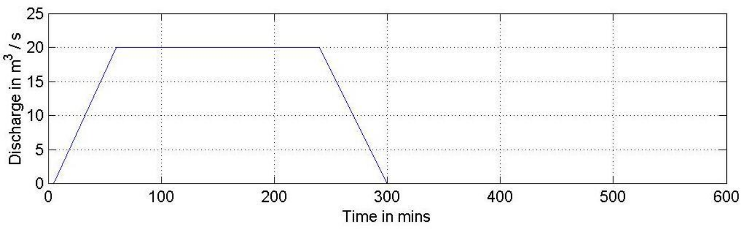

Figure A.8 Hydrograph applied as inflow boundary condition

A4.3 Boundary and initial conditions

Inflow boundary condition as shown in Figure A.7; table provided as part of data set

All other boundaries are closed.

Initial condition: Dry bed.

A4.4 Parameter values

Manning's *n*: 0.05 (uniform)

Model grid resolution: 5m (or ~80,000 nodes in the area modelled)

Time of end: the model is to be run until time t = 5h (if an alternative end time is used run times must be reported for t = 5h)

A4.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Raster grids (or TIN) at the model resolution consisting of:

- **Depths** at times 30min, 1h, 2h, 3h, 4h
- **Velocities** (scalar) at times 30min, 1h, 2h, 3h, 4h
- Plots of **velocity** and **water elevation** vs. time (suggested output frequency 20s) at the six locations represented in Figure A.7 and provided as part of data set

A4.6 Data set content

Description	File name
Upstream boundary condition table (inflow vs. time)	Test4BC.csv
Location of output points	Test4Output.csv

The model geometry is as specified in Section A.4.2. No DEM is provided as the ground elevation is uniformly 0.

A4.7 Additional comments

Linear interpolation should be used to interpolate inflow values.

Participants are asked to provide model results at least for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.5 Test 5: Valley flooding

A5.1 Modelling performance tested

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

A5.1 Description

This test is designed to simulate flood wave propagation down a river valley following the failure of a dam. The valley DEM is ~0.8km by ~17km (Figure A.9) and the valley slopes downstream on a slope of ~0.01 in its upper region, easing to ~0.001 in its lower region. The inflow hydrograph applied as a boundary condition along a ~260m long line at the upstream end is designed to account for a typical failure of a small embankment dam and to ensure that both supercritical and subcritical flows will occur in different parts of the flow field (see Figure A.10). The model is run until time t = 30h to allow the flood to settle in the lower parts of the valley.

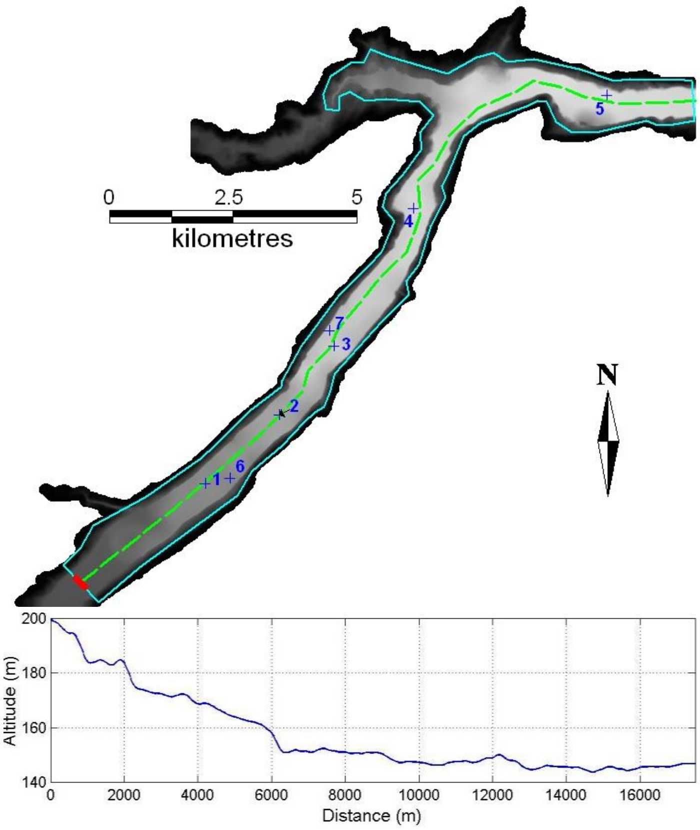

Figure A.9 DEM used, with cross-section along the centre line and location of the output points

Notes: The red line indicates the location of the boundary condition and the blue polygon is the modelled area.

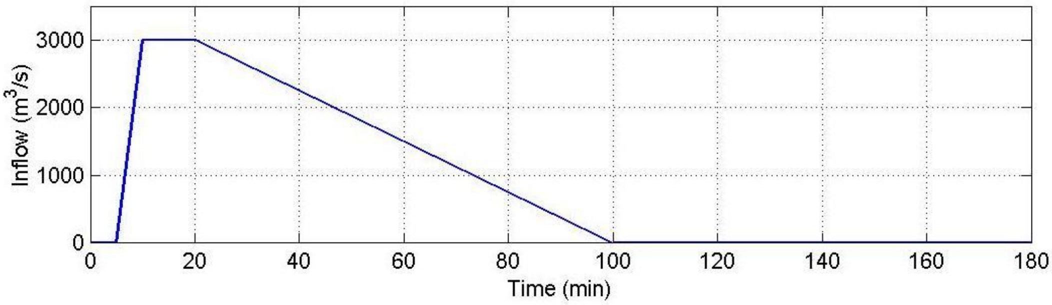

Figure A.10 Inflow hydrograph applied in Test 5

A5.2 Boundary and initial conditions

Inflow boundary condition along the dashed red line in Figure A.9; table provided as part of data set

All other boundaries are closed.

Initial condition: Dry bed

A5.3 Parameter values

Manning's *n*: 0.04 (uniform)

Model grid resolution: 50m (or ~7600 nodes in the 19.02 km^2 area modelled)

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

A5.4 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Raster grids (or TIN) at the model resolution consisting of:

- Peak **water level elevations** reached during the simulation
- Peak water **depths** reached during the simulation
- Peak **velocities** (scalar) reached during the simulation
- **Water level** vs. time (suggested output frequency 60s), at seven locations as shown in Figure A.9 and provided as part of the data set
- **Velocity** vs. time (suggested output frequency 60s), at seven locations as shown in Figure A.9 and provided as part of the data set

A5.5 Data set content

Description	File name
Georeferenced Raster ASCII DEM at resolution 10m	Test5DEM.asc
Upstream boundary condition table (inflow vs. time)	Test5BC.csv
Outline of modelled area (shapefiles)	Test5ActiveArea_region
Location of upstream boundary condition (shapefile)	Test5BC_polyline
Location of upstream boundary condition (backup text file)	Test5BC_backup.txt
Location of output points	Test5Output.csv

A5.6 Additional comments

The test can be set-up without access to the two shapefiles provided in case participants are unable to use these.

Linear interpolation should be used to interpolate inflow values.

Participants are asked to provide model results at least for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.6 Tests 6A and 6B: Dambreak

A6.1 Modelling performance tested

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

A6.2 Description

This dambreak test case has been adapted from an original benchmark test case available from the IMPACT project (IMPACT 2005, Soares-Frazão 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-Frazão and Zech (2002), where the physical dimensions are those of the laboratory model. The test involves a simple topography, a dam with a 1m wide opening, and an idealised representation of a single building downstream of the dam (see Figure A.11). An initial condition is applied, consisting in a uniform depth of 0.4m upstream from the dam and 0.02m downstream from the dam. The flow is contained by vertical walls at all boundaries of the DEM.

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

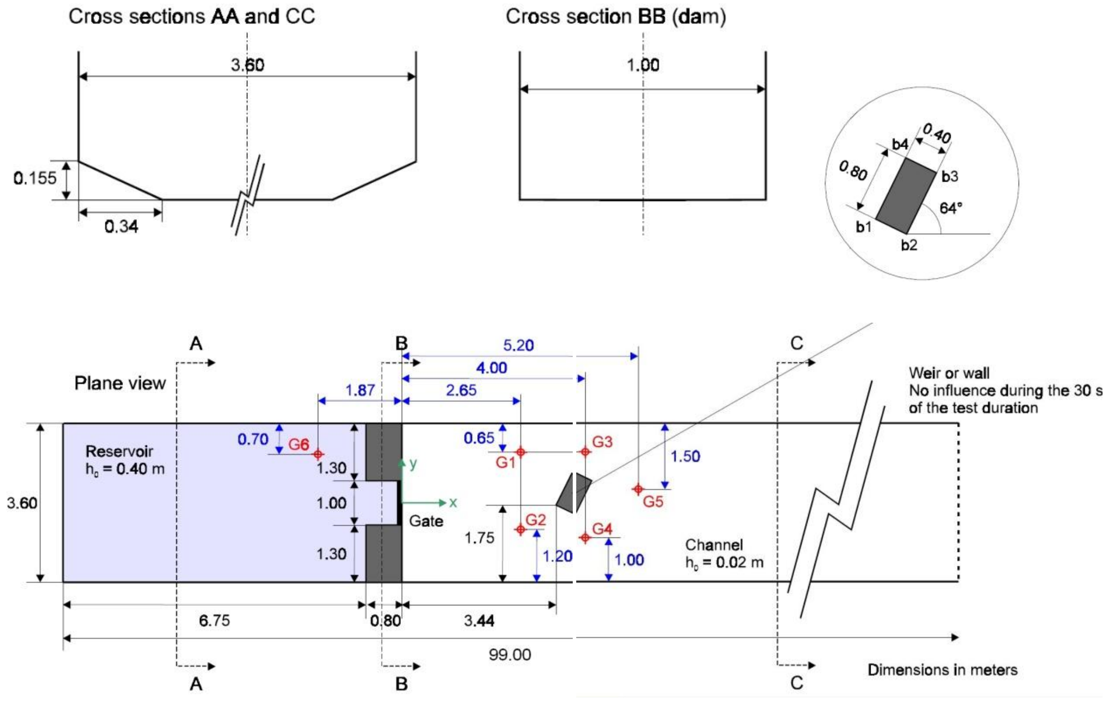

Figure A.11 Set-up for Test 6A (adapted from Soares-Frazão and Zech 2002)

A6.3 Boundary and initial conditions

No boundary condition specified as the flow is contained by vertical walls.

Initial condition:

In Test 6A: Depth = 0.4m upstream from the dam, that is, for X <0

Depth = 0.02m downstream from the dam, that is, for X >0

In Test 6B: Depth = 8m upstream from the dam, that is, for X <0

Depth = 0.4m downstream from the dam, that is, for X >0

A6.4 Parameter values

No preferred value of the eddy viscosity is specified.

In Test 6A:

Manning's *n*: 0.01 (uniform), as specified in Soares-Frazão and Zech (2002)

Model grid resolution: 0.1m (or ~36000 nodes in area bounded by vertical walls)

Time of end: the model is to be run until time t = 2min (if an alternative end time is used run times must be reported for t = 2min)

In Test 6B:

Manning's *n*: 0.05 (uniform)

Model grid resolution: 2m (or ~36000 nodes in area bounded by vertical walls)

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

A6.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Value of eddy viscosity coefficient used

From Test 6A:

- Plots of the **water level** elevation vs. time and **velocity** (scalar) vs. time at locations G1 to G6 in Figure A.11; output frequency 0.1s; coordinates provided as part of data set
- Raster grids (or TIN) at the model resolution consisting of:
  - **Peak** water **elevations** reached during the simulation
  - **Peak velocities** (scalar) reached during the simulation
  - **Water elevation at times** 1, 2, 3, 4, 5, 10, 15, 20, 25 and 30 seconds

From Test 6B:

- Plots of the **water level** elevation vs. time and **velocity** (scalar) vs. time at locations G1 to G6 in Figure A.11; output frequency 1s; coordinates provided as part of data set
- Raster grids (or TIN) at the model resolution consisting of:

- **Peak** water **elevations** reached during the simulation
- **Peak velocities** (scalar) reached during the simulation
- **Water elevation at times** 1, 2, 3, 4, 5, 10, 15 and 20 minutes

A6.6 Data set content

Description	**File name**
Georeferenced Raster ASCII DEM at resolution 0.05m for Test 6A	Test6ADEM.asc
Georeferenced Raster ASCII DEM at resolution 1m for Test 6B	Test6BDEM.asc
Location of output points for Test 6A	Test6Aoutput.csv
Location of output points for Test 6B	Test6Boutput.csv

A6.7 Additional comments

Participants are asked to provide model results at least for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.7 Test 7: River and floodplain linking

A7.1 Modelling performance tested

The objective of the test is to assess a package's ability to simulate fluvial flooding in a relatively large river, with floodplain flooding taking place as the result of river bank overtopping. The following capabilities are also tested:

- the ability to link a river model component and a 2D floodplain model component, with volume transfer occurring by embankment/bank overtopping and through culverts and other pathways
- the ability to build the river component using 1D cross-sections
- the ability to process floodplain topography features supplied as 3D breaklines to complement the DEM[11]

A7.2 Description

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

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

River channel geometry

The channel geometry is provided in the form of a text file with cross-sections labelled M013 to M054 (a separate CSV file containing cross-section locations and spacing is provided). A uniform channel roughness value is used. Any head losses due to the plan geometry of the river (meanders) are ignored. Along some sections the channel is adjacent to floodplains on just one or on both sides. Three-dimensional (3D) 'breaklines' are provided which define:

- the boundary between the river channel and the area expected to be modelled in 2D
- elevations along these boundaries (these are consistent with the DEM elevations)

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[11] The breaklines provided were derived from the 1m DEM and are a 'vector' representation of important crest lines in the topography (including embankments). The ability to recognise these important crest lines and apply the right elevations is tested, rather than the ability to process the 3D breaklines themselves.

These elevations are to be used in the prediction of bank/embankment overtopping. Wherever no floodplain is modelled along the river channel (more than 50% of the total length of river banks), a '**glass wall**' approach (or equivalent) should be applied if water levels exceed the bank elevation in the cross-section (that is, the water level rises above the bank without spilling out of the 1D model).

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

Floodplains

The extents of the three modelled floodplains are defined as follows (see Maps A.2, A.3 and A. 4):

- Floodplain 1: on west bank of the river, from upstream from cross-section M024, to upstream from M030 (floodplain breakline number 2, see below)
- Floodplain 2: on east bank of the river, from upstream from dross-Section M029, to upstream from M036.
- Floodplain 3: on west bank of the river, from half-way between cross-sections M031 and M032 to half-way between cross-sections M043 and M044 (this includes the 'island' on which the village of Upton lies)

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

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

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

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

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

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

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

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

1D–2D volume transfer

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

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

A masonry **culvert** immediately upstream from the village of Upton ('Pool Brook') is, however, modelled (see Map A.4). It is assumed to be circular in cross-section. A photograph and a spreadsheet containing various parameters (including X,Y coordinates and dimensions) are provided as part of the data set.

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

Miscellaneous

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

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

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

A7.3 Boundary and initial conditions

River channel

Upstream: inflow vs. time applied at the northernmost cross-section, cross-section M013

Downstream: rating curve (flow vs. head), applied at the southernmost cross-section, cross-section M054

Initial condition: a uniform water level of 9.8m

Floodplains

Linked to the river channel along the river bank breaklines provided, and through the Pool Brook culvert (floodplain 3) and the opening (sluice) at the south end of floodplain 1

All other boundaries are closed (no flow).

Initial condition: A uniform water level of 9.8m.

Pool Brook culvert

Initial water level: 9.8m

A7.4 Miscellaneous parameter values

Manning's *n*: 0.028 uniformly in river

0.04 uniformly in floodplains

Model grid resolution: 20m (or ~16700 nodes in the model extent defined in Section A.7.2 under 'Floodplains')

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

A7.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Raster grids (or TIN) at the model resolution consisting of:

- Peak water level elevations
- Peak water depths
- Peak velocities
- Water level elevations at T=72hours.
- Water depths at T=72hours.

The above concerns the floodplains only.

- **Water level elevation** and v**elocity** vs. time (output frequency 60s), at locations shown in Maps A.2, A.3 and A.4; coordinates provided as part of the data set
- **Water level elevation** and v**elocity** vs. time (output frequency 60s) at the following river cross-sections (1D model): M015, M025, M035 and M045

A7.6 Data set content

Description	File name
Georeferenced Raster ASCII DEM at resolution 1m	Test7DEM.asc
Georeferenced Raster ASCII DEM at resolution 10m	Test7DEM_10m.asc
1D model cross-sections	Test7-1DXS.txt
1D model cross-section locations and spacing	Test7-1DLoc-Spacing.csv
Location of output points	Test7-Output.csv
River bank breaklines	Test7-bank-bklines.csv
Floodplain breaklines	Test7-FP-bklines.csv
Photograph showing Pool Brook culvert	Test7-PoolBrookCulvert.jpg
Pool Brook culvert parameters	Test7-PoolBrookCulvert.xls
Photograph showing A4104 bridge	Test7-A4104bridge.jpg
A4104 bridge parameters	Test7-A4104bridge.xls
Downstream rating curve (flow vs. water level)	Test7-DSRatingCurve.csv
Upstream inflow (flow vs. time)	Test7-USInflow.csv

Notes: 1D model cross-sections file (Test7-1DXS.txt): this contains one table of six columns for each cross-section. The first (chainage in m) and second (elevation in m) columns only should be used. All other data can be disregarded. The location and spacing of cross-sections are contained in file Test7-1DLoc-Spacing.csv

All coordinates in the British coordinates system.

A7.7 Additional comments

Modelling instructions for this test have been provided as clearly as possible. Participants may contact Heriot-Watt University for more specific instructions. However, it is intended that any aspect of the modelling not considered in this specification is left to the modeller’s own initiative.

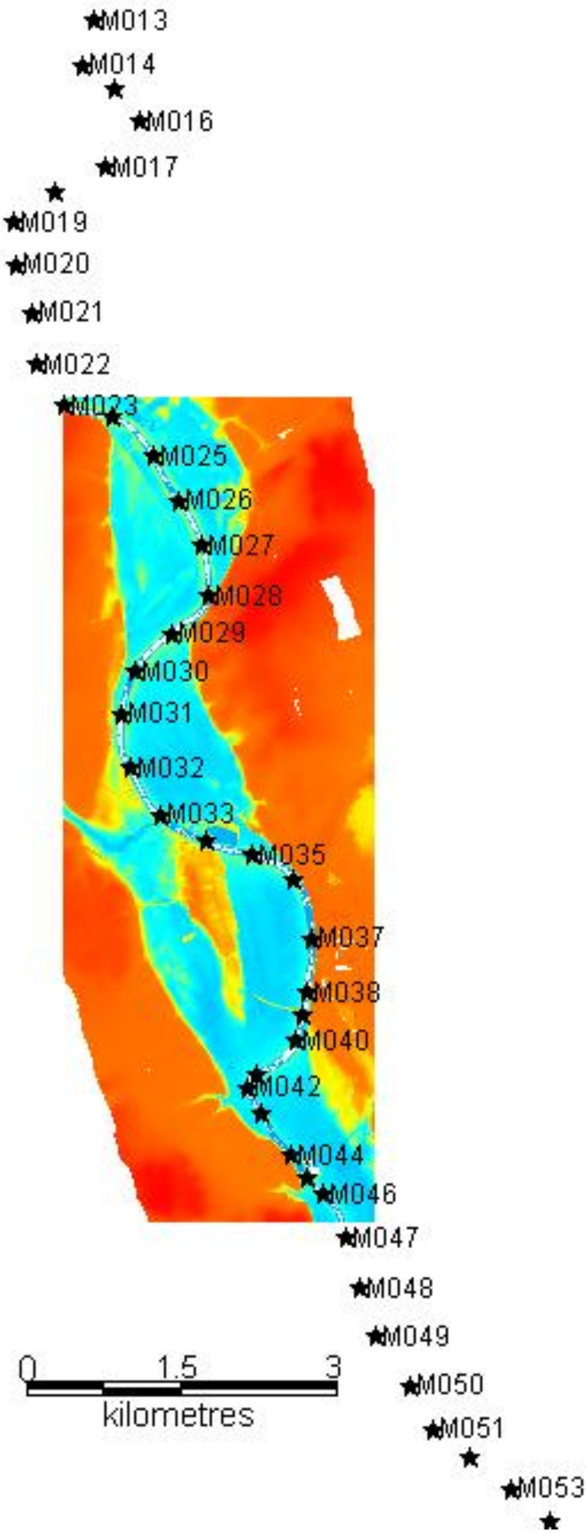
Linear interpolation should be used to interpolate inflow values.

Participants are asked to provide model results at least for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

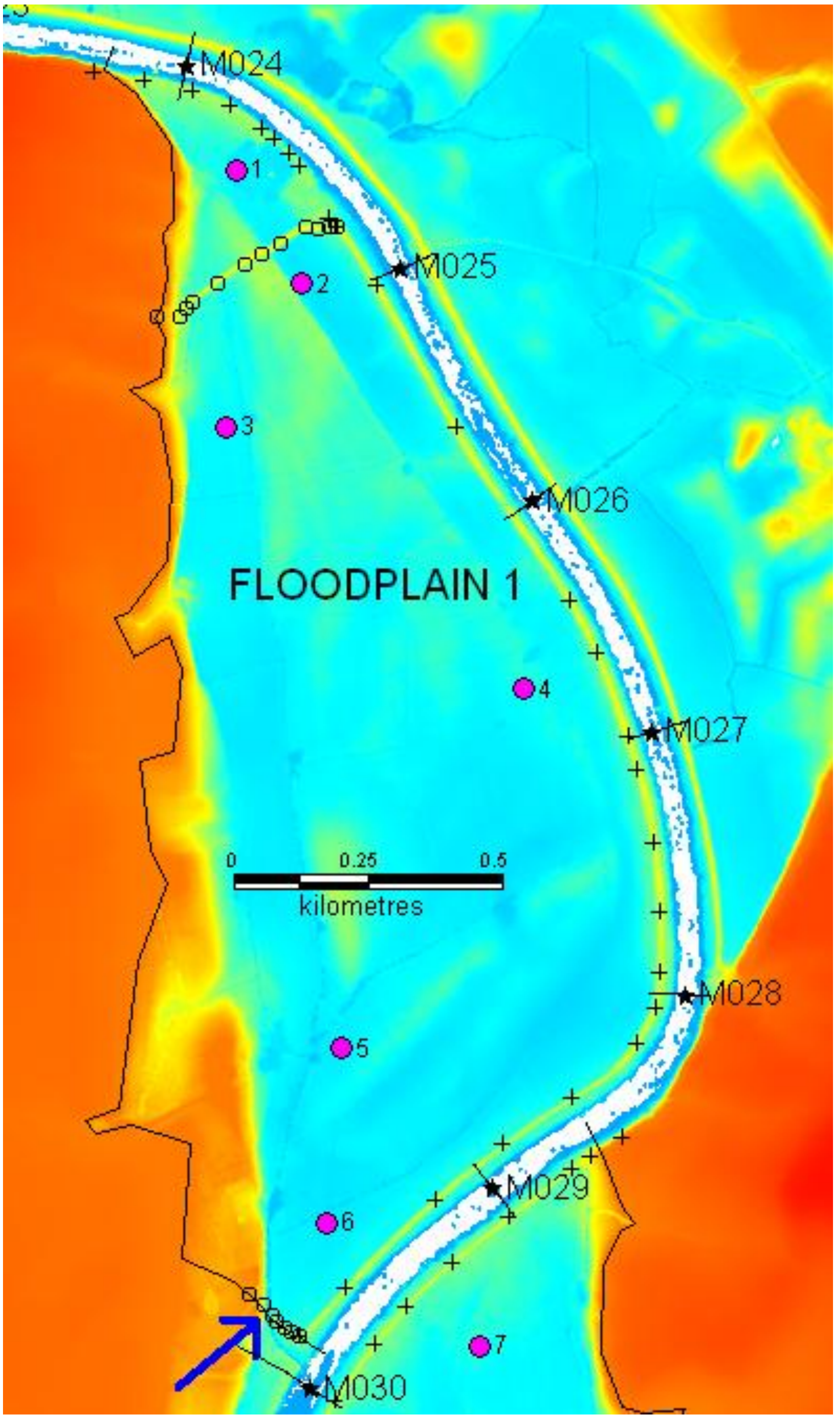
Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A7.8 Maps



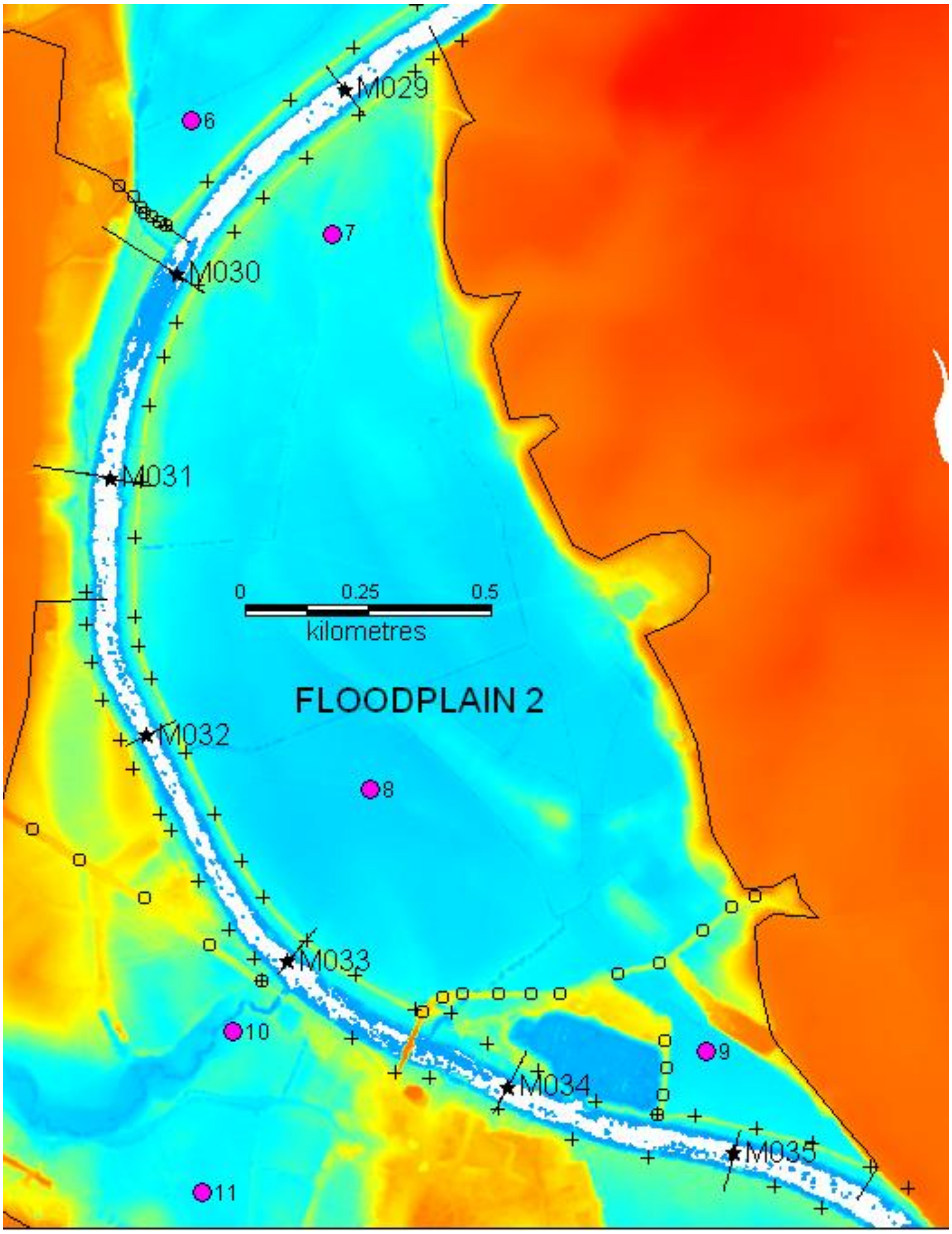
Map A.1 Map of the modelled reach of the river Severn and floodplain system around Upton-upon-Severn

Notes: The river flows from north to south.



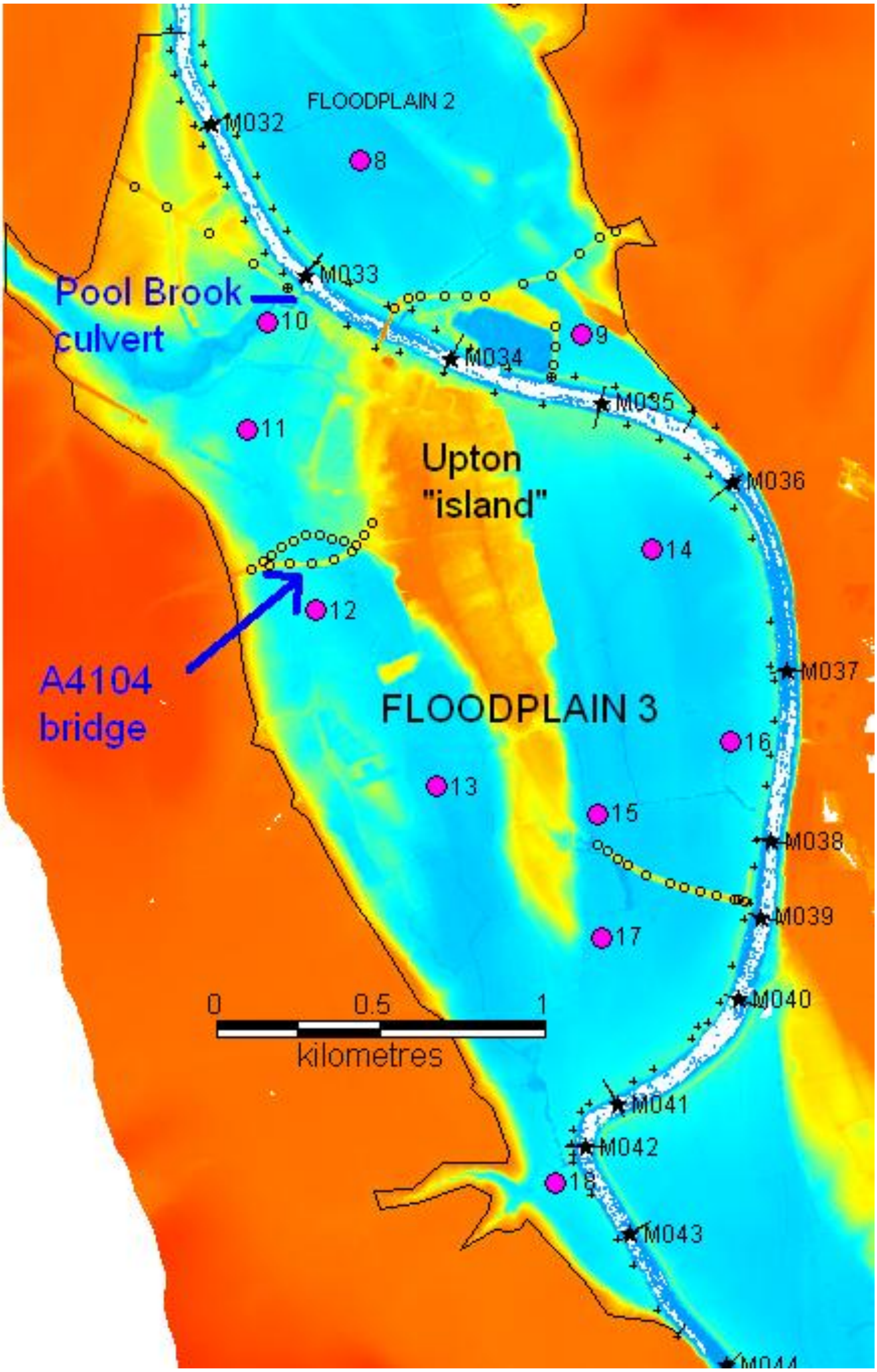
Map A.2 Map of floodplain 1

Notes: Blue arrow: opening in embankment (sluice). Crosses: bank breaklines vertices. Circles: floodplain breakline vertices. Purple dots: output points. Black line: outer extent of model



Map A3 Map of floodplain 2

Notes: Crosses: bank breaklines vertices. Circles: floodplain breakline vertices. Purple dots: output points. Black line: outer extent of model



Map A.4 Map of floodplain 3.

Notes: Crosses: bank breaklines vertices. Circles: floodplain breakline vertices. Purple dots: output points. Black line: outer extent of model

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

A8.1 Modelling performance tested

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

A8.2 Description

The modelled area is approximately 0.4 km by 0.96 km and covers entirely the DEM provided and shown in Figure A.12. Ground elevations span a range of ~21m to ~37m.

The flood is assumed to arise from two sources:

- a uniformly distributed rainfall event illustrated by the hyetograph in Figure A.13 – this is applied to the modelled area only (the rest of the catchment is ignored)
- a point source at the location represented in Figure A.12 and illustrated by the inflow time series in Figure A.14 (This may for example be assumed to arise from a surcharging culvert.)

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

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

A land-cover dependent roughness value is applied, with two categories:

- roads and pavements
- any other land cover type

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

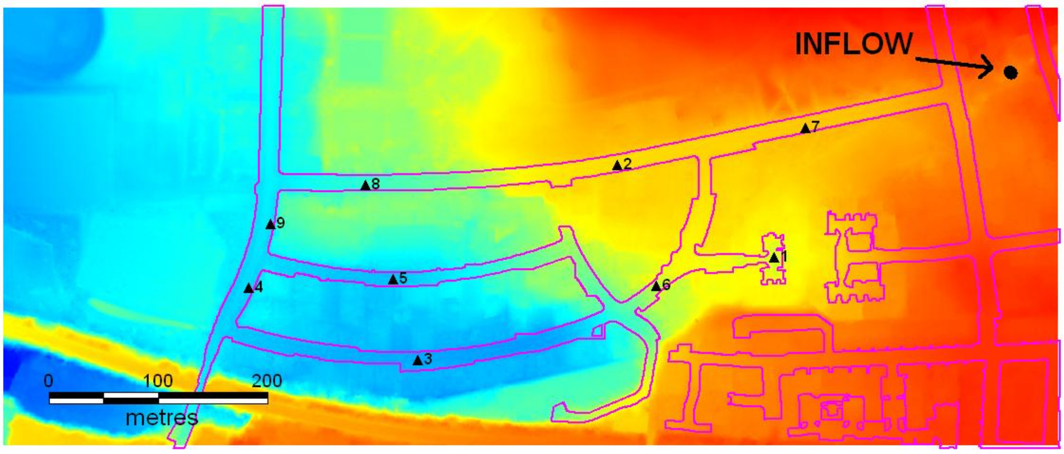


Figure A.12 DEM used, with the location of the point source

Notes: Purple lines: outline of roads and pavements. Triangles: output point locations.

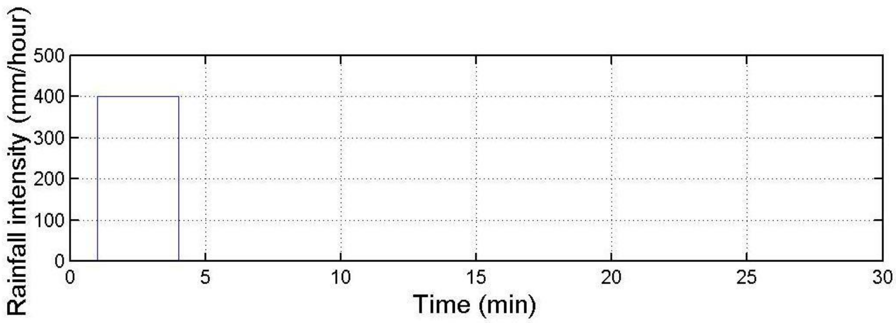


Figure A.13 Hyetograph applied in Test 8A

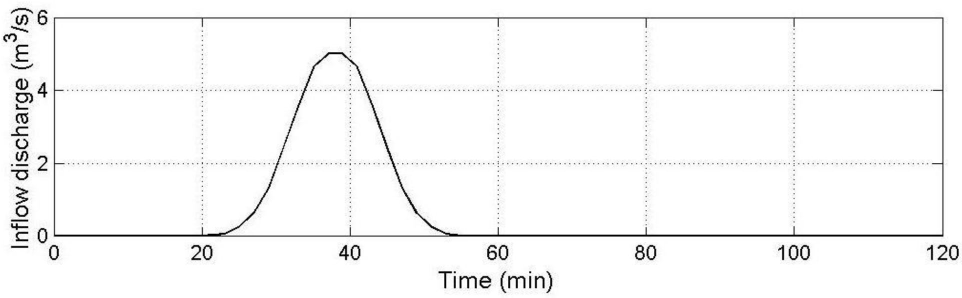


Figure A.14 Inflow hydrograph applied in Test 8A at point location shown in Figure A.12

A8.3 Boundary and initial conditions

Rainfall as described above. Hyetograph provided as table in data set.

The point source is applied as described above. Coordinates and time series provided as part of data set.

All boundaries of the modelled area are closed (no flow).

Initial condition: Dry bed

A8.4 Miscellaneous parameter values

Manning's n: **0.02** for roads and pavements

0.05 everywhere else

Model grid resolution: **2m** (or ~97000 nodes in the 0.388 km^2 area modelled)

Time of end: the model is to be run until time t = 5h (if an alternative end time is used run times must be reported for t = 5h)

A8.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Raster grids (or TIN) at the model resolution consisting of:

- Peak **water level elevations** reached during the simulation
- Peak water **depths** reached during the simulation
- **Water level elevation** and **velocity** vs. time (output frequency 30s), at locations shown in Figure A.12 and provided as part of the data set

A8.6 Data set content

Description	File name
Georeferenced Raster ASCII DEM at resolution 0.5m	Test8DEM.asc
Rainfall hyetograph (rainfall intensity vs. time)	Test8A-rainfall.csv
Point source boundary condition table (inflow vs. time)	Test8A-point-inflow.csv
Point source coordinates	Test8A-inflow-location.csv
Location of output points	Test8Output.csv
Outline of roads and pavements (shapefile polygons)	Test8Road_Pavement_polyg_region
Outline of roads and pavements (ASCII raster file)	Test8RoadPavement.asc

A8.7 Additional comments

The location modelled is in the City of Glasgow, UK (Cockenzie Street and surrounding streets)

Linear interpolation should be used to interpolate inflow values and rainfall intensity values.

Participants are asked to provide model results **at least** for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

A.9 Test 8B: Surface flow from a surcharging sewer in urban areas

A9.1 Modelling performance tested

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

A9.2 Description

The modelled area is approximately 0.4 km by 0.96 km and covers entirely the DEM provided and shown in Figure A.15. Ground elevations span a range of ~21m to ~37m.

A culverted watercourse of circular section, 1400mm in diameter, ~1070m in length, and with invert level uniformly 2m below ground is assumed to run through the modelled area. An inflow boundary condition is applied at the upstream end of the pipe, illustrated in Figure A.16. A surcharge is expected to occur at a vertical manhole of $1m^2$ cross-section located 467m from the top end of the culvert, and at the location shown in Figure A.15.

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

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

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

A land-cover dependent roughness value is applied, with two categories:

- roads and pavements
- any other land cover type

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

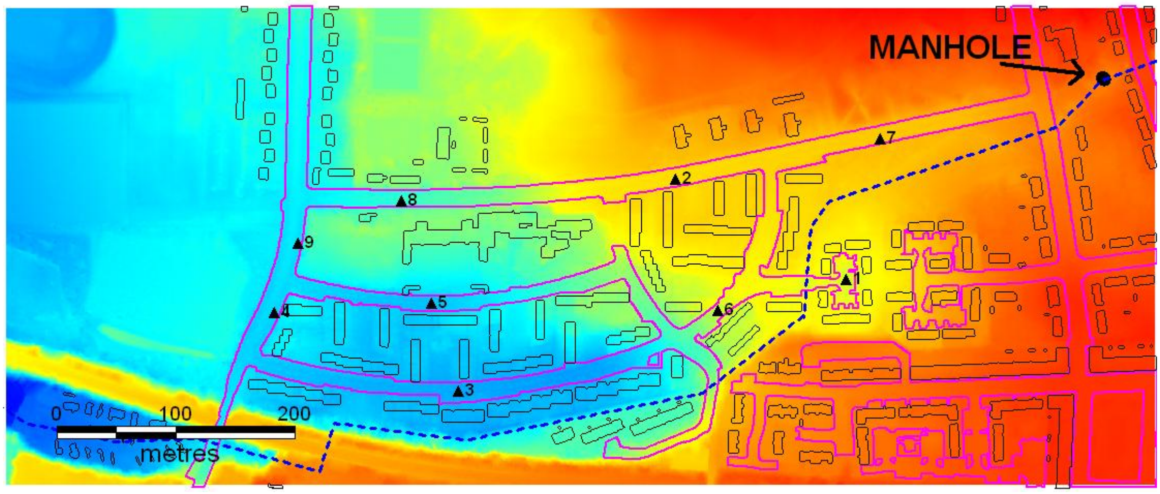


Figure A.15 DEM used, with the location of the manhole

Notes: The course of the underground pipe is indicated, although irrelevant to the modelling.

Purple lines: outline of roads and pavements. Black lines: building outlines. Triangles: output point locations.

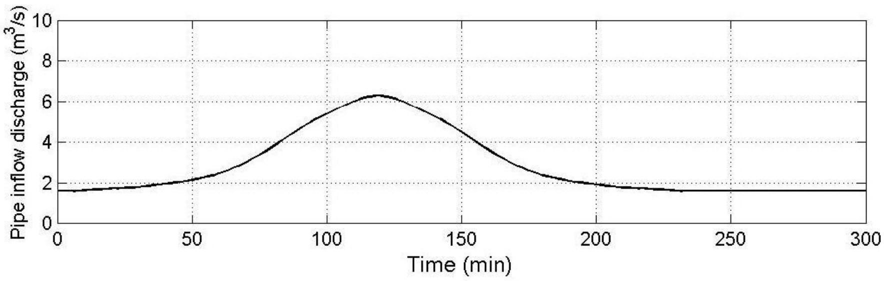


Figure A.16 Inflow hydrograph applied in Test 8B at upstream end of culvert

A9.3 Boundary and initial conditions

Underground pipe

- Upstream boundary condition: discharge vs. time provided as part of data set
- Downstream boundary condition: free outfall (critical flow)
- Baseflow (uniform initial condition): $1.6 m^3/s$

2D domain

Manhole connected to 2D grid in one point.

All boundaries of the modelled area are closed (no flow).

Initial condition: Dry bed

Conditions at manhole/2D surface link

The surface flow is assumed not to affect the manhole outflow.

A9.4 Miscellaneous parameter values

Manning's *n*: **0.02** for roads and pavements

0.05 everywhere else

Model grid resolution: **2m** (or ~97000 nodes in the 0.388km^2 area modelled)

Time of end: the model is to be run until time t = 5h (if an alternative end time is used run times must be reported for t = 5h)

A9.5 Required output

Software package used: version and numerical scheme

Specification of hardware used to undertake the simulation: processor type and speed, RAM

Minimum recommended hardware specification for a simulation of this type

Time increment used, grid resolution (or number of nodes in area modelled) and total simulation time to specified time of end

Raster grids (or TIN) at the model resolution consisting of:

- Peak **water level elevations** reached during the simulation
- Peak water **depths** reached during the simulation
- **Water level elevation** and v**elocity** vs. time (output frequency 30s), at locations shown in Figure A.15 and provided as part of the data set
- **Discharge** vs. time through the manhole (output frequency 30s)

A9.6 Data set content

Description	**File name**
Georeferenced Raster ASCII DEM at resolution 0.5m	Test8DEM.asc
Culvert upstream boundary condition table (discharge vs. time)	Test8B-pipe-inflow.csv
Geometry of pipe	Test8BPipeGeometry.xls
Location of output points	Test8Output.csv
Outline of roads and pavements (shapefile polygons)	Test8Road_Pavement_polyg_region
Outline of roads and pavements (ASCII raster file)	Test8RoadPavement.asc
Outline of buildings (shapefile polygons)	Test8Buildings_polyg_region

Outline of buildings (ASCII raster file)	Test8Buildings.asc

A9.7 Additional comments

The location modelled is in the City of Glasgow, UK (Cockenzie Street and surrounding streets). The above representation of the culverted watercourse is a gross simplification of reality and is for the purpose of the present test only.

Linear interpolation should be used to interpolate inflow values.

Participants are asked to provide model results **at least** for the grid resolution specified above.

Model results for one alternative resolution or mesh may also be provided.

Participants are asked to justify their reasons for not carrying out the test, or for carrying out the test using an alternative resolution.

Appendix B: Information on software packages

The following are comments and any relevant information that the participating software developers provided as part of their submission of results. They should be considered when interpreting the test results.

B.1 ANUGA

The reader is referred to http://anuga.anu.edu.au/.

B.2 Ceasg

(Source: AMAZI)

Ceasg was initially developed as a cellular automaton (http://mathworld.wolfram.com/CellularAutomaton.html) to study two-phase bed-flow interactions in the near-shore, before being redeveloped as a continuous-valued cellular automaton to study overland flows. The solver was developed from first principles (that is, the conservation laws – the same starting point as for the shallow water equations) and, by virtue of its origins as a cellular automation, is characterised by a very low degree of abstraction from the represented physics.

The Ceasg model is described as a 'simplified' flow model in the Environment Agency benchmarking exercise as it does not solve the shallow water equations, but instead a numerically efficient (and easily parallelised) set of equations that will deliver a close approximation to the full shallow water equations. This method has not yet been published.

The model formulation can be described as classically 'finite volume' as it partitions the space domain into control volumes (the version submitted to the benchmark tests uses a grid of regular 2D cells; however, quadtree, adaptive-quadtree, static/adaptive irregular triangular and irregular polygonal partitioning can also be used) and as 'explicit' as it performs no linear (or otherwise) approximation steps (in either time or space).

Ceasg is a fully heterogeneous parallel code, which can be used on GPU, multi-core CPU, and GPU + multi-core CPU (that is, domain decomposition across processors on a host), which can be run on one or more machines in a cluster. The Environment Agency benchmark tests are so small as to not benefit from any form of domain decomposition.

B.3 Flowroute-*i*™

(Source: Ambiental)

Flowroute-*i*™ uses an explicit, finite volume inertial formulation of the shallow water equations. Shallow water wave propagation is represented (as opposed to a diffusion wave as with the original Flowroute code), that is, acceleration is calculated.

B.4 InfoWorks ICM

(Source: Innovyze)

The 2D component of InfoWorks ICM is a fully hydrodynamic finite volume model, which solves the shallow water equations. It is based on the Gudunov numerical scheme and the so-called Riemann solvers. The solver is fully conservative and shock capturing, so it can deal with any changes in flow regime. The model is, therefore, particularly suitable for the simulation of rapidly varied flows, such as those occurring in typical flooding events.

InfoWorks ICM uses unstructured meshes, which makes the model fully flexible from the geometric point of view. InfoWorks ICM provides the ability to model the complete natural and engineered above- and below-ground drainage system including sewers, surface water, rivers and floodplain.

Comment regarding boundary conditions: the specification of boundary conditions is slightly ambiguous. In InfoWorks ICM, the approach taken is that subcritical flow is injected across the boundary line and hence the water entering the 2D mesh already has momentum. This may produce different results to other models in which there is no momentum entering the 2D zone.

B.5 ISIS 2D

(Source: Halcrow)

'The software package used in this report is ISIS 2D, a commercially available software application with the following solvers:

- ADI Solver (alternating direction implicit) with a focus on simulating subcritical flows
- TVD Solver (total variation diminishing) with a focus on simulating supercritical flows and therefore offering a shock capturing capability
- FAST Solver for a rapid solution of flows dominated by topography, where depression filling is the main mechanism.

Finite differences: ADI and TVD-MacCormack (explicit, shock capturing method)

B.5.1 Alternating direction implicit (ADI)

The ADI scheme solves the discretised equations by sub-dividing the computation at each time step into x- and y-directions. On the first half time step the water depth and the unit width discharge qx are solved implicitly in the x-direction, while the other variables are represented explicitly. Similarly, for the second half time step, the water depth and the unit width discharge qy are solved implicitly in the y-direction, with other variables being represented explicitly. The 2D problem is thus represented as a series of 1D problems, which can be solved efficiently, both in terms of processor time and memory.

The ADI scheme is second order accurate in both space and time. This gives accurate solutions for flows where spatial variations are smooth, but may cause oscillations where sudden changes in water elevation and velocity occur. The ADI scheme may therefore not be suitable for transcritical flows where hydraulic jumps may occur.

A threshold (‘drydepth’) determines the water depth above which a cell is activated/deactivated as it floods or dries.

The treatment of the friction term in the SWEs is also dependent on depth. Below a threshold (‘fricdepth’), a semi-implicit scheme is used to improve the model's treatment of large friction terms as depths approach zero. Since this is a better option for many floodplain flows, the default value for ‘fricdepth’ is large, meaning the semi-implicit is used all the time. A smaller value may improve model results for coastal flows.

Implicit schemes such as ADI should be stable for all time steps, but in practice the approximate treatment of the non-linear terms means that the time step is limited according to the Courant number. For ISIS 2D ADI, the maximum stable Courant number is around 8. This condition is necessary but not sufficient to ensure a stable computation. Lower values of the Courant number may be required in practical modelling situations.

B.5.2 Total variation diminishing (TVD)

For rapidly varying flow where hydraulic jumps may occur, ISIS 2D also includes a MacCormack-TVD scheme suited to modelling steep changes in velocity and water level. The MacCormack scheme uses predictor and corrector steps to compute depth and flow at the new time step; the TVD term is added to the corrector step to remove numerical oscillations near sharp gradients

The total variation is a good measure of spatial variations or oscillations in the solution and, by reducing this measure, spatial oscillations in the solution are suppressed.

The TVD scheme discretises the SWEs in a slightly different way to the ADI scheme, as flows are represented at the cell centres, rather than at the edges.

Since the TVD scheme uses explicit time stepping, the maximum stable Courant number is around 1. This means a much smaller time step must be used with the TVD scheme to ensure stability.

Partial parallelisation

‘Partial’ in the technical summary tables for each test refers to the hyper-threading (four threads) which was used with the ADI solver only. The main hydrodynamic ADI solution algorithm is not parallelised, but some auxiliary processes (pre-processing files for output for example) were able to use multiple threads. The speed improvement is not as significant as with a full parallel application.

B.6 ISIS 2D GPU

(Source: Halcrow)

ISIS 2D GPU harnesses the power of modern graphics cards to provide fast solutions to the full shallow water equations. It can be used to assess flooding in many environments, including urban areas subjected to coastal, fluvial or surface water (storm water, pluvial) flooding.

Modern graphic processing units (GPUs) can provide a significant computational speed-up compared with the standard CPUs of desktop and laptop computers. ISIS 2D GPU is designed to work with NVIDIA graphics cards – typical current consumer NVIDIA cards can have many hundreds of cores (for example, the GTX 560 has 336 CUDA cores).

ISIS 2D GPU uses a highly parallelised solution technique which can be ten times faster than solving the same equations on standard CPUs. Note that a finite volume scheme such as that used by ISIS 2D GPU can typically be much more computationally demanding than regular finite differences schema.

The GPU is a massively parallel processor that enables fast simulation of large domains, and, as a rule of thumb, the GPU is most efficient for domains with one million cells or more. The reason is that, for small domains, there is not enough work to fully saturate all the processors on the GPU, meaning a large part of the GPU is idle. Smaller domains may be more efficiently solved on the CPU.

ISIS 2D GPU uses an explicit finite volume solution (Kurganov–Petrova) to the 2D shallow water equations (which represent mass and momentum conservation). The solution scheme is provided with a TVD property to deal with transcritical flows, and uses a regular grid and an adaptive time step.

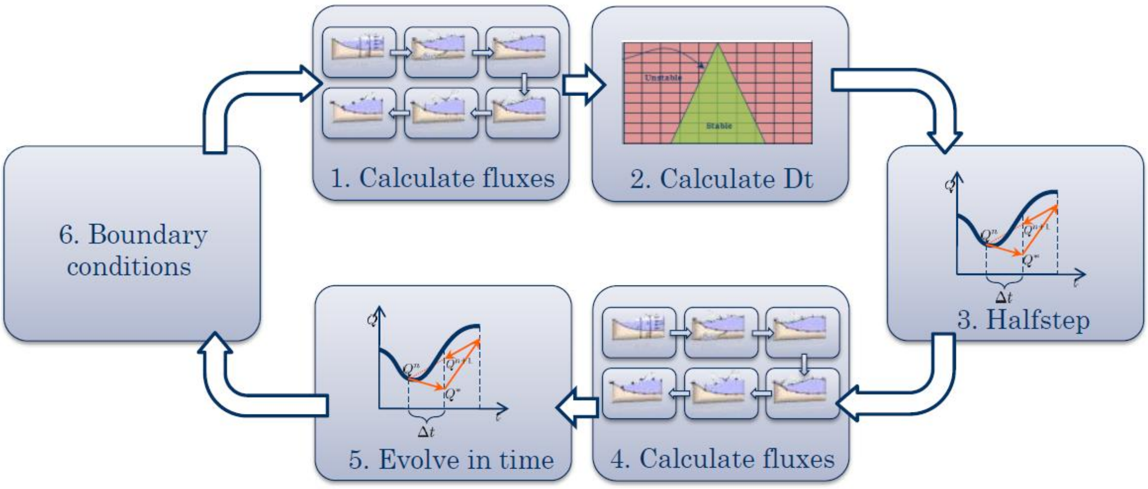


Figure B.1 Kurganov–Petrova scheme simulation cycle (Brodtkorb 2010)

Notes: ISIS 2D GPU is developed in partnership with SINTEF, the largest independent research organisation in Scandinavia.

B.7 ISIS Fast

(Source: Halcrow)

The latest release of ISIS FAST features a multi-spill option; previously ISIS FAST could spill water to only one of its neighbour depression. Now ISIS FAST can spill water to several of its neighbours. This may help the model to run faster and distribute water in a more logical way.

The ISIS FAST rapid flood inundation method routes water over the floodplain through a series of catchments or depressions. These catchments can fill with water either from sources (for example, rainfall) or by spilling in from neighbouring catchments. A catchment is defined in terms of its lowest point and all water with a source within that catchment will drain into that point.

The rules ISIS FAST follows to determine flows over the floodplain are described in brief as follows.

- Rule 1: Water appears instantly at the lowest point in a catchment.

- Rule 2: Water level in any given catchment can only rise up to the lowest connection level it has with its neighbouring catchment. A further rise will cause a spill over.
- Rule 3: The above rule is exempted if the water level in the neighbouring catchment is also above the connection level. Under this condition water levels in both catchments must be equal.
- Rule 4: If a catchment has boundary condition of type ‘Water elevation’ imposed on it, then the water level in the said catchment is fixed to that level. For neighbouring catchments two cases are possible:
  - If the water level in the neighbouring catchment is above minimum connection level and the water in the catchment with water elevation boundary condition (WLBC) is below the minimum connection level, then the water level in the neighbour is set to the height of the minimum connection level.
  - If water level in the catchment with WLBC is above the minimum connection level, the level in the neighbouring catchment is made the same and a WLBC is also imposed on the neighbour.

This implementation does not take into account any dynamic elements of hydraulics such as momentum, velocity and so on, and hence the progress of flood propagation can only be visualised by using a series of steady state snap shots.

The algorithm generates a table of water level for each catchment. Volumes are also calculated and summed as a check on model mass balance. The water level output is combined with a grid, where each cell contains the ID of the catchment to which it belongs, to generate a grid of water levels (which will be below ground level for some cells in catchments that are not full). The DTM is subtracted from the water levels to give depths and negative values are removed. The depth and water level grids are output as ASCII grid raster files.

The algorithm behind ISIS FAST focuses on obtaining the final flood extent from any source of flooding involved (pluvial or fluvial). Although this is acceptable in many cases, it is a severe limitation in others – especially where the flood water travels a significant distance, such as in cases involving inflow from dam or embankment breaching or other point sources. To overcome this constraint, a post-processing functionality called ‘Probable flow path mark-up’ has been introduced in ISIS FAST for ISIS release v3.5. As the name suggests, this tries to find the path water may have taken (based on terrain data) to get to the current flood extent.

B.7.1 Probable flow path mark-up

The flow path mark-up acts only as an indicator of the path water may have taken. To calculate these paths, ISIS FAST requires the user to specify two inputs:

- Padding depth: ISIS FAST uses this value (specified in metres) to assign a standard flood depth for all the cells that it expects to have been made wet by flowing water but are shown as dry in final extent
- Padding width: the expected width of an average flow path (in metres)

The results are exported as a file ‘path.asc’ in the results folder. When this is loaded along with the standard ‘depth.asc’, the full extent predicted by ISIS FAST can be visualised (note that when loading into ISIS Mapper, the pathway grid must have the ‘hillshading’ turned off to enable the data to be viewed).

Note (e-mail communication from Halcrow):

‘When ISIS FAST is in ‘linked mode’ (for example, ISIS FAST dynamically linked to ISIS 1D), then the reported water levels are the maximum values from the ‘link time steps’ and are thus estimates of the maximum water levels (for example, Test 7). When it is used with no linking, then the reported levels are the final water levels. So, for Test 7 (a linked model) the reported water levels are estimates of maximum water levels, whereas for other tests they are final water levels after the water has been spread over the terrain. In fact, when in linked mode, ISIS FAST is run many times over the hydrograph (once per link time step), hence it is able to attempt to determine the maximum, whereas the unlinked mode is run once and only calculates the final water level.’

B.8 ISIS Fast Dynamic

(Source: Halcrow)

ISIS FAST Dynamic uses Manning’s equation between depression to calculate flow and water depth. The definition of the depression and routing method are the same as the ones used in the multi-spilling version of traditional ISIS FAST. The multi-spill feature allows spilling water to several of its neighbouring depressions. This may help the model run faster and distribute water in a more logical way. Also, with this version an estimate for the flood mechanism can be obtained as temporal variation of water depth and velocity is calculated.

The ISIS FAST rapid flood inundation method routes water over the floodplain through a series of catchments or depressions. These catchments can fill with water either from sources (for example rainfall) or by spilling in from neighbouring catchments. A catchment is defined in terms of its lowest point, and all water with a source within that catchment will drain into that point.

The rules ISIS FAST follows to determine flows over the floodplain are described in brief as follows:

- Rule 1: Water instantly appears at the lowest point in a catchment.
- Rule 2: Water level in any given catchment can only rise till the lowest connection level it has with its neighbouring catchment. A further rise will cause a spill over.
- Rule 3: The above rule is exempted when the water level in the neighbouring catchment is also above the connection level. Under this condition water levels in both catchments must be equal.
- Rule 4: If a catchment has boundary condition of type ‘Water elevation’ imposed on it, then the water level in that catchment is fixed to that level. For neighbouring catchments two cases are possible:
  - If the water level in the neighbour is above minimum connection level and the water in catchment with WLBC is below the minimum connection level, then the water level in the neighbour is set to the height of the minimum connection level.
  - If the water level in the catchment with WLBC is above the minimum connection level, the level in the neighbouring catchment is made the same and a WLBC is also imposed on the neighbour.

This implementation does not take into account momentum. Velocity is calculated using interpolation methods. Hence, the progress of flood propagation in the result file may not be accurate. It can be regarded as an estimate of how the flood propagation progresses.

The algorithm generates a table of water level for each catchment. Volumes are also calculated and summed as a check on model mass balance. The water level output is combined with a grid, where each cell contains the ID of the catchment to which it belongs, to generate a grid of water levels (which will be below ground level for some cells in catchments that are not full). The DTM is subtracted from the water levels to give depths and negative values removed. The depth and water level grids are output as ASCII grid raster files.

B.9 JFLOW+

(Source: JBA Consulting)

Following on from the development and application of JBA's diffusion wave based model, JFLOW-GPU (Lamb et al. 2009), JFLOW+ (Crossley et al. 2010a, 2010b) has been developed. JFLOW+ solves the 2D shallow water equations and, like JFLOW-GPU, exploits GPU technology. Shallow water based models offer a number of benefits over the diffusion wave approach, as more physics is incorporated into the model including momentum effects. In addition velocity data are directly available, as both depth and velocity are solved by shallow water codes.

JFLOW+ uses a finite volume formulation and combines Roe's Riemann-based solver with an upwind treatment of the source terms. The model is both conservative and shock capturing, and maintains water at rest over irregular topography. The code had been developed using CUDA which is a C-based language developed by NVIDIA to enable programmers to exploit the benefits of GPU programming.

Both JFLOW-GPU and JFLOW+ have been evaluated using a test case incorporating real life topography (Hunter et al. 2008), and have been shown to produce comparable results to those obtained using other software (Lamb et al. 2009, Crossley et al. 2010a, 2010b).

B.10 LISFLOOD FP

(Source: University of Bristol)

The reader is referred to Bates et al. (2010), for the basic model formulation, Sampson et al. (2012) for the model in Test 8A, and De Almeida et al. (2012) for some updates to the basic formulation that improve the stability.

B.11 MIKE FLOOD

(Source: DHI)

MIKE FLOOD is a complete toolbox for flood modelling which includes a wide selection of 1D and 2D flood simulation engines, enabling the simulation of virtually any flood problem whether it involves rivers, floodplains, floods in streets, drainage networks, coastal areas, dam and dike breaches or any combination of these. The 1D and 2D engines can be coupled in a variety of ways providing full flexibility and capability of investigating complex environments.

B.11.1 MIKE 11 component

The MIKE 11 hydrodynamics (HD) module uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe subcritical as well as supercritical flow conditions through a numerical scheme which adapts according to the local flow conditions (in time and space). Advanced computational modules are included for description of flow over hydraulic structures, including the option to describe structure operation. The formulations can be applied to looped networks and quasi 2D flow simulation on flood plains. The computational scheme is applicable for vertically homogeneous flow conditions extending from steep river flows to tidal influenced estuaries.

B.11.2 MIKE 21 component

The MIKE 21 flow model (single grid) used in this study is a modelling system for 2D free-surface flows and the basic module is the hydrodynamics (HD) module. The HD module simulates water level variations and flows based on the numerical solution of the two-dimensional (depth-averaged) Navier–Stokes shallow water equations.

MIKE 21 HD makes use of a so-called alternating direction implicit (ADI) technique to integrate the equations for mass and momentum conservation in the space-time domain. The equation matrices that result for each direction and each individual grid line are resolved by a double sweep (DS) algorithm. MIKE 21 HD, therefore, has the following properties:

- zero numerical mass and momentum falsification and negligible numerical energy falsification, over the range of practical applications, through centring of all difference terms and dominant coefficients, achieved without resort to iteration
- second- to third-order accurate convective momentum terms, that is, second- and third-order, respectively, in terms of the discretisation error in a Taylor series expansion
- a well-conditioned solution algorithm providing accurate, reliable and fast operation

When using the 2D overland flow version of MIKE 21 HD within MIKE FLOOD, the inland flooding option is activated and flooding and drying are handled differently than in coastal applications. More specifically, the approach undertaken is to suppress certain terms of the momentum equation as the water depth approaches a defined drying value to allow a significantly more stable solution.

Other MIKE 21 components / engines

Multi-cell overland flow solver

Utilising higher resolution DEM information on a coarser simulation grid, the simulation speed is much faster compared with standard simulation with a fine resolution DEM.

Flexible mesh

For maximum flexibility for tailoring grid resolution within the model, it is based on the solution of the two-dimensional incompressible Reynolds averaged Navier–Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure. The discretisation in the solution domain is performed using a finite volume method. The spatial domain is discretised by subdivision of the continuum into non-overlapping cells

/ elements which can be triangular or quadrilateral. An approximate Riemann solver (Roe's scheme) is used to calculate the convective fluxes at the interface of the cells. Using Roe's scheme, the dependent variables to the left and to the right of an interface have to be estimated. Second-order spatial accuracy is achieved by employing a linear gradient-reconstruction technique. To avoid numerical oscillations a second-order TVD slope limiter (Van Leer limiter) is used.

Table B.1 Additional information on parallelisation techniques available in MIKE FLOOD

Application	Software product / version	Parallelisation
Pure 2D modelling	MIKE 21 'Classic' (ADI)	CPU, OpenMP (Shared Memory)
	MIKE 21 Flexible Mesh (FV) [1]	CPU, MPI (Distributed Memory)
Integrated 1D-2D modelling	MIKE FLOOD (comprising MIKE 11, MIKE 21 and MIKE URBAN) in all versions	CPU, OpenMP (Shared Memory)

Notes: [1] For pure 2D modelling, the MIKE 21 flexible mesh (FV) version has been optimised for both Microsoft Windows and LINUX High Performance Computing (HPC) environments, utilising MPI (distributed memory) parallelisation with 64-bit hardware architecture. A recent test of MIKE 21 FM on an 864-core LINUX (HPC) cluster produced a relative simulation speed-up factor of 687 (that is, only a 20% decrease from the theoretical maximum / ideal speed of the available cores).

Other 2D software packages from MIKE by DHI

MIKE 21C

MIKE 21C is a special module of the MIKE 21 software package based on a curvilinear (boundary fitted) grid, which makes it suitable for detailed simulation of rivers and channels where an accurate description of bank lines is required. Areas of special interest can be resolved using a higher density of grid lines at these locations. The MIKE21C is particular suited for river morphological studies.

MIKE SHE

MIKE SHE is DHI's integrated catchment model. It delivers truly integrated modelling of groundwater, surface water, recharge and evapotranspiration (all hydrological processes). The 2D overland flow module includes simplified overland flow routing and finite difference (using the diffusive wave approximation) methods. 1D–2D linking of MIKE SHE is possible (with MIKE 11 and MIKE URBAN) in order to consider groundwater–surface water, two-way flow exchange with rivers and groundwater–pipe flow interactions.

Additional information

MIKE by DHI is modular and numerous add-on modules are available across DHI's software portfolio for integrated rainfall–run-off modelling, advection–dispersion modelling, sediment transport, environmental and ecological modelling, wave modelling and so on.

For more information, please visit the MIKE by DHI website (http://www.mikebydhi.com/) or see the current software catalogue (http://www.mike-by-dhi.com/).

B.12 RFSM Direct and RFSM EDA

(Source: HR Wallingford)

RFSM EDA is based on a diffusive approximation to shallow water equations, including local acceleration (local inertia) term, with sub-grid-scale representation (Jamieson et al. 2012a,b). A number of remarks on the RFSM EDA characteristics relevant to these tests are made below.

RFSM-EDA is a new model that uses the concept of 'Impact Zones' (Gouldby et al. 2008, Lhomme et al. 2009), where depressions in the ground are identified and sub-element characterisation is derived as volume / level 'look-up' tables (as used by previous versions of RFSM (Rapid Flood Spreading Method). Each Impact Zone is used as a computational element. This enables the model to be run using large computational elements with minimal degradation in the topographic representation, hence reducing the number of computational elements compared with a conventional meshing approach. This in turn allows for rapid simulations, especially at very large scales, which is necessary for probabilistic flood risk analysis and very large (national) scale flood modelling.

The acronym 'EDA' stands for 'Explicit Diffusion wave with Acceleration term' and is a useful description for how RFSM has been developed and improved. It uses a diffusion wave approximation of the shallow water equations, yet differs from many simplified diffusive models by incorporating an additional term – the local acceleration (or local inertia) term, which provides increased stability and faster runtimes (Bates et al. 2010).

B.12.1 Domain discretisation

If RFSM-EDA was used with the specified grid resolution for these tests then it would not be able to utilise the sub-grid representation, which is a major feature of RFSM-EDA. Also, because the algorithm is designed around the concept of sub-grid representation, RFSM-EDA would not be efficient if it was run with computational elements at the size of the topography cells. With small computational elements, the overhead generated by the sub-grid calculations becomes prohibitive.

In all tests a significantly coarser resolution has been used to demonstrate the potential of the approach. RFSM-EDA is most efficient on very large domains, with naturally varying topography and is therefore not very well suited to some of the tests undertaken here, which are often artificially smooth and very small scale.

When analysing the results of these tests, one must bear in mind the scale at which RFSM-EDA was run.

The other models that undertook these tests will extract point results from cells that are exactly in the location of the test points. Because of the size of the RFSM-EDA Impact Zones they encompass a large area around each test point, and therefore may represent different flow conditions to those of the other models. This makes direct comparison between RFSM-EDA and the other models challenging.

B.12.2 Topography

RFSM-EDA is designed around the concept of Impact Zones, which are distinct depressions in the ground with definable crests between them, with each Impact Zone being used as a computational element. For this reason the current version of the model does not perform optimally in situations where such depressions cannot be identified (idealised flat geometries or extended steep areas).

While there are some minor pre-processing issues with idealised flat geometries, the model is challenged by steep hill slopes where a constant downwards gradient means no crests can be identified. In these situations the model can predicts some 'ponding' at the lower end of each Impact Zone, rather than a continuous free-surface elevation. This can lead to an overly rapid advance of the inundation wave. This can be seen in the results for Test 5 and is particularly evident in the valley centre line profiles and depth /velocity contours.

B.12.3 Simulation runtimes

RFSM-EDA has been developed to allow for parallelisation in multi-core computers. Although this has the potential to decrease runtimes significantly, the benefits of this approach only become apparent when the number of computational elements is several thousands. As these tests have been undertaken with a coarse mesh, there was no gain in using the parallel scheme and so for all tests reported here the model was run in serial form.

The computational time step is adjusted automatically by the algorithm using a stability constraint for unstructured mesh derived from the Courant–Friedrich–Levy (CFL) condition. This is scaled by a parameter, which for these tests varied between 1 and 4. This value of the parameter was chosen to ensure a stable simulation with minimal mass balance errors. For all tests, the final mass balance error was never greater than 0.03%.

B.12.4 Predicted velocities

RFSM-EDA calculates accurately the flow discharge and velocity for each interface between two Impact Zones, and then calculates an average discharge and velocity in each Impact Zone. Considering the complex shape and geometry of the Impact Zones, some assumptions are necessary to calculate the average velocity (that is, the average velocity calculation is based on a simplified geometry). Also it is likely the velocity will significantly vary in different points within one Impact Zone.

For this reason, it is expected that the discrepancy between the velocity calculated by RFSM-EDA and the one calculated by a full shallow water model is larger than the discrepancy between the water levels at the same location.

B.12.5 Hardware specifications

We have provided some recommended minimum hardware specifications for these tests, which are quite low requirements as these are small extent tests, and as the RFSM-EDA can be run with a wide range of computer specifications. If RFSM-EDA were to be used on very large domains it would be advisable to use a computer with a higher specification.

B.12.6 Water tracking capability

Like previous versions of RFSM, RFSM-EDA has the ability to track the origin of flooding (for example, which defence is contributing flood volume to a given Impact Zone) for all inundated areas. This feature is crucial for incorporation within a system like the Modelling and Decision Support Framework (MDSF2) software where the damages in the floodplain are attributed back to the defences that let some flow into the floodplain. When using RFSM-EDA one can turn this option on or off depending on the need. For these tests this option was turned off, as the outputs are not used, and it can increase the simulation runtimes.

B.12.7 Differences to previous versions of the RFSM

The Rapid Flood Spreading Method (RFSM) has been used by several different models in the past. Originally it was used in a simplified approach to spread a volume of water through the domain, but did not calculate the dynamic effects of an inundation event. This model is called the 'Direct RFSM' and is currently used in the Environment Agency's National Flood Risk Assessment (NaFRA) and MDSF2 due to its very rapid simulation times and ability to be used in a probabilistic framework. It has been updated to account for the time-varying flow conditions using a diffusive-wave approach, called the Dynamic RFSM. This model calculates the fluxes between Impact Zones using either the Manning or Weir formula. Results of the Dynamic RFSM were shown in the 2010 edition of the benchmarking report (Néelz and Pender 2010), but it did not perform satisfactorily.

RFSM-EDA, the latest model, has been shown in this report to provide a significant improvement over both the Direct RFSM and Dynamic RFSM. Some of the key reasons for this are as follows.

- An adaptive time step is used to control the model stability. This is a better solution to the 'flow limiters' used in the Dynamic RFSM, which impact on simulation accuracy.
- Using the 'inertial formulation' of the diffusive wave from Bates et al. (2010) provides a greater stability in the scheme, so that longer time steps can be employed and therefore faster runtimes.
- There is a more efficient scheme for calculating the interface fluxes between Impact Zones.

B.13 TUFLOW suite

(Source: BMT WBM)

Table B.2 Software and hardware details

	TUFLOW		TUFLOW FV
	'Classic'	**GPU module**	
Version of software	2012-05-AA		2012.000b
Software developer	BMT WBM Pty Ltd	BMT WBM Pty Ltd	BMT WBM Pty Ltd
Numerical scheme of software	2D: second order finite difference ADI scheme over a regular grid of square elements 2D scheme solves all terms of the 2D shallow water equations including inertia and eddy viscosity.	Finite volume scheme over a regular grid of square elements. Several order options, with first order spatial, fourth order time used. 2D scheme solves	Finite volume first and second order schemes over a flexible mesh of triangular and/or quadrilateral elements 2D scheme solves all terms of the 2D shallow water

	TUFLOW		TUFLOW FV
	1D: finite difference Runge–Kutta explicit scheme 1D scheme solves all terms of the St Venant equations.	all terms of the 2D shallow water equations including inertia and eddy viscosity.	equations including inertia and eddy viscosity.
Shock capturing scheme	1D and 2D schemes automatically switch between upstream and downstream controlled flow regimes to represent shocks.	Finite volume shock capturing capability used.	Finite volume shock capturing capability used.
1D–2D linkages	Yes. Range of 1D/2D linkages based on one of: Full 2D solution across 1D–2D interface that preserves momentum for downstream controlled regimes, and automatically switches with upstream controlled regimes (for example, weir or supercritical flow). 2D sink/source ideally suited to linking drains/gully traps/pits/manholes and small culverts under embankments. TUFLOW 2D scheme is linked with the internal scheme (ESTRY), ISIS and XP-SWMM 1D. ESTRY is also linked with ISIS via ISIS-TUFLOW-PIPE.	Not yet available.	Embedding of 1D stage discharge relationships to model structures available. More advanced 1D–2D linking similar to TUFLOW 'Classic' are under development.

For any queries or additional information on TUFLOW or TUFLOW FV, please email support@tuflow.com.

B.13.1 TUFLOW

TUFLOW uses a 2D ADI finite difference solution of the full shallow water equations, including sub-grid scale turbulence (eddy viscosity term). The 2D ADI scheme has been adapted to automatically switch with upstream controlled flow regimes (supercritical flow over non-adverse slopes and weir flow over crests). TUFLOW's 1D solution is an explicit solution of the full St Venant equations. There are several mechanisms for linking the 1D and 2D schemes. The two most commonly used are:

- the transfer of the 1D water level profile along a 1D open channel to the 2D domain with momentum preservation and flow exchange across the 1D/2D interface back to the 1D scheme
- a sink / source linkage between 1D pits / drains / gully traps and other 1D structures with the overlying or adjacent 2D domain with a water level exchange back to the 1D scheme

TUFLOW 2D solution uses ground elevations at the cell centre and the cell mid-sides, so essentially each cell has five elevation points used in the hydraulic computations. The elevations at the cell corners are only used for output purposes. Whole cells or just the cell sides can wet and dry, with the default wet/dry depths being 2mm and 1mm respectively.

The TUFLOW 2012-05 release includes enhanced handling of supercritical flows and shocks as demonstrated by the improved performance in the tests that required shock handling functionality.

The following observations arising from the benchmarking may be of interest to TUFLOW modellers:

- The ‘Number Iterations ==’ command was set to 4 (rather than the default of 2) for some models with rapidly varying flows (Tests 2, 5, 6A and 6B) to improve convergence and reduce mass error close to zero. Virtually identical results are achieved for these models with the default 2 iterations, although mass error exceeded 1%.
- For models with rapidly varying inflows onto a dry bed (Tests 2, 3, 4 and 5), 2D SA (source–area) inflow boundaries performed better than 2D QT (flow ‘Q’ vs. time ‘T’) boundaries in terms of stability and mass error in the vicinity of the boundary. 2D QT boundaries are more suited to the inflow boundary of a river or stream where the flow has a directional or inertial component as QT boundaries preserve momentum across the boundary and adjust the flow distribution according to variations in Manning’s *n* and depth.
- All models were run using single precision except for Tests 8A and 8B which used double precision.
- The TUFLOW 2012-05 release showed improved performance compared with the 2010 benchmarking on all tests in terms of greater stability, improved handling of shocks, and less or no mass error.

B.13.2 TUFLOW GPU module

TUFLOW’s GPU module is a powerful new solver available via the existing TUFLOW software. As the name implies it utilises the immense parallel computing ability of modern graphics processor units (GPUs). TUFLOW GPU is an explicit solver for the full shallow water equation set, including a sub-grid scale Eddy viscosity model. As such it is both volume and momentum conserving. Presently the solver runs 2D models only, but thanks to the power of modern GPUs, very large models with fine grids can now be run in a sensible timeframe, yielding excellent in-bank resolution of rivers and waterways. Various explicit formulations are available including first, second and fourth order in time, with adaptive (default) or fixed time stepping. The front end is still TUFLOW and very little modification of the model input is needed to utilise the GPU solver. Similarly the output data are still written by TUFLOW and the same range of output formats are available.

The simulation times reported for TUFLOW GPU in this report are not indicative of the significant speed gains achieved for larger models (for example, >1,000,000 cells for which TUFLOW GPU is typically 10–100 times faster than TUFLOW when using mid to top end NVidia graphics cards).

B.13.3 TUFLOW FV

The TUFLOW-FV numerical scheme solves the conservative integral form of the non-linear shallow water equations (NLWSEs), including viscous flux terms and source terms for Coriolis force, bottom friction, and various surface and volume stresses. The scheme is also capable of simulating the advection and dispersion of multiple scalar constituents within the model domain.

The spatial domain is discretised using contiguous, non-overlapping but irregular triangular and quadrilateral ‘cells’. Advantages of an irregular flexible mesh include the ability to:

- smoothly resolve bathymetric features of varying spatial scales
- smoothly and flexibly resolve boundaries such as coastlines
- adjust model resolution to suit the requirements of particular parts of the model domain without resorting to a ‘nesting’ approach

The flexible mesh approach has significant benefits when applied to study areas involving complex coastlines and embayments, varying bathymetries, and sharply varying flow and scalar concentration gradients.

A cell-centred spatial discretisation is currently employed in TUFLOW-FV and requires the calculation of numerical fluxes across cell boundaries. As with many finite volume schemes, non-viscous boundary fluxes are calculated using Roe’s approximate Riemann solver. Viscous flux terms are calculated using the traditional gradient-diffusion model with a variety of options available for the calculation of Eddy viscosity and scalar diffusivity. The Smagorinsky Eddy viscosity model and the non-isotropic Elder diffusivity model are the options most commonly adopted by BMT WBM modellers.

Both first order and second order spatial discretisation schemes are available in TUFLOW-FV. The first order scheme assumes a piecewise constant value of each conservative constituent in a model cell. The second order scheme assumes a 2D linear polynomial reconstruction of the conservative constituents within the cell (that is, a MUSCL scheme). The total variation diminishing (TVD) property (and hence stability) of the solution is ensured using a choice of gradient limiter schemes.

The second order spatial reconstruction scheme allows for much sharper resolution of gradients in the conserved constituents for a given level of spatial resolution and was used in the run-up modelling. This is important for resolving relatively short waves (for example, tsunamis) without excessive numerical diffusion or without over-refining the spatial mesh discretisation. The numerical resolution of sharply varying current distributions and sharp scalar concentration fronts are also much improved with the second order scheme.

Spatial integration is performed using a midpoint quadrature rule. Temporal integration is performed with an explicit Euler scheme and must therefore maintain a stable time step bounded by the Courant–Friedrich–Levy (CFL) criterion. A variable time step scheme is implemented to ensure that the CFL criterion is satisfied with the largest possible time step.

Outputs providing information relating to performance of the model with respect to the CFL criterion are provided to enable informed refinement of the model mesh in accordance with the constraints of computational time.

In very shallow regions (~<0.05m depth), the momentum terms are dropped to maintain stability as the NLSWEs approach the zero-depth singularity. Mass conservation is maintained both locally and globally to the limit of numerical precision across the entire numerical domain, including wetting and drying fronts. A conservative mass redistribution scheme is used to ensure that negative depths are avoided at numerically challenging wetting and drying fronts without recourse to adjusting the time step. Regions of the model domain that are effectively dry are readily dropped from the computations. Mixed subcritical / supercritical flow regimes are well handled by the FV scheme which intrinsically accounts for flow discontinuities such as hydraulic jumps or bores that may occur in transcritical flows.

Transport of scalar constituents is solved in a fully coupled fashion with the NLWSE solution. Simple linear decay and settling are optionally accommodated as source / sink terms in the scalar transport equations.

TUFLOW-FV accommodates a wide variety of boundary conditions, including those necessary for modelling the processes of importance to 2D hydraulics:

- water level time series
- in / out flow time series
- bed friction
- Coriolis force
- mean sea level pressure gradients
- wind stress
- wave radiation stress

TUFLOW FV accommodates structures, including a weir equation insert across a specified string of cell faces or, alternatively, an h-Q-h matrix representing a user-defined structure equation. Beyond the scope of 2D hydraulics, TUFLOW FV can simulate 3D, advection dispersion (AD), density-driven processes, heat exchange and sediment transport.

B.14 UIM

(Source: Exeter University)

UIM is a 2D non-inertia overland flow model which neglects the acceleration terms in the shallow water equations. The model adopts finite difference explicit scheme as numerical solver.

Adaptive time stepping function is included in UIM to avoid chequerboard oscillations, which is common in explicit models when a too big time step is applied (Hunter et al. 2006). However, the tolerance setting influences the model efficiency significantly. The highly restrictive setting may end up with an unrealistically small time step but the improvement of accuracy is limited. The attributes of UIM limit its application to problems like Test 6 with a sudden change of water surface. Although the model can run the simulation, the results are not realistic.

UIM model is also fully integrated with the 1D sewer network model SIPSON. The two models are linked by the discharge through manholes and, therefore, the feature of 1D sewer and 2D overland linkage is available. Nevertheless, the 1D river channel and 2D overland flow linkage is still under development, due to the type of linkages is lines along the channel, rather than points. Hence, Test 7 was simulated by separate 1D ISIS and 2D UIM models, instead of an integrated software package. The model can be executed on both Window-based and Linux-based machines, and OPENMP is recently introduced into UIM for multi-processing.

B.15 XPSTORM

(Source: Micro Drainage Ltd)

B.15.1 Integrated stormwater modelling

XPSTORM provides comprehensive hydrology and hydraulics in the same model. It is possible to model the real world including channels, pipes, streets, inlets, ponds, weirs, pumps, catchments, groundwater table, overland floodplains, bioretention, infiltration trenches and more. Stable, fully linked 1D and 2D modelling allows you to see the true behaviour of stormwater flow in natural and engineered systems.

The advanced design automatically identifies flow choke points and lets XPSTORM design solutions (pipe sizes, slopes). Detention pond optimisation methods are used to configure storage. Fully dynamic hydraulic analysis allows completion of sustainable drainage system (SuDS) design to maximise benefits at lower costs.

With over 15 hydrologic methods available and numerous ways to input real or synthetic rainfall data, XPSTORM allows users to model the appropriate rainfall/runoff for their project.

B.15.2 ANALYSIS

XPSTORM fully couples 1D network flow with 2D overland flow to accurately model interaction between flood waters and drainage systems, including underground pipes and natural channels.

The 1D engine solves the full St Venant dynamic flow equations to account for the effects of storage, flood backwater and hydrograph timing in stormwater and river systems.

The surface flow engine uses a 2D ADI finite difference solution of the full shallow water equations, including sub-grid scale turbulence (viscosity term). The 2D ADI scheme has been adapted to represent upstream controlled flow regimes for supercritical and weir flow between cells.

The 2D solution uses ground elevations at the cell centre and the cell mid-sides, so essentially each cell has five elevation points used in the hydraulic computations. The elevations at the cell corners are only used for output purposes. Whole cells or just the cell sides can wet and dry, with the default wet/dry depths being 2mm and 1mm respectively.

For some of the benchmark models, the wet/dry depths were reduced to 0.2mm and 0.1mm due to the very shallow flows experienced during the simulation.

Appendix C: Modelling approaches used in Test 7

In Test 7 there was room for modellers to use their initiative on how to model a number of features. This section contains all information provided by the participants on modelling approaches. NB Any figure referred to is not reproduced.

C.1 ISIS2D

(Source: Halcrow)

All break lines and link levels were taken into account in the 2D domain as topographic features.

The culvert in pool brook, the bridge, and the open gate (connecting section M030 and FP1) were modelled as 1D elements linked dynamically to the 2D domain. The modelling of the gate in floodplain 1 allows the drainage of this area once the level of the river decreases. In the case of the culvert it can be observed that the water from the river enters the floodplain from this point several minutes before the water level reaches the top bank levels

C.2 MIKE FLOOD

(Source: DHI)

C.2.1 River channel geometry

Cross sections have been applied as supplied. However, in order to smooth the volume transfer between river and flood plain additional cross sections have been interpolated at approximately 100 meter distance between the given cross sections.

Cross sections conveyance is calculated with the specified Manning number and using hydraulic radius (rather than resistance radius).

C.2.2 Floodplains

The bridge opening under the A4104 road has been modelled as a box 40 meter wide box culvert using the culverts feature within the 2D component of MIKE FLOOD (MIKE 21).

C.2.3 1D-2D volume transfer

The masonry culvert at the downstream end of Pool Brook is modeling as a 1D river channel connecting from the 2D model to the 1D model (at cross section M033). A 1D culvert controls the flow through the 1D river channel.

Similarly, a 1D channel with a 10 meter wide sluice gate is used to model the flow between flood plain 1 and cross section M030.

Generally, the 1D-2D volume transfer id done with a so-called lateral coupling between the 1D and the 2D model. This implies using a weir equation for the calculating the exchange flow between 1D and 2D models.

C.3 SOBEK

(Source: Deltares)

'Regarding the Test7 model schematisation, we like to mention the following:

1. The floodplain bathymetry is based on file 'Test7DEM_10m.asc', having a 2D grid cell size of 10m.

2. As requested, in breakline 7 the sample point x = 385068, y = 240140, z = 13.211 has been omitted. Breaklines 'Test7-Bank-bklines_1 to _7' and 'Test7-FPbklines_1 to _8' were transferred into corresponding elevated 2D gridcells.

3. Modelling river flow as 1D flow and its adjacent floodplains as 2D flow has the disadvantage that the modeller defines the locations, where exchange of 1D river flow and 1D floodplain flow (and vice versa) can occur. These locations are not necessarily the locations where, in real-time situations, exchange of river flow and floodplain flow will occur. Based on good modelling practice, we recommend modelling both the river and its adjacent floodplains as 2D flow. Hence, in this way the location(s) where exchange of river flow and floodplain flow (and vice versa) occurs, depends on the actual governing hydraulic conditions in both the river and its adjacent floodplains. In sections where the river has no adjacent floodplains, we prefer to model the river as 1D flow only in order to reduce required computational time. Taking the above into account, the overall 1D2D model set-up of Test7, comprised:

(a) a section with 1D flow only, covering cross-section M013 up to M023

(b) a section with 2D flow only, covering cross-sections M023 to M044 as well as floodplain 1, 2 and 3

(c) a section with 1D flow only, covering cross-section M044 to M054

Please note that:

- The above described three sections (a), (b) and (c) are run simultaneously. In other words all the St Venant equations, concerning sections (a), (b) and (c) are solved simultaneously in one and the same matrix. More precisely, sections (a) and (b) are internally connected to each other. The same applies for sections (b) and (c).
- The river part in section (b) comprises a 2D model schematisation. The 2D bathymetry of this river section is based on cross-sections M023 to M044.

4. The Pool Brook culvert (see Fig 2a and 2b) is modelled as a 1D pipe, having a length of 28.284m and linking the river at 2D grid cell (x = 384910, y = 240900) with floodplain 3 at 2D grid cell (x = 384890, y = 240880). The invert level of the pipe at both the river side and the floodplain 3 side amounted to 6.25m. A Manning value of 0.025 for the 1D pipe, having a diameter of 5000 mm, was applied. Locally near the pipe outflow in floodplain 3, 2D bed elevations were lowered to 6.00m. Furthermore, for some extent, 2D gridcells lying under the Pool Brook were locally lowered.

5. An opening (see Fig 3) in the embankment (floodplain breakline no 2) was modelled by lowering 2D gridcell (x = 384610, y = 242490) to an elevation of 10m. Furthermore, locally 2D grid cells were reduced in such way that a small channel (10m wide) is running from the opening in the embankment toward the local river bed

6. An opening (see Fig 4) in the A4104 road was made as follows. A 40m wide opening, with an invert level of 11.40m, was made in floodplain breakline no. 7 and in floodplain breakline no. 6. Furthermore, locally around the opening some 2D grid cells were lowered.’

‘In the meeting held on 15 January 2010 it was suggested that Deltares could, if it was felt necessary, still supply for Test 7 a model in which the entire river is modelled as 1D flow, the floodplains are modelled as 2D flow, and exchange of water from river to flood plain and vice versa is done by means of 1D flow links. We would like to mention that, from the SOBEK functionality point of view, there are no limitations to constructing a model schematisation as described above. However, we decided not to submit such a model schematisation for test 7, based on Good Modelling Practice.

Deltares nowadays prefers to model a river directly adjacent to the flood plains as 2D flow, meaning that the river as well as its adjacent flood plain are modelled as 2D flow, avoiding arbitrary 1D–2D links and human errors in defining the model parameters of the 1D–2D links.

Within a SOBEK 2D model schematisation, no special efforts are needed by the hydraulic engineer to ensure that the correct discharge is flowing over dikes and elevated (rail)roads, since a limiting algorithm automatically ensures this. Correct discharges over dikes mean proper exchange of water between river and floodplain and vice versa.

In the meeting we understood that the Environmental Agency has for several rivers quite a number of 1D river schematisations. In that respect, we would like to mention that the incorporation of an existing 1D river model schematisation into a SOBEK 2D model schematisation, including river as well as adjacent floodplains, is a fast and simple process.’

‘The construction of a 2D grid on basis of 1D cross-sections refers to a pre-processing GIS-type of activity (for example, index triangulation). We offer SOBEK clients the RFGRID and QUICKIN for this purpose. These tools are against additional payment available for any SOBEK user and form part of the Deltares systems modelling suite’.

C.4 TUFLOW

(Source: BMT WBM)

‘The conventional hydraulic radius formulation for 1D cross-sections was used so as to be consistent with the other solutions (that is, TUFLOW .ecf file command ‘Conveyance Calculation == Change in Resistance’ was used; please refer to the TUFLOW manual). This is not the TUFLOW default, which is to carry out a complete parallel channel analysis that treats every segment across the section as a separate parallel channel. This approach ensures that conveyance never decreases with height, as can occur with the hydraulic radius approach, but can result in higher conveyance values of around 10%. It is similar to the effect / intent of the resistance radius approach except that side wall friction is taken into account.

The 2D domain sampled elevations from the 1m DEM at the cell centres, mid-sides and corners (that is, a sample grid of 10m resolution).

The A4104 bridge opening was modelled as a causeway using the dimensions specified within the 2D domain.

The DEM elevations at the inlet to the Pool Brook culvert (on the floodplain side) are significantly higher than the culvert invert. A gully line (‘Read MI Z Line’ command) was created along the natural watercourse leading into the culvert to lower ground elevations near the culvert and direct water into the culvert. The culvert was modelled as specified.

The sluice gate at the southern end of floodplain 1 was modelled as specified. No modifications to the elevations on the floodplain side were necessary as fortuitously the elevation sample points fell within the open channel leading to the gate.

The results submitted are based on 1D computational network of the same resolution as the frequency of cross-sections. A sensitivity test was carried out with typically two interpolated cross-sections between the provided cross-sections, producing a higher resolution 1D network; this is often needed especially where the 1D longitudinal water level profile is not linear (for example, around a meander). For this model, using a higher resolution 1D network had only a very minor effect on flood levels in both 1D and 2D domains'.

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