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Testing and application of a practical new 2D hydrodynamic model

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Testing and application of a practical new 2D hydrodynamic model

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ABSTRACT: A significant amount of effort is being directed towards finding ways to improve the management of urban drainage to reduce flooding. It is recognized that an integrated modelling approach is required, linking rivers and their floodplains with surface water and foul drainage systems. As a result of this, flood inundation modelling methods are starting to converge. The existing 1D InfoWorks software has recently been enhanced to include a 2D flood modelling capability. This 2D hydrodynamic modelling software incorporates links with the already existing 1D software for rivers (InfoWorks RS) and network systems (InfoWorks CS). This paper describes the results of a series of analytical tests used to validate the robustness of the new 2D modelling engine, results of its application to a real case study and, in some cases, comparisons of the results with other 2D flood models.

1 GENERAL BACKGROUND

1.1 *Current situation in the UK*

Making Space for Water is a cross government initiative relating to the developing strategy for flood and coastal erosion risk management in England. As part of this program, a significant amount of effort is being directed towards finding ways to improve the management of urban drainage to reduce flooding. This need was highlighted during the summer floods of 2007, when the City of Hull suffered from severe flooding due to an overwhelmed drainage system. It is recognized that an integrated approach is required, linking rivers and their floodplains with surface water and foul drainage, and as a result of this, modelling methods are starting to converge.

River modellers are increasingly modelling fluvial flood events with linked 1D (river channel) and 2D (floodplain) hydrodynamic models. Drainage modellers have long understood that accurate modelling of extreme urban flood events requires a better understanding of overland flow paths and the capability of representing the re-entry of surface flows into the below ground drainage network. Due to the complexity of both the underground and above ground systems within urban areas, there have been difficulties in representing both systems interactively. This paper addresses these issues.

1.2 *Traditional approaches*

Some of the traditional approaches to 2D hydrodynamic flood model simulations and their limitations are describe below.

One of the first approaches was by means of 1D elements included in existing 1D models, whereby lateral spills (weir type equation elements) deliver water to storage areas (area-level relationship defined). For drainage models, overland 1D links connected to the network system have been used to provide a representation of the most likely surface water paths (roads in urban areas, steepest gradient line in grass and rural areas) in conjunction with storage nodes (area-level relationship defined). Water levels in these 1D elements can be interpolated and used with a digital terrain model (DTM) to produce approximate flood maps. The main advantage of this method is that it is computationally efficient. The main disadvantage is that it is a 1D approach to what is clearly a 2D problem. Although the 1D approach, when handled with care, can give a good approximation of the flooding process, the model set up and construction are time consuming and are based on a number of simplifying assumptions. As well as this, there are a number of simplifying assumptions of the hydraulic process.

An alternative, more refined approach was to use 1D model outputs (river spills, flood water from manhole) as inputs to a 2D spreading model. The advantage of this method is that a 2D approach will naturally define more complex and accurate flow paths and ponding areas. The hydraulic calculations involved are less simplified and it is also a much more flexible, dynamic and reliable flood mapping approach. The main disadvantage is that the two models (1D and 2D) are not actually coupled. This means that 2D flows are not allowed to re-enter into the 1D model and therefore results have some degree of distortion. Having to run two different software packages in tandem can be inefficient, particularly when required to test a large number of scenarios.

1.3 *Current tendencies*

Integrated models, comprising different computational cores (model engines) working together by exchanging data during computation (at run times) are proving to be the most effective way forward.

Probably the most relevant and ambitious example of this is OpenMI (http://www.openmi.org) which targets integrating models over the water domain. This software component interface definition enables combined systems to be created, based on OpenMI-compliant models from different providers. This enables the modeller to use those software codes that are most appropriate for any particular project. This practice is however not currently widespread: it can be time consuming to set up and the number of connections between models can become an issue in terms of computational efficiency. Experience shows that industry would rather use a more compact modelling approach (Bamford, T. et al. unpubl.). Consequently, for the frequent case of needing 1D and 2D hydraulic models working together, it is a natural progression to seamlessly couple them.

1.4 *New 2D hydrodynamic model linked with existing 1D models*

InfoWorks2D (IW2D) was released by Wallingford Software in September 2007. This 2D hydrodynamic modelling software incorporates links with the existing 1D software for rivers (InfoWorks RS) and network systems (InfoWorks CS). The main characteristics of the 2D component are:

- Finite volume formulation (weak solution of the shallow water equation)
- Numerical scheme based on the Gudonov scheme and the Riemann solvers (Shock capturing scheme)
- Use of an unstructured mesh
- Full integration with the 1D existing engine

The 1D components have been in use, worldwide, for many years and are well known and well tested. This paper, therefore, describes the results of a series of analytical tests used to validate the robustness of the new 2D modelling engine and the results of its application for a real case study. For these tests InfoWorks 2D was compared against the analytical solution, a widely used finite difference 2D model (FD1) and another 2D finite volume model (FV1).

2 ANALYTICAL TESTING

2.1 *Introduction*

A series of analytical tests have been used to validate the robustness of the new 2D modelling engine. These tests are:

- Test 1: Water at rest over varying sloping terrain (testing stability/accuracy of the model)
- Test 2: Theoretical dam-break wave—initially wet bed (testing the robustness of the model in rapidly varying and supercritical flow)
- Test 3: Circular dam-break wave—initially dry bed (testing the robustness of the model in rapidly varying and supercritical flow, as well as the regular distribution of flow across the domain)

Also tested was a theoretical dam-break wave with initially dry bed which is omitted from this paper as the conclusions obtained are very similar to the conclusions achieved from Test 2 and Test 3.

In the context of rapid flooding over a steep slope (such as the case presented in section 3) and water spreading rapidly over a dry area, the dam-break tests are the most suitable to verify the capability of the models. Steep slopes found in the higher parts of catchments where pluvial flooding is critical are often associated with issues within existing 2D modelling solutions, giving rise to inaccurate velocities and instabilities.

2.2 *Test 1: Water at rest over varying sloping terrain*

This test consisted of simulating a constant water level over a complex sloping terrain domain. The objective of this test was to assess whether a steady water level, especially in those areas where there is a vertical jump in the terrain, was correctly maintained in the model. Depths and velocities over time should remain constant and display no variation.

The test zone was a 50 m size square basin (see Figure 1) limited by vertical walls. Two different sloping terrains were included, both of them with a maximum elevation of 3 m above the bed of the test area but with different slope gradient (approx. 5.7 and 14.3% respectively). At the end of the slopes a vertical fall of 2.0 and 0.5 m respectively, connected these sloping terrains with the flat bed of the testing area. The constant water level was equal to 2.5 m above the bed of the flat area and the test was run for one hour (simulation time).

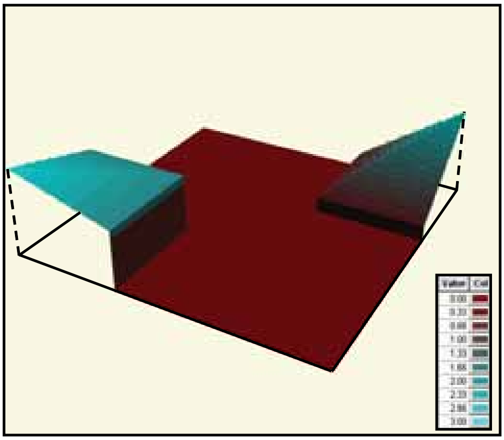

Figure 1. Test 1—Ground model 3D view.

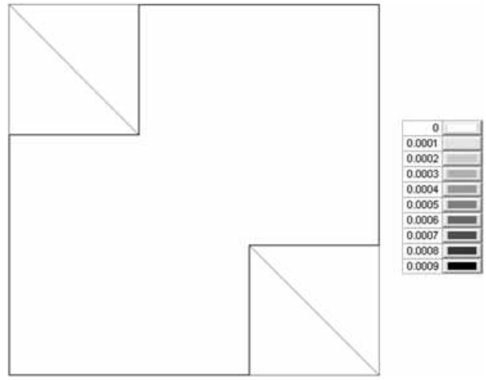

Figure 2. Test 1—InfoWorks 2D maximum velocity (m/s).

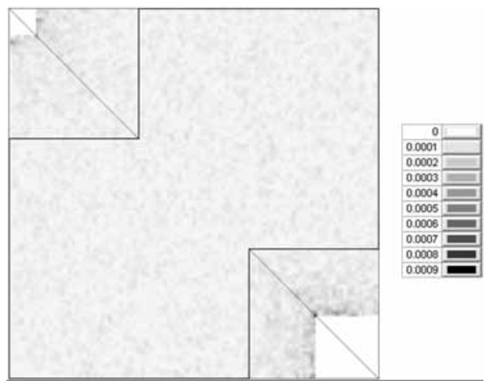

Figure 3. Test 1—Finite difference maximum conditions (m/s).

2.2.1 *InfoWorks2D*

During this test, depths and velocities remained constant and without variation through all the simulation as can be seen in figure 2.

2.2.2 *FD1*

As shown in Figure 3, there is a progressive excitement of the mesh elements. Variations in velocities began to appear around the vertical jumps by the slopes. During the course of the simulation, these variations spread to cover the whole model.

Whilst the magnitude of the variations is small, in practice this can yield more significant numerical instabilities, resulting in inaccurate velocity estimates. It is apparent that FD1 is not as robust as the finite volume scheme in InfoWorks 2D, in this test.

2.3 *Test 2: Linear dam-break with initially wet bed*

This test involved simulating a dam break wave propagating on a straight and initially wet bed. The primary objective was to assess the capability of the model to solve this particular case of dam break. Assessing the model stability during transition from subcritical to supercritical flow and assessing the ability of the engine to model steep surface gradients and shock waves were additional objectives of this test.

The test zone was a 6 by 24 km rectangular flat basin (see Figure 4) limited by vertical walls. Initially, the first 12 km of the basin has a 6 metres deep body of water whilst in the remaining 12 km it is 2 metres deep. The dam break was assumed to be instantaneous. Stocker (1957) was used to define the analytical solution for this test.

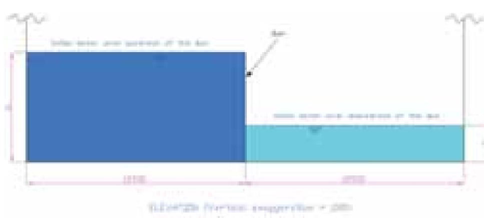

Figure 4. Linear dam break with wet bed domain dimensions.

2.3.1 *InfoWorks2D*

InfoWorks was run with a refined mesh of about 54000 elements generated with the application embedded in InfoWorks.

Figure 5 shows there is a good agreement between the analytical and the InfoWorks2D solutions. The figure represents for different time steps and for both

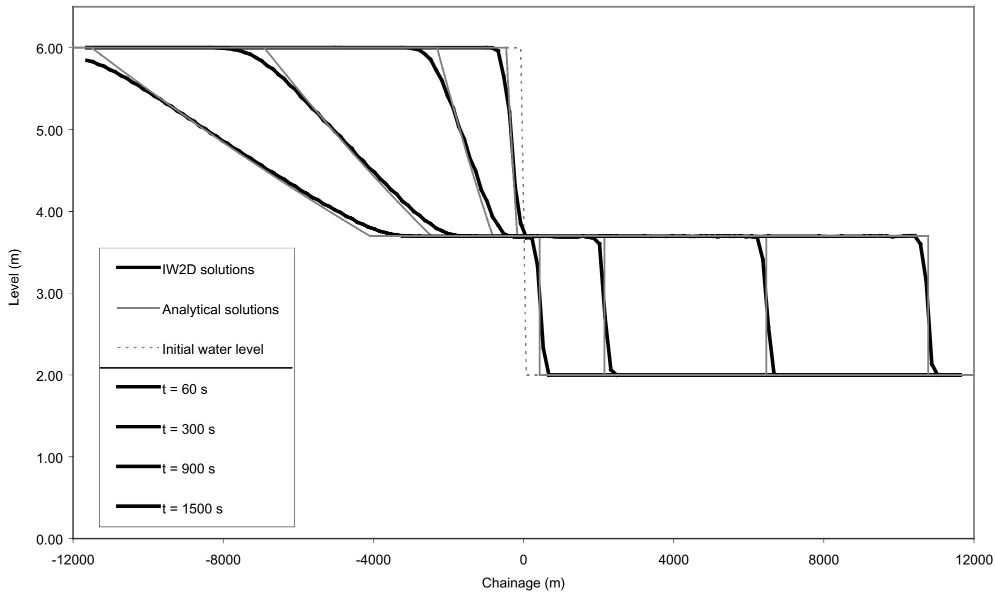

Figure 5. Test 2—IW2D and analytical solution comparisons.

solutions, the water level on a longitudinal section along the basin.

Minor deviations occurred at the advancing wave front and at the transitions from the reservoir level to the falling water (rarefaction wave) mainly due to the finite mesh (there is not always a mesh element in the exact position of the wave front).

2.3.2 *FV1*

The same test was run with FV1 which has the capability of operating two different finite volume numerical schemes (scheme kinetic 1 and kinetic 2). Additionally, to make a fair comparison and reduce to a minimum the effect of the mesh into the model results, the test was re-run in InfoWorks 2D using the same mesh as FV1. The results are shown in Figure 6. Both finite volume schemes and InfoWorks2D give a good prediction when compared with the analytical solution. This good match with the analytical solution was also observed for the above models during the test on the dry bed.

2.3.3 *FD1*

The test was performed on FD1 model using regular grid (14400 elements). As shown in Figure 7, the finite difference model does not provide a good match to the analytical solution. Initially, the model results are very similar to the ones given by the analytical solution but significant instabilities occur (probably due to the transition from subcritical to supercritical flow). Inspection of Figure 7 shows this model could produce results that are in error by over 1 m when modelling breaches and dam breaks.

The wave celerity of the FD1 model results is very similar to the analytical solution.

2.4 *Test 3: Circular dam-break with initially dry bed*

This test consisted of simulating a circular dam break wave propagating on a circular and initially dry bed.

Although there is not an analytical solution for this particular test, a pseudo-analytical solution was used to compare results (see LeVeque 2002). In this test the wave propagation should be exactly the same for any direction considered. As in the previous test, assessing the model stability during transition from subcritical to supercritical flow and assessing the ability of the engine to model steep surface gradients and shock waves were the objectives of this test.

The test zone was a circular basin of 24 km radius (see Figure 8) limited by vertical walls. There is initially a circular dam of 12 km radius that contains a 6 m deep volume of water. The dam break is assumed to be instantaneous.

2.4.1 *InfoWorks2D*

The model has been run on a mesh of about 56,000 elements. Depth against time graphs were plotted for 5 different directions and four distances from the centre (10,000, 16,000, 20,000 and 22,000 metres),

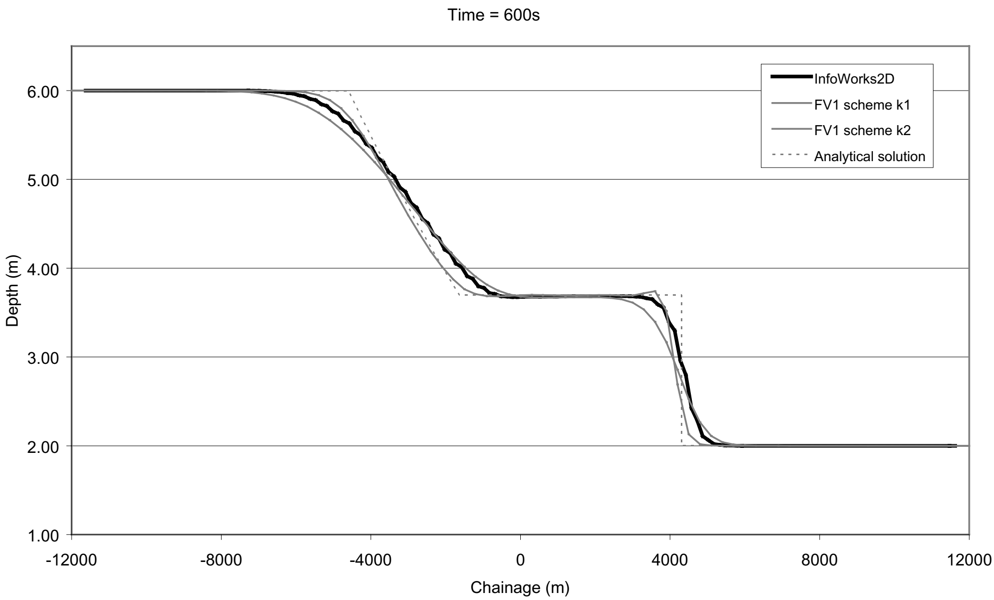

Figure 6. Test 2—InfoWorks2D, other finite volume schemes and analytical solution comparison for a particular time step.

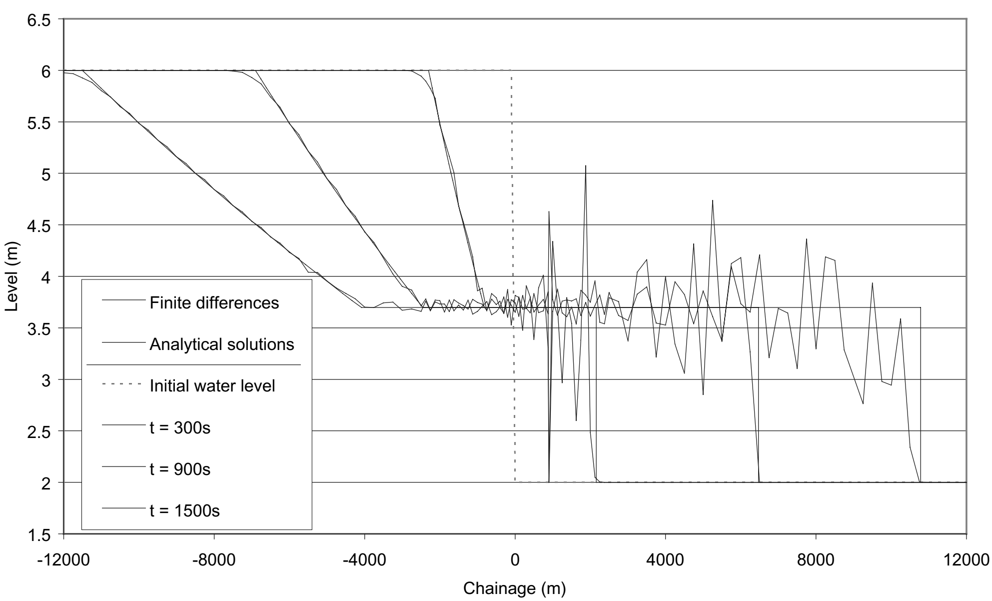

Figure 7. Test 2—Finite difference model (100 m size grid) and analytical solution comparison.

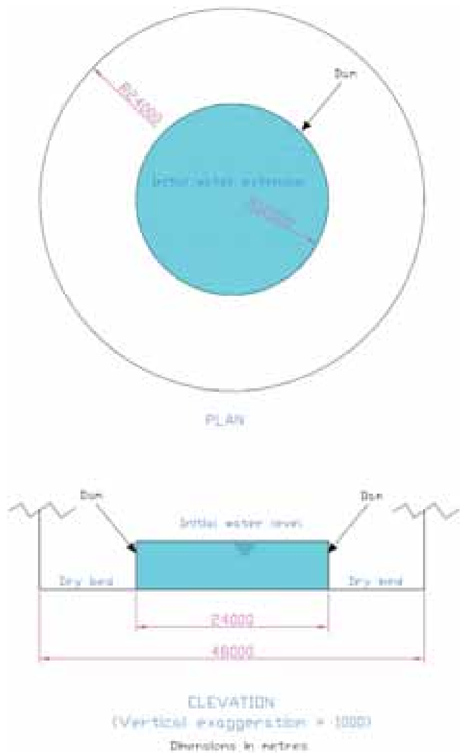

Figure 8. Circular dam break with dry bed domain dimensions.

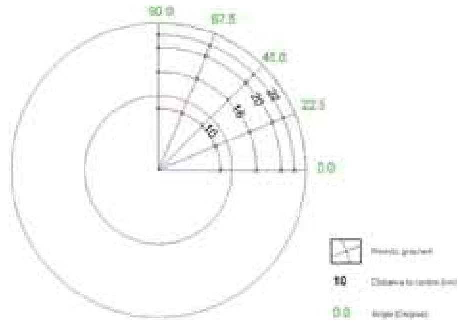

Figure 9. Measurement points across several directions.

as shown in Figure 9. This was compared with the analytical solution.

The results show that any differences between directions are minimal and random, oscillating around the analytical solution (see Figure 10 for water depth at a distance from the centre of 16 km).

Figure 11 shows, for a single direction of the wave propagation, that there is good agreement between the pseudo-analytical and the InfoWorks 2D solutions.

2.4.2 *FD1*

The test was performed on the same finite difference model using a regular grid (about 180,000 elements).

Figure 11 shows the flow propagation is faster in the direction of the grid diagonals. After 30 minutes of simulation time this difference is of the order of 500 metres (1 concentric circle). This can be attributed to the regular grid used, but is the opposite of the difference one would expect (faster travel in the u and v directions).

During this test it was also apparent that the propagation of the wave was considerably slower than in the analytical solution and InfoWorks (where the limit of the basin is reached after approximately 15 minutes). This anomaly has potential implication in the calculation of velocities and timing of flood propagation within flood modelling studies. In terms of the propagation in the radial direction, the same type of instabilities as in the previous test (wet bed) occurred, with a front propagation speed much slower than the analytical solution.

3 CASE STUDY: BRECHIN

3.1 *Background to site*

There were different aspects that made Brechin an interesting case study. The local topography is varied, having steep gradient areas where high flow velocities can be achieved (Figure 13), as well as flat ponding areas in the vicinity of the flood defences. Whilst the city has a limited spatial extent, the layout of the buildings is sufficiently complex to test the meshing capabilities of the different models.

Following severe flooding on the River South Esk in Brechin in November 2002, a flood defence scheme was proposed by Angus Council. The proposed scheme involved constructing flood defences along the north bank of the river in Brechin (see Figure 13 and Gutierrez, J. et al. 2008). One of the main concerns regarding the proposed scheme was an expected increase in flooding of properties in the lower areas of Brechin due to sewer flooding caused by either flood water being trapped behind the flood defences and not being able to reach the river, or insufficient head to allow discharge through the outfalls as the river level itself increases. As part of the Brechin Flood Alleviation Scheme, a pumping system was therefore proposed, to deal with excess storm water and sewer flows that could not be discharged during periods of high river levels.

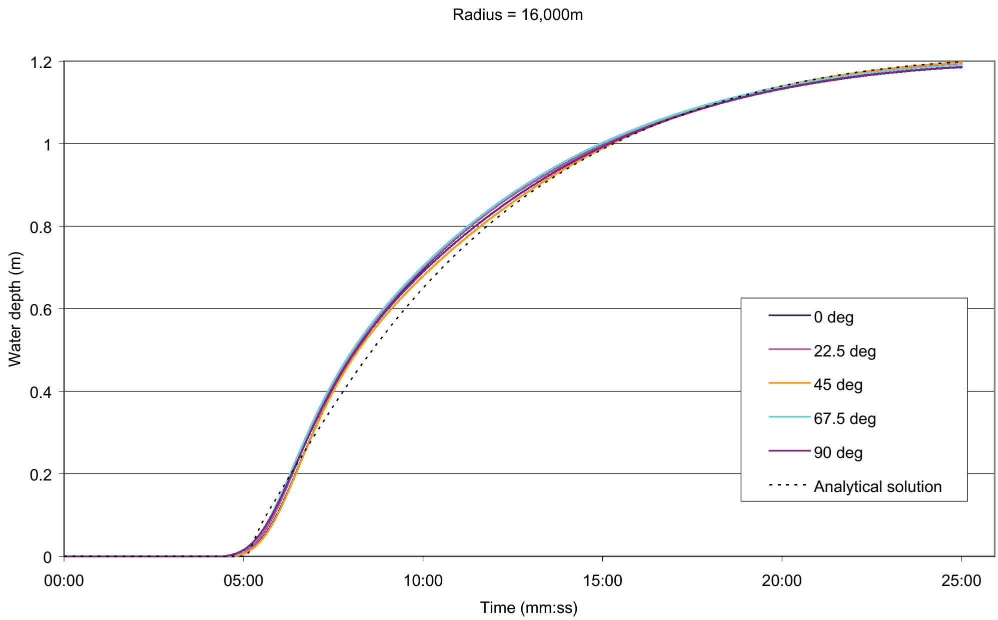

Figure 10. Test 3—Comparison of propagation speed across several directions and comparison with analytical solution.

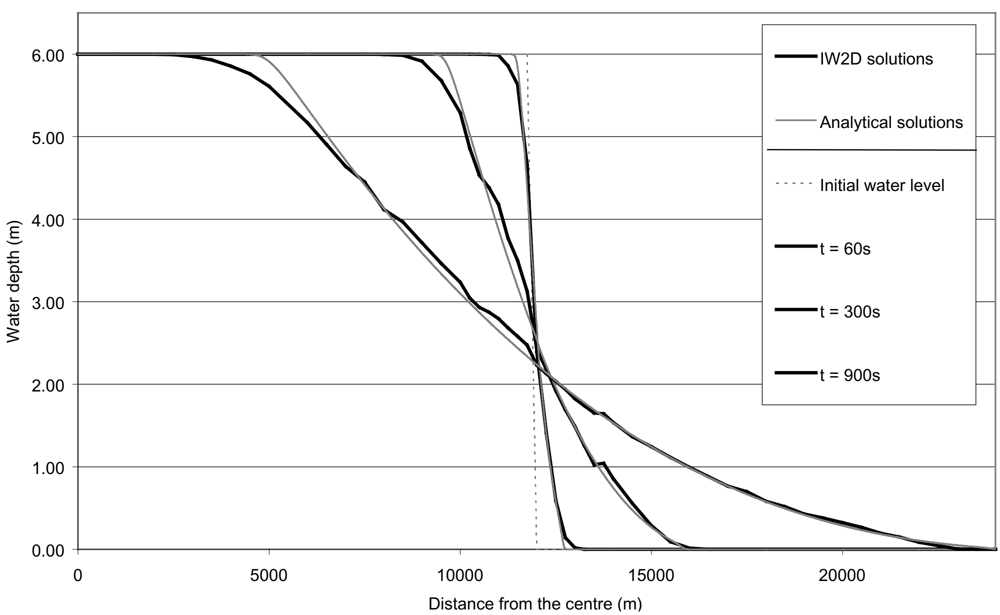

Figure 11. Test 3—IW2D and analytical solution comparison for direction 0 degree.

3.2 *Meshing capabilities*

InfoWorks 2D uses an unstructured mesh. The mesh generator is specifically designed for complex urban environments, and is capable of using the vertices of the building layout as vertices of the mesh elements. The meshing process therefore, becomes simple, quick and adjustable to the urban areas, allowing the user the capability of forcing the mesh by means of breaklines and other meshing elements, and defining different mesh size areas according to the degree of detail required.

The finite difference model tested (FD1), used a regular grid that was less flexible when trying to mesh the urban environment of the model (see Figure 14).

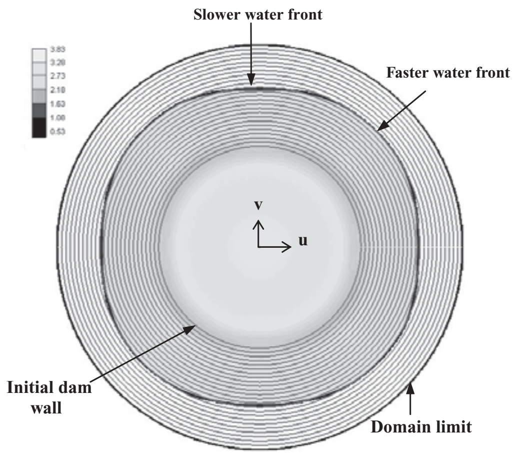

Figure 12. Test 3—Finite difference model solution at time 30 min. (Grid size 100 m).

3.3 *Simulation runs*

Table 1 and Figure 15 show the characteristics for the two different events chosen as the initial tests.

The models require specification of the Manning roughness coefficient over the floodplain area. In this study the friction coefficients *n* were set to 0.03 all over the study area and the simulations have been run for a 10 h simulated time. The results were stored every 5 minutes.

InfoWorks 2D was run for two different mesh sizes and uses a variable maximum stable time-step. The

Table 1. Rainfall event characteristics for the real case study.

Event	1 peak event	2 peak event
Return period	100 yr + 10%	10 yr/2 yr (both +10%)
Duration	60 min	30 min/30 min
River levels	100 year return period	
Pumping rate*	None	

* At flood defences.

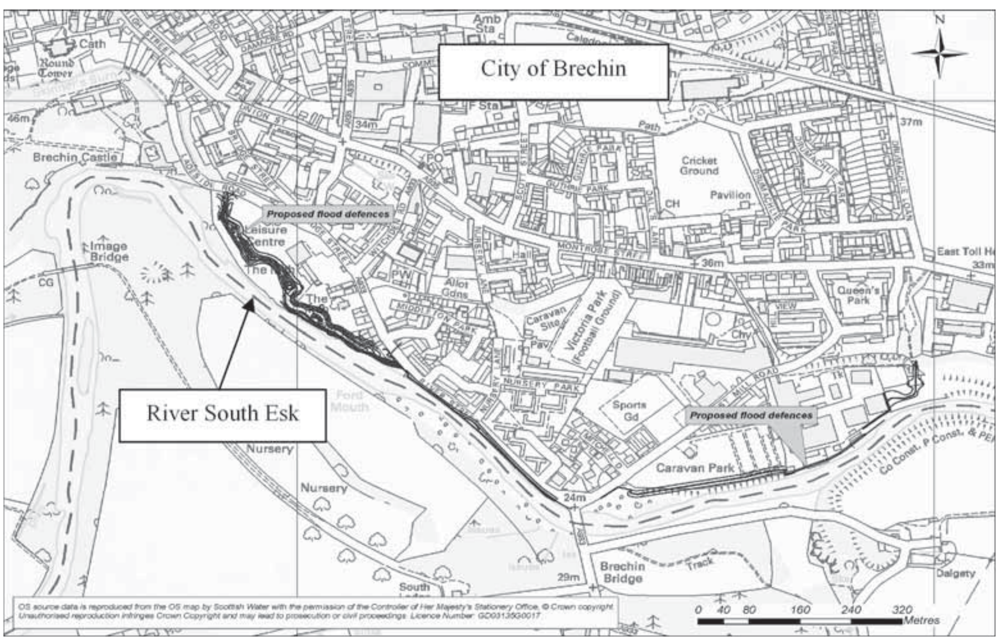

Figure 13. Brechin flood defence scheme.

finite difference model was run for three grid sizes and with a fixed time-step (see Table 2).

3.4 *Simulation results*

As seen for the dam break cases in the analytical tests, the InfoWorks 2D model proved to be far more stable than the FD1, especially on the steepest areas of the catchment where supercritical flows were achieved (see Figure 16). Mass balance problems were identified in the early time-steps of the FDl.

Table 2. Mesh/grid characteristics for the case study.

	Finite difference (FD1)	
InfoWorks2D* Average size m^2	Grid size m^2	Time-step s
65.1	100	2
–	25	1
7.9	9	0.5

* InfoWorks 2D uses a variable maximum stable time-step.

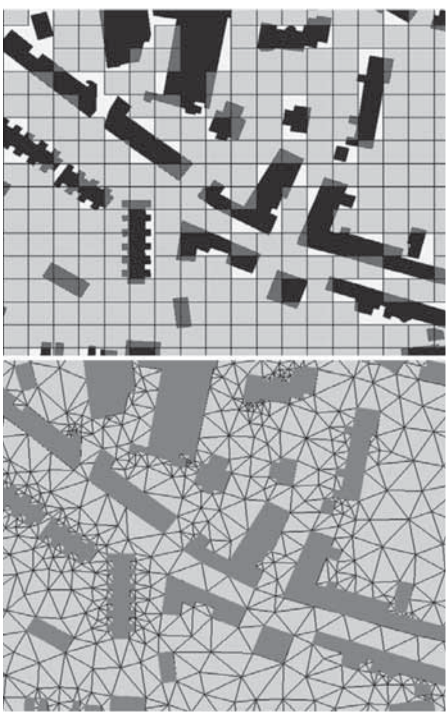

Figure 14. Finite difference regular grid and InfoWorks2D unstructured mesh.

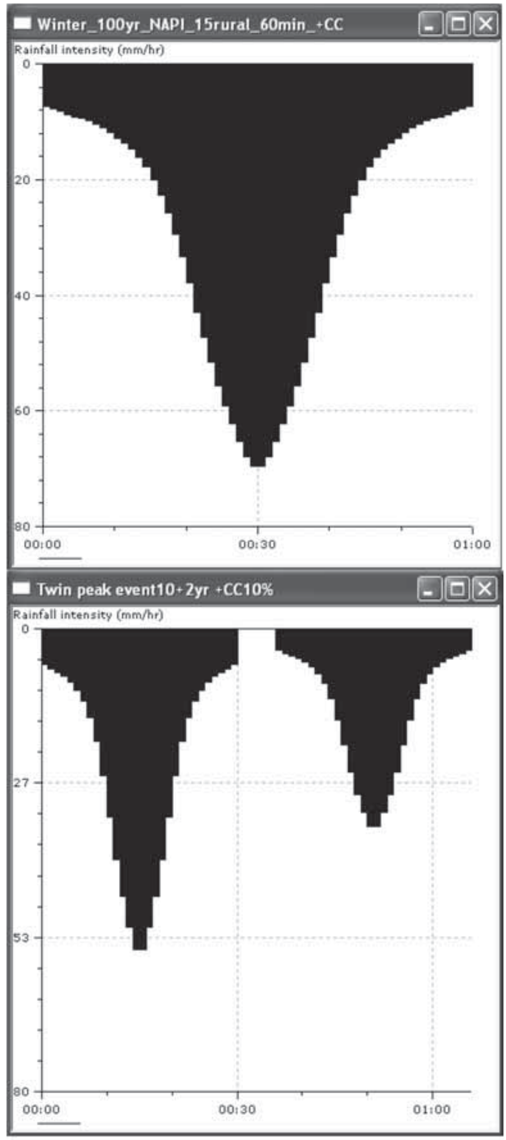

Figure 15. Rainfall event graphs for the real case study.

In general, the FD1l is under-predicting depths when compared with InfoWorks2D. In addition, it has been noticed that InfoWorks2D is less sensitive to mesh size than the finite difference model in relation to flood extent, depth and velocity.

In the simulation conducted on this site InfoWorks performed significantly faster (see Figure 17). The refined management of dry cells makes the Info Works 2D model computationally more efficient.

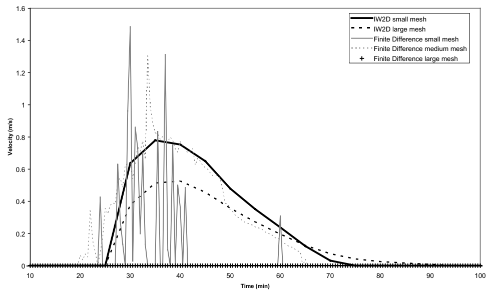

Figure 16. Velocity comparison at steep area.

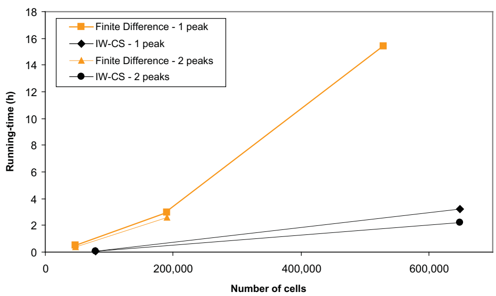

Figure 17. Comparison of running time and number of cells for the real case study.

4 CONCLUSIONS

Flood modelling of urban areas requires integrated models that can represent different hydraulic phenomena occurring simultaneously. A first step in the development of these complex models has been achieved through the coupling of 1D models (for rivers and network system) with 2D models (for flood plains and overland flow paths). A dynamic communication between the models, in both directions, is essential to represent accurately flooding events in the urban environment.

Unstructured meshes have proved to be more flexible and adjustable to urban areas than regular grids, especially when the mesh generator is able to deal easily with the building layouts. In addition, unstructured meshes have also shown a better performance when spreading the flow, regardless of the direction, whilst regular grids seem to have some directions that spread faster than others.

Through the dam break analytical tests, and later on confirmed by the real case study, it has been shown that finite volume models can outperform finite difference models when used in urban areas. In particular in the areas of:

- Changes of dry mesh elements into wet elements
- Transitions from subcritical to supercritical flows

InfoWorks2D is fully integrated with the 1D modelling packages already available. As it is an unstructured mesh model with a robust finite volume solution, (with an urban orientated mesh generator) it is a practical 2D hydrodynamic model ideal for the management of flood risk, particularly in urban and steep areas.

ACKNOWLEDGEMENTS

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