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Modelling Flood Inundation of Urban Areas in the UK Using 2D / 1D Hydraulic Models

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Abstract: Urbanised floodplains present significantly more complex hydraulic modelling challenges than those for rural floodplains. Urban areas require consideration of fences, highly varying land-use, buildings, narrow flow paths and underground stormwater drainage. The application of a 2D/1D hydraulic modelling approach to an urban flood study in Bristol, and a comparison of approaches benchmarked for the Thames Embayments Inundation study are presented. The Bristol study demonstrates the successful use of a 2D/1D system to model overland urban flows in 2D, whilst the river (open channel and long sprung arch culverts), stormwater sewer and narrow gaps are modelled as 1D elements. The Thames study is investigating the inundation risk from a breach or overtopping of the flood defence walls of 23 embayments along the River Thames, London. The findings from Stage 2a of the study provide an interesting comparison of four approaches, ISIS, LISFLOOD, TUFLOW and TELEMAC, when benchmarked to the Greenwich embayment.

Keywords: flood; hydraulic modelling; 1D; 2D; raster routing; finite difference; finite element

1. INTRODUCTION

In the UK, national planning guidance policies on Development and Flood Risk (PPG25) states “Policies in redevelopment plans should outline the consideration which will be given to flood issues, recognising the uncertainties that are inherent in the prediction of flooding, and that flood risk is expected to increase as a result of climate change” (DTLR, 2001). It goes on to state that “Planning authorities should apply the precautionary principle to the issue of flood risk, using a risk-based search sequence to avoid such risk where possible and managing it elsewhere”.

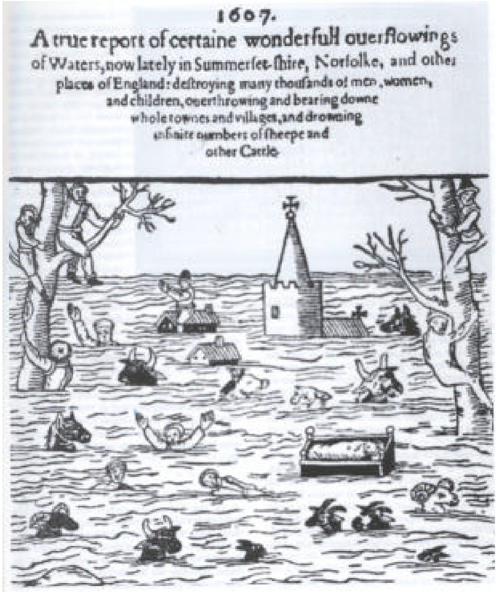
The Environment Agency (EA) of England and Wales is charged with advising planning authorities on the application of PPG25, which in part it discharges through the creation and publication of maps that indicate areas considered to be at risk from flooding. This national dataset is, and by necessity remains, indicative, the intention being that refinement of the understanding of flood risk be considered more closely at a local level through the planning process. The methods used to derive these indicative maps are based on well-understood and standard techniques, and are applied through a national specification. However, in considering flood risk at a local level, and in particular in circumstances where the assumptions inherent in these techniques are exceeded, there is a need to reduce the uncertainties associated with estimation of flood water levels and flood extents. This is particularly the case in urban environments where the predominance of culverted watercourses, extensive development on the natural floodplain, and the interaction of urban drainage systems warrant close scrutiny of the techniques used to determine flood risk (Pinnell, 2003).

This paper describes innovative approaches that have been adopted to understand and reduce the uncertainty associated with defining the flood risk. The paper draws upon two investigations recently carried out for:

- fluvial (catchment flood) study for the centre of the City of Bristol, England; and
- benchmarking of different hydraulic modelling approaches for predicting storm tide inundation of urban areas along the River Thames in the City of London, England.

2. BRISTOL CASE STUDY

The city of Bristol has long suffered from flooding. There are records of significant flood events of the River Frome in the city of Bristol dating back to the 1600's. Many significant floods have occurred in the 20th century with documented events occurring in 1926, 1935, 1936, 1937, 1960, 1974, 1980, 1982, 1999 and 2000.



Upstream of Bristol the Frome catchment is dendritic and drains a number of rural and semi-rural sub-catchments. The catchment and study area include significant areas of urbanisation, notably Bristol, and in recent years there has been extensive development in the lower catchment. Within the city, the Frome culvert system is intended to carry floodwaters entirely underground through to the floating harbour. Despite the construction of these large culverts, and also major flood attenuation and diversion schemes further upstream, flood risk in the city remains a concern.

In 2002 the EA completed a study to prepare indicative flood mapping (IFM) as part of the Agency's commitments to defining the flood risk. In addition to mapping a river length of approximately 47km, a baseline unsteady ISIS 1D hydraulic model was developed. A number of assumptions in the ISIS modelling were made that were considered acceptable for the production of indicative flood risk maps.

The indicative flood maps were constructed using engineering judgement applied to the results of the ISIS model. This involved the extension of predicted flood levels outwards to either high ground or to parallel flow paths in the model. However, in urban areas ground levels typically vary greatly over small distances, and the built environment, channel walls, buildings, road and hard surfaces etc, heavily influence the topography and flood flow patterns creating significant uncertainties and difficulties in producing flood maps.

For the lower, fully culverted section of the River Frome that passes through the City of Bristol, the uncertainties were deemed too great and flood risk mapping for this section was not produced. It was accepted that the overland flooding in this area would require more detailed analysis that considers the interaction of the culverted watercourse, stormwater sewers and manholes, and overland flooding routes along roads, pathways and other open areas.

In August 2002, the EA was consulted on a planning application relating to the redevelopment of low-lying areas of the centre of Bristol for mixed retail, office, residential and public open space. In part, because of the results of the IFM study, the EA advised that the redevelopment area was affected by extreme fluvial flows in the River Frome and tidal events from the River Avon.

Symonds Group was commissioned by the Bristol Alliance (the development proposers) to undertake a Flood Risk Assessment (FRA) for the urban redevelopment proposal. The scope of works included detailed computational modelling to more clearly define the flood risk resulting from overland flows, surface and sub-surface flow interactions, and the operation of the culverted sections of the River Frome.

In these areas, the characteristics of the built environment dominate and control the flood risk. The more detailed hydraulic modelling needs to be able to represent the following characteristics:

- Complex flow routes and variation in flood levels through the built environment.
- The presence of discrete lengths of flood defences along open channels.

- Interaction between overland flows and sub-surface pipe systems.

For these reasons, it was decided to research two-dimensional (2D) modelling systems and select one for carrying out the more detailed hydraulic modelling.

In addition, the benefits of fully 2D hydraulic modelling are noticeably realised in the urban environment where the flood hazard needs to be mapped in addition to flood extent. It is not only the frequency and extent of flooding that needs to be quantified, but also the depth, duration and velocity. 2D models provide detailed information on these parameters and deliver the required strategic planning information. The benefits accrued through the use of 2D fully hydrodynamic models in the urban environment can be summarised as:

- Improved analysis of floodplain (out of bank) flows via better definition of physical situations and hence improved accuracy and confidence in results.
- Prediction of flood hazards through parameters such as the velocity depth product and flood duration.

For the detailed flood risk assessment, a 2D/1D hydrodynamic model was constructed to overcome these limitations. The modelling package chosen was TUFLOW. WBM Pty Ltd were contracted to provide training and help develop and validate the model.

TUFLOW solves the full 2D depth averaged momentum and continuity equations for shallow water free surface flow, and incorporates the full functionality of the ESTRY one-dimensional (1D) hydrodynamic network software (Syme 2001). A powerful feature of TUFLOW is its ability to dynamically link 1D and 2D domains. Its strengths include rapid wetting and drying, powerful 1D and 2D linking options, multiple 2D domains, 1D and 2D representation of hydraulic structures, automatic flow regime switching over embankments, 1D and 2D supercritical flow, effective data handling and quality control outputs.

The TUFLOW Bristol model is constructed from several connected 1D domains and a single, regular grid, 2D domain using a cell size of 4m. The 1D and 2D domains represent a variety of flowpaths as follows:

- 1D open channel flow upstream of the culverted section.
- Culverted section of the River Frome as branches of 1D culvert elements.

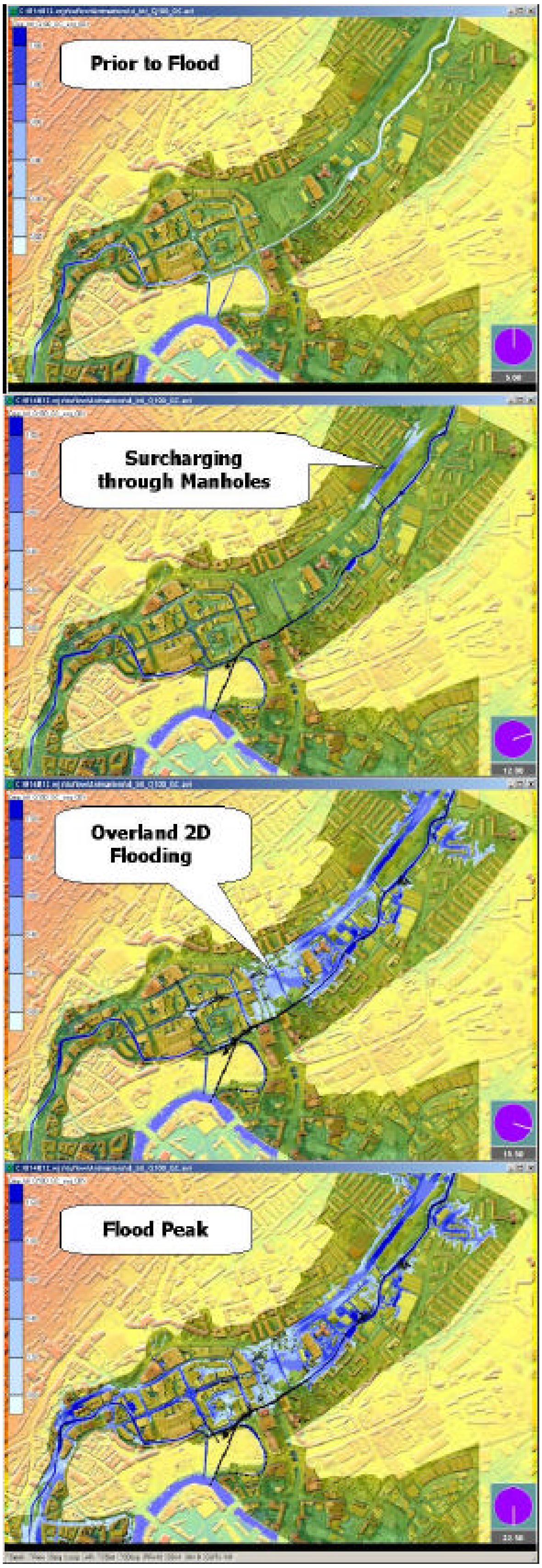


Figure 1 Predicted Flood Depths, Bristol TUFLOW Model

- Stormwater sewer pipes as a 1D system of culverts with connections between stormwater pipes and the overland 2D domain at manhole locations.
- Low-lying overland areas of the centre of Bristol as a 2D domain linked to the 1D domains.
- Replacement of 2D solution in three narrow and critical flowpaths between buildings that could not be adequately represented by the resolution of the 2D 4m cells.

The 1D open channel and culverted sections were based on those in the existing ISIS model. The stormwater sewer data was provided via a GIS layer. The 2D domain was based on sampling elevations from LIDAR (air-borne laser) DEMs provided by the UK, Environment Agency. DEMs were available with buildings and vegetation unfiltered or filtered from the data. For the TUFLOW model, the DEM with vegetation filtered out and buildings remaining was used. The DEM was problematic in that some re-working of elevations was required to remove features such as pedestrian bridges and overpasses that were incorrectly blocking overland flows. Also, key hydraulic controls, such as a stone wall alongside the open channel, are poorly defined in the DEM, and need to be incorporated into the TUFLOW model as 3D survey lines. Bed roughness (Manning's n) values were assigned to the 2D domain using existing GIS layers of land-use. Each land-use category was assigned a Manning's n value using a lookup table. For the 1D domains, similar Manning's n values as in the ISIS model were adopted.

The upstream inflow boundary condition was extracted from the existing ISIS model. Comparisons were made between the ISIS and TUFLOW results up until the point where flow was confined to the 1D domains (this is close to the 100 year event). A good correlation between the models resulted providing a validation of the TUFLOW model's 1D domains.

No major problems were encountered whilst setting the model up and carrying out simulations. As much of the data was available in digital formats, the setting up of the model was relatively straightforward. A site inspection carried out after preliminary modelling helped cross-check the predicted inundation and flow patterns, and to identify any need for additional detail in the model. Several locations were identified as needing more detail, such as the insertion of 1D elements for three key flowpaths between buildings as mentioned above.

Outputs of water level, depth, velocities and velocity depth product were generated from the 2D/1D model for a number of scenarios. Figure 1 shows predicted flood depths at different times of the simulation for one of the scenarios modelled.

As part of the flood risk assessment ongoing studies are investigating mitigation methods through the incorporation of additional storage, culverted and surface flow routes and building thresholds and floor levels for development proposals planned for the city centre. The ability of the TUFLOW 2D/1D model to represent a wide range of hydraulic processes within the urban environment was of considerable benefit in establishing accurately the flood risk, and for identifying measures to manage the risk.

3. TIDAL THAMES EMBAYMENTS INUNDATION STUDY

Over the course of history, development in and around London has encroached significantly into the River Thames floodplain. As a result, approximately 116 km2 between Teddington Weir and Dartford Creek, covering 23 hydraulically discrete embayments, is at risk of storm tide flooding during an extreme event. The risk is predicted to increase in the future due to a combination of sea level rise and geological settlement of southeast England. There are also the risks associated with failure of flood defence walls and/or the Thames Barrier.

The EA requires a tool to improve its ability to plan for and manage a tidal flood event that breaches or overtops the defences. This tool would generate predictions to give emergency response teams and the public reliable information regarding the extent, timing and nature of the propagation of floodwaters. On this basis, Halcrow, in conjunction with HR Wallingford, and WBM as a sub-consultant, were commissioned to carry out the Tidal Thames Embayments Inundation Study.

The first stage in the development of the tool involved the benchmarking of different modelling approaches on a single representative embayment, and make recommendations on the most suited modelling solution. The Greenwich embayment, located adjacent to the Thames Barrier, was selected as the trial area. Ideally an embayment for which observed flood extents are available would have been selected, however, in the absence of such data, an embayment was selected that was of 'average' size, contains many of the relevant features of the other embayments and is well known by the Agency team.

For modelling of floodplains, the main approaches used in the UK industry are:

- Quasi-2D (1D network) models
- 2D raster routing models
- Full 2D regular grid (typically finite difference) hydrodynamic models
- Full 2D irregular grid (typically finite element) hydrodynamic models
- Combinations of 1D hydrodynamic models with one of the above

The quasi-2D approach delimits a series of cells that correspond to distinct flood compartments, often separated by topographic features. This approach is incorporated in many standard 1D modelling packages as a means of representing off channel storage as a series of networked flood cells. The flow between the cells is modelled using simple analytical formulae such as the Manning or weir equations, or using the 1D St. Venant equations as used in the main river channels. Level/volume or level/flooded surface area relationships are used to define the storage of the floodplain.

More recently, the availability of topographic data in a grid format (eg. from air-borne laser) has led to the development and use of the storage cell concept applied to a raster DTM grid. These models use the raster DTM to discretise the floodplain as a regular grid with each pixel in the grid treated as an individual storage cell. Inter-cell fluxes use the uniform flow formulae or the weir equation (see for example Bates and De Roo, 2000). Each cell is assigned an elevation derived from the raster DTM. The computational burden compared with the quasi-2D approach is increased, but set up costs are greatly minimised. Raster routing methods are known to suffer from scale dependency (different results are generated with different grid sizes / time steps), and these are being investigated as part of the Greenwich Embayment application.

Fully 2D hydrodynamic models solve the complete 2D free-surface shallow water flow equations. They differ with the raster routing approach in that they model inertia, turbulence and other physical processes. The numerical solution of the full 2D equations requires increased computational effort.

For regular numerical grids (as predominantly used in finite difference models), model set up is relatively easy and similar to that for raster routing models as described above. The difficulty with regular numerical grids, of any type, is that the narrow and important flow routes (such as streams and drains) may force the cell or pixel size to be very small, and may create large, unworkable grids (on present day computers).

Irregular numerical grid models (as used in finite element solutions) are more difficult to construct and tend to be subject to a degree of user subjectivity. Irregular grid models, however, better represent linear features on the floodplain in a computationally efficient mesh (ie. higher density of elements through narrow flow paths). Set up costs in terms of time and necessary operator skill can be significant, and run times can be substantial.

One of the most important recent advances in floodplain modelling is the adaptation and use of full 2D hydrodynamic models dynamically linked with 1D models (Syme 2001). These combined models provide an efficient modelling environment in which small or narrow flowpaths (such as weirs, pipes and narrow streams) are modelled using 1D equations, while 2D flow (eg. overland flow) is solved using the full 2D solution. The 1D solution takes as input cross-sections, pipe dimensions, etc, providing a better representation of the geometry of these small or narrow flowpaths.

In order to provide recommendations on the most appropriate techniques to adopt, the following software were selected and applied to the Greenwich embayment to assess their accuracy and fitness for purpose.

- ISIS Flow (Quasi-2D)
- LISFLOOD-FP (Raster Routing)
- TUFLOW (Fully 2D, Regular Grid with 1D/2D dynamic linking)
- TELEMAC 2D (Fully 2D, Irregular Grid)

Experts in each of the modelling systems applied a consistent approach to development of the Greenwich models. Unfiltered (ie. includes buildings) air-borne laser data was used to generate a 1m raster DEM from which each model sampled its elevation data. The same distribution of five different bed roughness values was applied to all models using 30,000 polygons extracted from land-use mapping of London. Three scenarios were defined (an upstream breach, a downstream breach and an extreme overtopping event). The results of the upstream breach are presented in this paper. The following discussion, and Figures 2a, 2b and 3, on the comparison of modelling approaches are taken from Wicks, et al (2004).

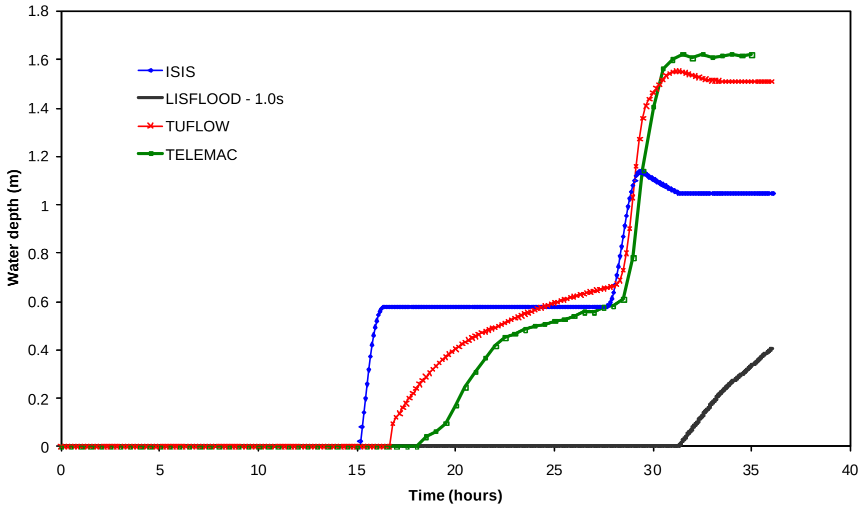


Figure 2a Comparison of Flood Depths at Location A (Wicks et al, 2004)

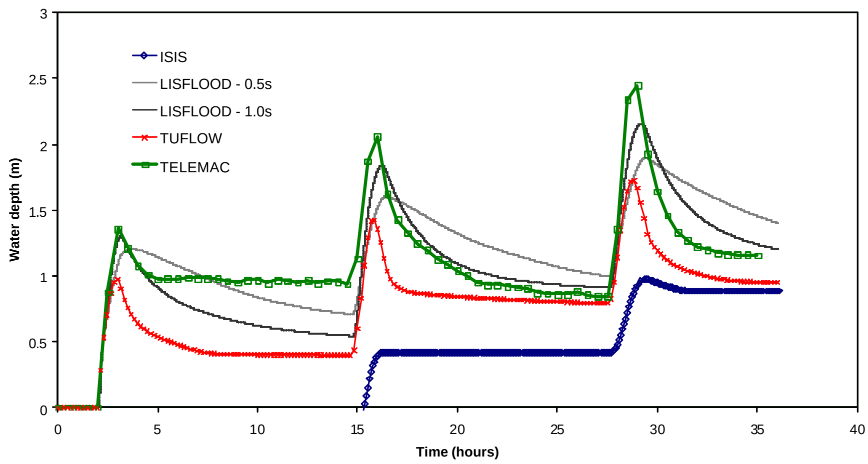


Figure 2b Comparison of Flood Depths at Location B (Wicks et al, 2004)

Based on the limited results presented in this paper a number of interesting conclusions can be made. Firstly, the time series of water depths in the floodplain demonstrate different aspects of the behaviour of the models. Depth time-series charts are presented in Figures 2a and 2b for locations A and B (refer to Figure 3). Location A is located further from the breach at an elevation of 1.3m above sea level, whilst location B is close to the breach at an elevation of 1.8m. At location A the TUFLOW and TELEMAC time series are very similar and the ISIS results are quite similar (but give a 0.5m lower final water depth). The LISFLOOD result at location A is very different - the predicted flooding does not reach this location until about 15 hours after that predicted by the other three models. It also appears that the final LISFLOOD water level has not been reached at this location during the 36-hour simulation. At location B larger water depths are predicted and the TUFLOW, LISFLOOD and TELEMAC results show similar behaviour. LISFLOOD results were also shown to be dependent on the computational timestepThe effect of changing time step in raster routing approaches is clearly seen from the 0.5s and 1s LISFLOOD simulation results. ISIS predicts onset of flooding at location B to occur about 13 hours after the other models but the final ISIS predicted flooding depth is close to that predicted by TUFLOW.

Secondly, the ISIS and TUFLOW maximum flood depth/extent maps (Figure 3) are both similar and seem reasonable. The LISFLOOD maximum extent is similar to the ISIS and TUFLOW extents in the southern part of the embayment but the LISFLOOD flooding does not extend northerly towards the Millennium Dome (as does the ISIS and TUFLOW extents). The TELEMAC extent is similar in the southern part and does extend further north than the LISFLOOD results (but not as far as the ISIS or TUFLOW results). In the TELEMAC results there are a number of large buildings that are shown flooded which are not shown flooded in the results of the other three models. Table 1 contains a summary of flooded areas for the models – the LISFLOOD flooded area is clearly the smallest.

As no 'observed' or theoretical data are available, it is not possible to definitely state that one particular model is more accurate than another. However, a subjective assessment of the results suggests that the TUFLOW model appears to give reasonable results that in all comparisons are similar to at least one other approach. For the other three models their results seem less reasonable in at least one of the comparisons.

For the selection of the most appropriate approach for the next stage of the Thames Embayment project, the criteria include run time, robustness, total cost, likely sustainability and ease of linkage to the ISIS 1D Tidal Thames model and other systems, as well as expected accuracy. The EA will be assessing the results presented here (and further results presented in the formal project report) to inform their decision on which modelling approach to adopt.

Table 1: Comparison Summary – Upstream Breach Scenario, 36h Simulation

Model	Cell Size (m)	Timestep (s)	Approx Simulation Run Time	Flooded Area (km^2)
ISIS	n/a	Adaptive	< 1min	0.417
LISFLOOD	10	0.5	8 hrs	n/a
LISFLOOD	10	1	2 hrs	0.244
TUFLOW	20	10	4 min	0.466
TUFLOW	10	5	23 min	0.448
TUFLOW	5	3	2.5 hrs	0.437
TELEMAC	10 - 25	2	> 24 hrs	0.580

4. CONCLUSIONS

A number of drivers are changing the needs for floodplain mapping and flood risk assessment in the UK. The publication of PPG25 in July 2001 led to a major change in the way local planning authorities consider flood risk as part of the Town and Country Planning process. Additionally other organisations (financial planning services and insurance bodies) are increasingly using flood risk information. There is therefore a fundamental need to recognise the limitations and uncertainties of the (mapped) data available to such organisations, and where required there must be amendment and improvement of the techniques which underpin these studies.

In the urban environment in particular, it is essential that the model and techniques adopted for the study be fit for purpose. The model selected must accurately reflect the flow/flood mechanisms; be calibrated and verified wherever possible and must demonstrate that it is not sensitive to the selection of influential parameters.

Incumbent upon specialists in the field of flood risk and flood mapping is the need to identify concerns and uncertainties in the hydrological and hydraulic models used. Whenever required these uncertainties must be reduced through the application of the most appropriate techniques available, together with the collection of good quality hydrometric and supporting information.

In urban areas, fully 2D modelling offers a major step forward in the prediction of flood extents through superior representation of the complex hydraulic processes. Additional benefits include velocity and flood hazard mapping at a much finer resolution and greater accuracy than quasi-2D or 2D raster routing methods can offer. For hydraulic features that are poorly represented by the 2D domain (eg. pipe networks, narrow waterways, etc), 2D/1D dynamically linked modelling offers a near complete solution. In the case of the Thames Embayments Inundation study, the ability to dynamically link 2D domains along the length of the established and calibrated 1D ISIS model of the River Thames would be a very powerful tool.

Through the use of this next generation of flood modelling tools, considerable assistance is given to those required to make decisions where flood risk is an issue.

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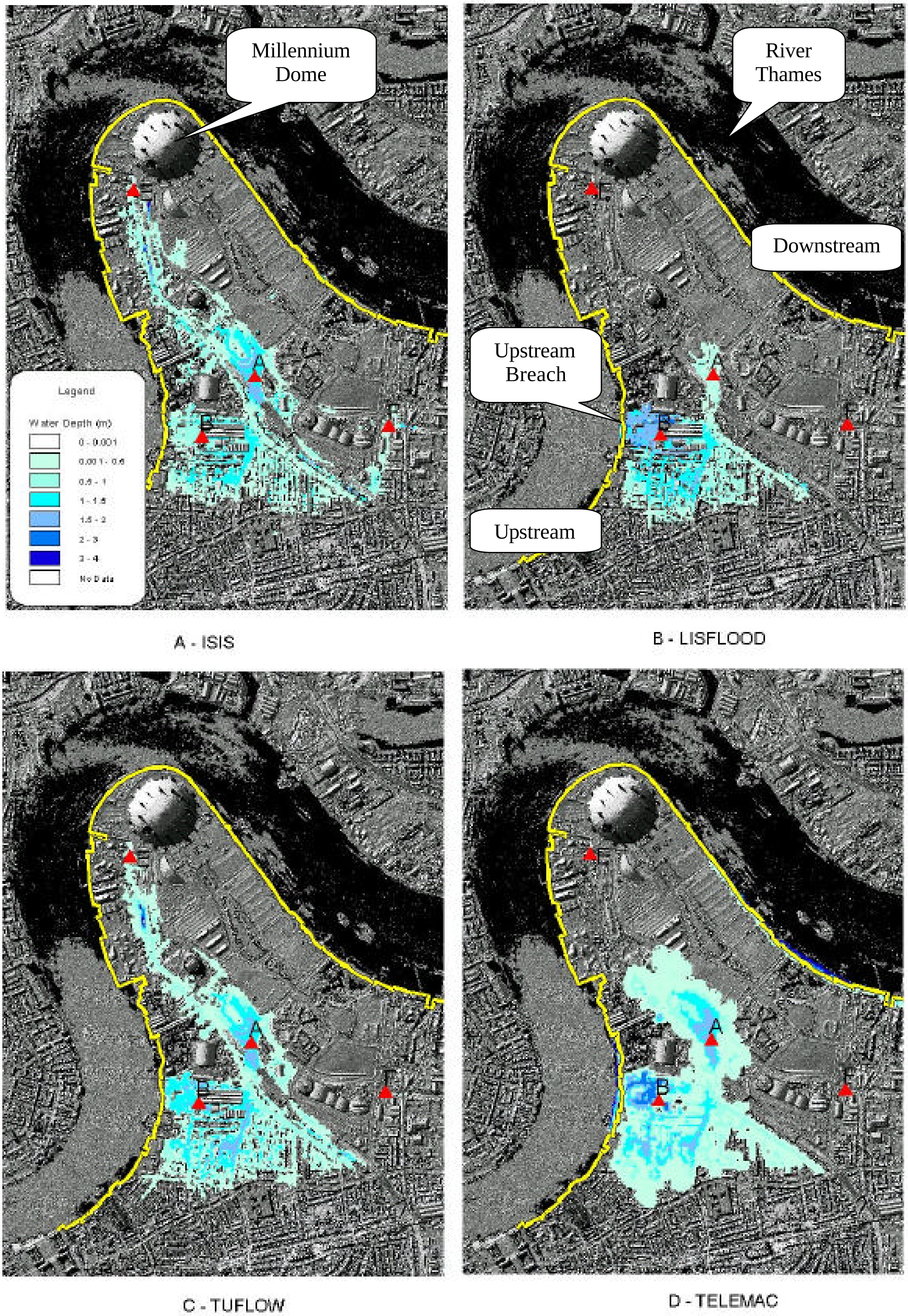

Figure 3 Comparison of Simulated Maximum Flood Depths (Wicks et al, 2004)