Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme

Desktop review of 2D hydraulic modelling packages

Science Report: SC080035

Environment Agency

defra
Department for Environment Food and Rural Affairs

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned by the Environment Agency's Science Department and funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84911-079-2

Further copies of this report are available from:
The Environment Agency's National Customer Contact Centre by emailing:
enquiries@environment-agency.gov.uk
or by telephoning 08708 506506.

Author(s):
S. Néelz and G Pender

Dissemination Status:
Publicly available / released to all regions

Keywords:
Flood inundation, computer modelling, model benchmarking

Research Contractor:
Heriot Watt University, Edinburgh, EH14 4AS

Environment Agency's Project Manager:
J Walker

Collaborator(s):
P Bates, R Falconer, B Lin and N G Wright

Science Project Number:
SC080035/SR

Product Code:
SCHO0709BQSE-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

The work of the Environment Agency's Science Department is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The science programme focuses on five main areas of activity:

- **Setting the agenda**, by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science**, by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science**, by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards;
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Head of Science

Executive summary

The increasing availability of two-dimensional (2D) inundation prediction models to simulate flood flows on floodplains has provided the Environment Agency with a set of powerful tools to help decision-making in flood risk assessment and management. In fact, the Environment Agency would not be able to fulfil many of its responsibilities in this area without the use of such models.

A number of 2D inundation modelling packages are available and the appropriate application of each modelling package depends upon:

1. the physical processes simulated by the model's mathematical formulation;
2. the approximate numerical method used to solve the mathematical formulation within the modelling package;
3. the representation of the problem geometry on the numerical grid upon which the numerical method is applied;
4. the representation of boundary conditions (inflows to and outflows from) to the modelled domain;
5. the manner in which the 2D inundation model interfaces with other models of the flood system, which can include river models and sewer models.

There is now a significant body of literature on the above issues but little of it evaluates how choice of model type will impact on practical decision making at the level required by the Environment Agency.

The purpose of this report is to set out the theoretical background to 2D inundation modelling packages used on Environment Agency projects, evaluate these packages against key performance indicators and recommend benchmark test cases that will provide practical guidance on choosing 2D inundation modelling packages for future application on Environment Agency projects.

The report summarises the physics, mathematical formulation, numerical scheme, numerical grid type and method of linking with other models for all 2D inundation modelling packages used on Environment Agency projects. While theoretical aspects of model development are appropriate in all cases, better practical understanding of the range of package applicability can be achieved by benchmarking package performance, to confirm the following:

1. Where estimates of flood hazard are required, models based on shallow water equations should provide predictions of flood water velocity that are closer to reality than those obtained from models based on simplified equations.

2. Where one is interested in predicting inundation extent at a broad scale, the performance of models based on simplified equations should be compared with that of models using shallow water equations on a coarse numerical grid.

3. The choice of numerical method should be a secondary consideration compared with the physical processes included in model equations.

4. The exception to Point 3 may be where hydraulic conditions alternate between super and subcritical flows; such circumstances can occur close to embankment breaches, in dam break flows following reservoir failures and during inundation of urban areas. In such circumstances the literature suggests that shock capturing schemes will perform better

5. Two-dimensional hydraulic modelling packages using a variety of grid methods to represent problem geometry are available. There is no clear evidence that these different techniques possess any particular advantage for Environment Agency problems at a practical level, although there may be a preference for structured grids due to the ease with which data from this configuration can be transferred to and from GIS software.

6. The capacity to link to other packages is essential for many Environment Agency applications. A number of methods exist to link 1D and 2D models and an evaluation of these is required through a systemic benchmarking exercise.

Using a questionnaire survey, the four 2D hydraulic modelling packages most commonly applied to Environment Agency problems were identified as TUFLOW, InfoWorks, Mike 21 and JFLOW. The questionnaire also captured information on the performance of these and other packages against the following key performance indicators:

1. User manual and technical reference
2. Technical support (including training)
3. Data compatibility
4. Flexibility of data input
5. Model setup
6. Adding structures
7. Run time
8. Stability
9. Presentation of flood depth and velocity predictions
10. Visualisation tools
11. File management
12. Sensitivity testing
13. Uncertainty analysis

In broad terms the four packages listed above perform satisfactorily against these measures.

The report provides an outline specification for eight practical benchmark test cases that, with further development, could be used to help Environment Agency staff assess the best use of 2D hydraulic modelling packages for flood risk and management decision-making.

Finally, the report recommends that the Environment Agency complete the second phase of benchmarking described in Section 4 prior to deciding on which 2D inundation modelling package to adopt for in-house use. However, if business needs dictate an early decision, the range of application and popularity of the existing TUFLOW software (marketed by BMT-WBM) suggests that the purchase of a multi-user licence for this package would be a relatively safe short-term investment.

Acknowledgements

We are grateful for the valuable help provided by Environment Agency staff (particularly Project Executive Iain Andrews, Project Manager Jim Walker, and Business End-User Leanne Wilson).

We also acknowledge the help and support of the Department for Environment, Food and Rural Affairs/Environment Agency Flood and Coastal Erosion Risk Management Joint Programme: Modelling and Risk Theme.

Additionally, we thank the staff of the Environment Agency's Strategic Flood Risk Management Framework Contractors who took the time to respond to the questionnaire survey.

Contents

1 Introduction

This review aims to better understand the role of 2D hydraulic computer modelling packages in flood risk mapping and management within the Environment Agency.

This need has arisen from:

1. A significant growth in the use of 2D hydraulic modelling packages for flood inundation prediction. This growth is driven by the greater availability of high resolution digital terrain models of floodplains (fluvial, coastal and urban) and low-cost computing facilities with sufficient power to run such models.

2. The European Floods Directive which requires the prediction of flood hazard. This in turn requires an assessment of flood depth and flood water velocity. 2D hydraulic models provide a relatively low cost means of predicting these.

3. The Pitt Review following the 2007 floods in England recommends:

    - better visualisation of the Environment Agency's flood mapping data;
    - development of maps that consider surface water risks;
    - creation of inundation maps arising from possible reservoir dam failure.

    2D hydraulic models have the potential to contribute to these needs.

A second aim of the review was to align use of 2D hydraulic modelling within the Environment Agency to the aims of its Flood Risk Modelling Strategy, which includes consideration of:

- the need to reuse 2D models and model data;
- building in-house modelling capability within the Environment Agency;
- local improvement of published flood maps and other flood risk data
- appraising 2D modelling undertaken by third parties for activities such as strategic flood risk assessments.

The review considered the use of 2D models in the main modelling applications required by the Environment Agency across all of its flood risk mapping and management responsibilities covering: large-scale flood mapping, catchment flood management plans, flood hazard mapping, contingency planning for real-time flood management, dam break inundation mapping, rating curve extension, appraisal of flood risk assessments, and guidance on strategic flood risk assessments.

A review of the theoretical background to 2D hydraulic modelling is presented in Chapter 2. This includes an overview of the governing equations, numerical methods, numerical grids, data requirements and 1D to 2D model linking. The theoretical review is summarised and linked to 2D hydraulic modelling packages currently used on Environment Agency projects in Table 2.2.

Chapter 3 presents the outcomes of the questionnaire analysis to determine the current use of 2D hydraulic modelling software on Environment Agency projects. The analysis highlights the most commonly used packages, the tasks to which they are applied, the resources required for 2D modelling versus those for 1D modelling and ratings of the four most commonly used packages (TUFLOW, InfoWorks 2D, Mike 21 and JFLOW) against the following criteria:

- User manual and technical reference
- Technical support (including training)
- Data compatibility
- Flexibility of data input
- Model setup
- Adding structures
- Run time
- Stability
- Presentation of flood depth and velocity predictions
- Visualisation tools
- File management
- Sensitivity testing
- Uncertainty analysis

Our recommendations for benchmark test cases designed to differentiate between model types in terms of performance and predictive capability are given in Chapter 4.

2 Flood inundation modelling

This section provides an introduction to the broad subject of mathematical and numerical modelling of river and coastal flooding and floodplain inundation. Model types are classified according to their dimensionality and introduced in general terms in Section 2.1. In Sections 2.2 and 2.3, the most important concepts of mathematical modelling of shallow water flows are introduced first in one dimension (St-Venant equations), then in two dimensions (shallow water equations). A discussion of the comparative merits of these two approaches is provided in Section 2.4. Essential concepts of numerical solution techniques applied to the shallow water equations are provided in Section 2.5, and other issues related to modelling are explained in Section 2.6 (including the data needs, model parameterisation and validation).

2.1 Classification of model types

Flood modelling methods currently in use in the UK can be divided into a number of approaches presented in Table 2.1 (adapted from Pender 2006), characterised by their dimensionality or the way they combine approaches of different dimensionalities. The table provides a summary of the methods and range of applications for each method. Those of greatest interest in the current discussion are referred to in Table 2.1 as 1D, 1D+, 2D- and 2D methodologies. These cover most modelling applications necessary to support the implementation of flood risk management strategies in the UK.

Three-dimensional methods derived from the 3D Reynolds-averaged Navier-Stokes equations can be used to predict water levels and 3D velocity fields in river channels and floodplains. However, significant practical challenges remain to be overcome before such models can be routinely applied at the scale necessary to support flood risk management decisions.

Hydrodynamic models based on the two-dimensional shallow water equations are classed here as 2D approaches. The 2D shallow water equations (also referred to as 2D St-Venant equations, by extension to 2D of the use of this terminology, see Hervouet 2007) can be derived by integrating the Reynolds-averaged Navier-Stokes equations over the flow depth. In this integration process, a hydrostatic pressure distribution is assumed (see Hervouet 2007). A solution to these equations can be obtained from a variety of numerical methods (such as finite difference, finite element or finite volume) and use different numerical grids (such as Cartesian or boundary fitted, structured or unstructured) all of which have advantages and disadvantages in the context of floodplain modelling. Further detailed considerations are provided in Sections 2.3 and 2.5.

One-dimensional models are based on some form of the one-dimensional St-Venant or shallow water equations (Barré de St-Venant 1871), which can be derived by integrating the Navier-Stokes equations over the cross-sectional surface of the flow. The assumptions used in the derivation of the St-Venant equations limit their use to where the direction of water movement is aligned to the centre line of the river channel. Over the years their use has been extended to the modelling of flow in compound channels, that is, river channels with floodplains. In this case, floodplain flow is part of the one-dimensional channel flow and simulation of inundation is an integral part of the solution of the St-Venant equations. The technique has at least two disadvantages, namely that 1) floodplain flow is assumed to be in one direction parallel to the main channel, which is often not the case, and 2) the cross-sectional averaged velocity predicted by the St-Venant has a less tangible physical meaning in a situation where large variations in velocity magnitude exist across the floodplain. The approach has been enhanced in recent years thanks to significant advances in parameterisation through the development of the conveyance estimation system (see, for example, Samuels *et al.* 2002).

In contrast with the 1D approach, the 1D+ approach involves the 1D approach to model the main channel flow only. Floodplains are modelled as storage cells that can cover up to several km^2 and are defined only through a water level/volume relationship. The flow between the 1D channel and these floodplain storage cells is modelled using discharge relationships (for example based on weir flow equations) often referred to as spill units or spill links. These may also be used to link storage cells to each other. The water level in each storage cell is then computed using volume conservation. Unlike the 1D approach, the 1D+ approach does not assume that flow is aligned with the river centre line, and therefore may be more appropriate to model floodplains of larger dimensions. However, these models do not include any momentum conservation on floodplains, meaning that water can be transferred instantaneously from one end of the storage cell to the other. The calculation of inter-cell flows may also be significantly in error (because of difficulties in defining spill discharge equations). Significant errors in predicted water levels can also occur locally if the storage cells are too large and the assumption of water level horizontality cannot be met. The 1D+ approach is also referred to as "pseudo-2D" (Evans *et al.* 2007) or "quasi-2D".

The 2D- models are a class of model that encompasses: 1) 2D models based on a simplified version of the 2D shallow water equations where some terms are neglected, resulting in the kinematic and diffusive wave representations (approach used in JFLOW); 2) models relying on square-grid digital elevation models and a simplified 1D representation of the flow between the raster DEM cells (LISFLOOD-FP). In effect the latter approach is similar to that adopted for the 1D+ approach, but usually with a much finer regular discretisation of the physical space. As with the 1D+ approach, momentum is not conserved for the two-dimensional floodplain simulation in 2D- models.

Almost limitless possibilities exist to combine 1D, 2D and 3D modelling approaches. In particular, a number of commercial software packages include the possibility to link a 1D river model to 2D floodplain grids. This has become popular in recent years because it allows the modeller to take advantage of the established tradition of 1D river modelling while at the same time modelling floodplains in two dimensions. This also results in computational savings over structured fully 2D approaches where a finer grid would be required to correctly represent the river channel geometry. In fact, the modelling of rivers using fully 2D approaches is relatively rare in the UK. The modelling of the 1D/2D linkage is an area where further research and development is needed, as most approaches in application represent exchange processes rather crudely (see Section 2.7). Combined 1D/2D modelling approaches where a 1D sewer system model can be linked to 2D floodplain models are also commercially available.

Finally, some models do not strictly fall in any of the above categories. This is the case for the rapid flood spreading methods (Gouldby *et al.* 2008) which are the subject of some research in the context of national scale flood risk assessment (for which simulation run times many orders of magnitudes shorter than conventional 2D models are needed). These methods are based on much simpler representations of the physical processes than 2D- models and the removal of the time discretisation in the computation. In addition, Pender (2006) also refers to a so-called 0D class of inundation modelling methods, which are methods that do not involve any modelling of the physical processes of inundation. One may consider emulation techniques making use of a limited number of training runs of a hydraulic model (see, for example, Beven *et al.* 2008) to belong to this category. Simple geometric methods which project river water levels horizontally over a floodplain can also be termed 0D as far as the modelling of floodplain inundation is concerned (this is also referred to as the "bath tub" approach). These can be applied to both river and coastal inundation cases.

Table 2.1: Classification of inundation models, adapted from Pender (2006)

Method	Description	Application	Typical computation times	Outputs	Example Models
1D	Solution of the one-dimensional St-Venant equations.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size.	Minutes	Water depth, cross-section averaged velocity, and discharge at each cross-section. Inundation extent if floodplains are part of 1D model, or through horizontal projection of water level.	Mike 11 HEC-RAS ISIS InfoWorks RS
1D+	1D plus a storage cell approach to the simulation of floodplain flow.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data.	Minutes	As for 1D models, plus water levels and inundation extent in floodplain storage cells	Mike 11 HEC-RAS ISIS InfoWorks RS
2D-	2D minus the law of conservation of momentum for the floodplain flow.	Broad scale modelling and applications where inertial effects are not important.	Hours	Inundation extent Water depths	LISFLOOD-FP JFLOW
2D	Solution of the two-dimensional shallow water equations.	Design scale modelling of the order of 10s of km. May have the potential for use in broad scale modelling if applied with very coarse grids.	Hours or days	Inundation extent Water depths Depth-averaged velocities	TUFLOW Mike 21 TELEMAC SOBEK InfoWorks-2D
2D+	2D plus a solution for vertical velocities using continuity only.	Predominantly coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects.	Days	Inundation extent Water depths 3D velocities	TELEMAC 3D
3D	Solution of the three-dimensional Reynolds averaged Navier Stokes equations.	Local predictions of three-dimensional velocity fields in main channels and floodplains.	Days	Inundation extent Water depths 3D velocities	CFX

2.2 1D modelling

2.2.1 The de St-Venant equations

The St-Venant equations can be expressed as follows:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \qquad (1)$$

$$\underset{(i)}{\frac{1}{A}\frac{\partial Q}{\partial t}}+\underset{(ii)}{\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)}+\underset{(iii)}{g\frac{\partial h}{\partial x}}-\underset{(iv)\quad(v)}{g\left(S_0-S_f\right)}=0 \qquad (2)$$

where Equation (1) is referred to as the *continuity* or *mass conservation* equation, and Equation (2) is the *momentum conservation* equation. In this, *Q* is the flow discharge (*Q = U.A* where *U* is the cross-sectional averaged velocity and *A* in the cross-section surface area), *g* is the acceleration of gravity, *h* is the cross-sectional averaged water depth, S_0 is the bed slope in the longitudinal direction and S_f is the *friction slope* (the slope of the *energy line*).

The various terms in the momentum conservation equation are as follows: (i) local acceleration term; (ii) advective acceleration term; (iii) pressure term; (iv) bed slope term and (v) friction slope term. Here the momentum equation is expressed in *conservative form*. It is possible to substitute UA for Q in Equations (1) and (2), expand Equation (2) and simplify it using Equation (1) to yield the mathematically correct *non-conservative form* of the momentum equation. Use of the non-conservative form may, however, lead to practical difficulties in its numerical solution, see Section 2.5.

The St-Venant equations can be extended by adding inflow and loss terms to Equation (1) and an inflow momentum term to Equation (2).

The friction slope *Sf* is a measure of the friction acting on the flow. Several friction slope models exist, namely:

$$S_f=\frac{f}{8gR}U|U| \qquad (3)$$

or $$S_f=\frac{1}{C^2R}U|U| \qquad (4)$$

or $$S_f=\frac{n^2}{R^{4/3}}U|U| \qquad (5)$$

where *f* is the *Darcy-Weisbach* friction factor, *C* is the *Chézy* coefficient, *n* is the *Manning-Gauckler* or *Manning's* coefficient (*Manning's n*), and *R* is the hydraulic radius (*R=A/P*, where *P* is the wetted perimeter). Manning's n is the most commonly applied friction parameter in the UK.

S_f can be further expressed as a function of the *conveyance K* ($K=AR^{2/3}/n$ - see next section), as follows:

$$S_f = \frac{A^2}{K^2} U|U|$$

A number of theoretical assumptions must be met for the St-Venant equations to apply, mainly:

- the bed slope is small;
- the pressure is hydrostatic, that is, streamline curvature is small and vertical accelerations are negligible;
- the effects of boundary friction and turbulence can be accounted for by representations of channel conveyance derived for steady-state flow.

The momentum conservation equation (Equation 2) can be rearranged to yield:

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{1}{gA} \cdot \frac{\partial}{\partial x}\left(\frac{Q}{A}\right)^2 - \frac{1}{gA} \cdot \frac{\partial Q}{\partial t} \tag{6}$$

Kinematic Diffusive Quasi-steady

Neglecting the local acceleration term (this is justified in many applications) yields the quasi-steady form of the momentum equation as indicated below in Equation (6). In most rivers, the flow is subcritical and all acceleration terms can be neglected, yielding the so-called *diffusive wave* equation (Julien 2002). Finally, the *kinematic wave* equation is obtained by neglecting all but S_f and S_0.

Numerical solution techniques for flow modelling are introduced in Section 2.5.

2.2.2 Recent advances and ongoing research

One of the principal strengths of 1D river models is their capability to simulate flows over and through a large range of hydraulic structures such as weirs, gates, sluices and so on (Evans *et al*. 2007). Techniques to represent structures in 1D models are constantly improving.

Recent and ongoing research advances in 1D modelling include enhanced conveyance estimation techniques and afflux estimation techniques. The Conveyance Estimation System (Samuels *et al.* 2002, HR Wallingford 2003) focused particularly on the effects of riverine vegetation, the momentum exchange between river channel and floodplain flows, and the behaviour of natural shaped channels. It is implemented in a number of commercial packages such as ISIS and InfoWorks-RS. The afflux estimation system (Lamb *et al.* 2006) is an improved method for predicting the increase in water level upstream of a structure (caused by energy losses at high flows through bridges and culverts).

One of the most significant advances in 1D models is the ability to link 1D and 2D models (Syme 1991, Evans 2007). This can be applied in various ways:

- within a channel that one wishes to model partly in 1D and partly in 2D;
- between a 1D drainage network model and a 2D surface flood model;
- between a 1D river model and a 2D floodplain model;
- within a mainly 2D model where, for example, culverts are modelled in 1D linking 2D cells between themselves

More details on 1D/2D linkages are provided in Section 2.7.

2.2.3 1D urban drainage modelling

Flow in urban drainage networks is often modelled using the 1D St-Venant equations. However, specific approaches need to be applied when the flow is pressurised (the pressure at the surface is not equal to the atmospheric pressure). Such approaches include the use of the so-called Preissmann slot, a conceptual vertical and narrow slot in the pipe soffit, which provides a conceptual free surface condition for the flow when the water level is above the top of a closed conduit (a smooth transition between free surface and surcharged conditions is thus enabled).

2.3 2D shallow water equations

The two-dimensional shallow water equations expressed in vector form are:

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=H \qquad (7)$$

where x and y are the two spatial dimensions. The four vectors U, F, G, H are defined as follows:

$$U=\begin{pmatrix} h \\ hu \\ hv \end{pmatrix},\quad F=\begin{pmatrix} hu \\ g\frac{h^2}{2}+hu^2 \\ huv \end{pmatrix},\quad G=\begin{pmatrix} hv \\ huv \\ g\frac{h^2}{2}+hv^2 \end{pmatrix},\quad H=\begin{pmatrix} 0 \\ gh\left(S_{0x}-S_{fx}\right) \\ gh\left(S_{0y}-S_{fy}\right) \end{pmatrix} \qquad (8)$$

where *u* and *v* are the depth-averaged velocities in the x and y directions, respectively. S_{ox} and S_{oy} are the bed slopes in the x and y directions. The friction slopes in the *x* and *y* directions can be expressed in a manner analogous to the 1D formulation, as follows (assuming the use of Manning's n):

$$S_{fx}=-\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}} \quad \text{and} \quad S_{fy}=-\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}} \qquad (9)$$

It can be shown that Equation (8) reverts the 1D St-Venant equations by assuming $v = 0$, ignoring any gradient in the *y* direction and multiplying by the depth-averaged channel width. Equation (7) is expressed in conservative form. Similarly with the 1D St-Venant equations, a non-conservative formulation can also be derived.

Equation (7) is in fact a simplified version of the full 2D shallow water equations, which also include the following:

- Viscosity terms *Fd* and *Gd* (to be added to *F* and *G* respectively), expressed as follows:

$$F_d = \begin{pmatrix} 0 \\ -\varepsilon h \dfrac{\partial u}{\partial x} \\ -\varepsilon h \dfrac{\partial v}{\partial x} \end{pmatrix} \quad \text{and} \quad G_d = \begin{pmatrix} 0 \\ -\varepsilon h \dfrac{\partial u}{\partial y} \\ -\varepsilon h \dfrac{\partial v}{\partial y} \end{pmatrix} \qquad (10)$$

where ε is the so-called *viscosity* coefficient which strictly speaking should account for the combined effect of a) kinematic viscosity b) the turbulent eddy viscosity and c) the apparent viscosity due to the velocity fluctuations about the vertical average. The subscript *d* stands for "diffusion" as these terms are effectively analogous to a diffusion process.

- Coriolis terms which account for the effects of the Earth's rotation.
- Wind shear stress terms.
- Possible wall friction terms along any vertical flow boundaries.
- Inflow volume and inflow momentum terms as for the 1D equations.

Coriolis effects are considered negligible in the context of flood inundation studies. Wind shear stresses may result in non-negligible effects on water depths in very large floodplains but their prediction is intimately dependent on the ability to predict wind strength and direction. Wall friction terms are only relevant in very high resolution modelling studies and are therefore rarely included.

The contribution of the kinematic viscosity to the value of ε is typically at least an order of magnitude smaller than the turbulent eddy viscosity and for this reason is neglected. The apparent viscosity resulting from non-uniformity in the horizontal velocity along the vertical direction is recognised as a much more significant contributor to the value of ε (Alcrudo 2004). However, this effect is poorly understood and is therefore neglected in most applications. The turbulent eddy diffusivity has been the object of more significant research (see Rodi 1980), but in the context of flood modelling it is generally not considered an important parameter (Alcrudo 2004). For overland flow conditions, it is unlikely that the eddy viscosity will have a major effect on model predictions as friction will dominate. It may however, for flow in and around structures, have a significant effect upon local high-resolution predictions (DHI 2007a).

Similarly with the 1D formulation, it is possible to neglect the acceleration terms in the 2D shallow-water equations (the terms involving *u* and *v* in *U*, *F* and *G*) to yield the *2D diffusion wave equations* (Bradbrook *et al*. 2004). This is appropriate where the flow is predominantly driven by local water surface slope and momentum effects are less important, as is often the case in the context of UK fluvial floodplains. Such modelling approaches and recent practical applications (such as Bradbrook *et al.* 2005) are discussed in Hunter *et al.* (2007).

An important mathematical property of the shallow water equations is that they are non-linear (they do not satisfy the principle of superposition), in accordance with the true non-linearity of the flow processes being modelled. One of the implications is that shallow water flows are subject to *shock* waves, which are understood to be discontinuous solutions of the shallow water equations (Toro 2001). Shocks on floodplains are mainly encountered in the form of hydraulic jumps, that is, transitions from supercritical to subcritical flows. These may be caused by local changes in terrain topography (diminution of bottom slope, lateral expansion), or by the effect of bottom friction.

2.4 1D versus 2D floodplain inundation modelling

The choice between a 1D and a 2D model is relevant primarily in the context of river floodplain modelling. The theory of open channel flow in the form of 1D St-Venant equations is not applicable to urban flood flows where extreme non-uniformity and spatial variability of flow patterns is common. Flows may happen in sequences of fast moving shallow flows (possibly supercritical) and large still ponds, rather than in the form of channels that are well defined over long distances. The significance of storage and recirculation areas that clearly do not fit in a 1D description should not be underestimated. Besides, urban flows rarely happen along routes that are clearly identifiable in advance of building a model and running the simulations (unlike rivers). However, a case where 1D modelling is as close as possible to being appropriate can be found, for example, in Lhomme *et al.* (2005) (deep flooding in a network of well-defined narrow streets). Similarly, in coastal flooding it is not generally the case that floodplains may be reasonably represented as networks of well-defined channels and therefore 1D floodplain modelling is rarely appropriate.

In river flooding contexts, however, 1D models in the sense defined in Section 2.1 (that is, 1D models of rivers with cross-section extending over lateral floodplains) are appropriate for narrow floodplains, typically where their width is not larger than three times the width of the main river channel. The underlying assumption should be that the contribution of the floodplains to conveyance can be quantified using recent advances in the estimation of compound channel conveyance (for example HR Wallingford 2003). An additional condition for such models to be valid is that the floodplains should not be separated from the main channel by embankments, levees or any raised ground, where the channel floodplain unit effectively behaves as a single channel.

It is clear that 1D river models have limitations that can become significant in many practical applications. The flow is assumed to be unidirectional (generally happening in the direction parallel to the main channel flow), and where this is not true (recirculation areas) conveyance predictions can be severely overestimated. Situations where floodplain flow "makes its own way" are frequent, but perhaps an even more significant issue is the fact that 1D cross-sections will offer a rather crude representation of floodplain storage capacity in the case of large floodplains.

A better balance between the correct representation of floodplain conveyance and the correct representation of floodplain storage capacity can be obtained through the use of 1D+ models, where large "disconnected" floodplains are modelled as storage reservoirs (while narrow floodplains can still be modelled as part of channel cross-sections). This latter modelling approach has its own limitations: exchange flows between the river and reservoirs and between the reservoirs are typically modelled using broad-crested weir equations (Evans *et al.* 2007), which are not always appropriate. Weir equations adapted for drowned (downstream controlled) flows are also used, but the assumption that water levels are horizontal within each reservoir results in incorrect water level predictions in the vicinity of reservoir boundaries, often causing large errors in the predictions of exchange flows. These do not matter if the time duration of the floodplain filling and draining is small compared to the duration of the flood. Lastly, the size and location of floodplain storage cells and links between them are user-defined and therefore require some *a priori* understanding of flow pathways in the floodplain which may result in circular reasoning within models

As already mentioned above, the choice of a model type (1D, 2D- or 2D) for surface flow modelling is mostly relevant in river flooding applications. 2D is the preferred choice in urban and in coastal environments. 2D modelling of river floodplains can itself be divided into two important classes of approaches, namely the one where only floodplains are modelled in 2D (as part of a combined 1D/2D model) and the one where floodplain flow and channel flow are modelled as part of the same 2D grid. This latter class of approaches is discussed in the final paragraph of this section. The main advantage of 2D modelling (over any other approach for floodplain modelling) are that local variations of velocity and water levels and local changes in flow direction can be represented (Syme 2006). The approach also does not suffer from the limitations of the 1D and 2D- approaches detailed in the previous paragraphs. It allows in principle a better representation of floodplain conveyance, but a major limitation of combined 1D/2D models for river and floodplain systems is that the exchange processes between the river and the floodplains are still modelled crudely (momentum transfer is not modelled). This is discussed further in Section 2.7. A major drawback of 2D models is their computational cost (Syme 2006), with a computational run time typically proportional to $1/L^3$, where *L* is the grid resolution.

The approach where the whole river and floodplain system is represented as part of a 2D unstructured grid deserves special attention (see for example Sauvaget *et al*. 2000, Horritt and Bates 2002). This approach is not particularly common in UK practice, perhaps because there is a long-established tradition of 1D river modelling. Surveyed cross-sections which are intended primarily for 1D models exist for a large proportion of rivers in the UK. Numerous existing 1D models have been calibrated using measured data, and 1D Manning's n values are well-known for many rivers or river types. There is therefore a clear incentive to make use of these data and knowledge by continuing to build 1D river models or to use existing ones. In addition, the grid resolution needed to model a river in 2D is significantly finer than what is typically applied on floodplains, resulting in significantly increased computation times. These reasons explain the current enthusiasm for combined 1D/2D modelling for river and floodplain systems.

2.5 Numerical modelling

This section provides a brief introduction to the numerical modelling approaches used in inundation modelling software. It is limited to the techniques used to solve the shallow water equations or some simplified form, as introduced above.

The first step in numerical modelling consists of replacing the differential equations such as the shallow water equations by a set of algebraic equations which are relationships that link variables calculated at a finite set of points in the space-time domain. The process of representing space and time using such points and converting the differential equations into algebraic equations is called *discretisation*. The many numerical methods in existence can be split into classes depending on the discretisation strategy, that is, the specific approach applied to do this. The great majority of methods used to solve the shallow water equations fall into one of three discretisation strategies: finite difference, finite element, and finite volume methods. These are introduced in the following section. Section 2.5.2 provides a further introduction to a number of concepts of numerical modelling that are relevant to more than one class of numerical methods. Section 2.5.3 introduces the problem of meshing.

2.5.1 Classes of numerical methods

Finite difference methods

Finite difference (FD) methods rely on Taylor series expansions to express the value taken by a variable (h, u, v and so on) at a given point, as a function of the values at neighbouring points and of local derivatives of increasing orders. These Taylor series are then combined to yield approximate expressions for the derivatives involved in the shallow water equations, as a function of a finite number of neighbouring point values. The accuracy of the approximations can be controlled by the order to which the Taylor series expansions are developed (the order of the so-called *truncation*), which is also linked to the number of neighbouring points involved.

The implementation of finite difference methods is significantly more straightforward on a structured grid, which is a computational grid that can effectively be represented on a square matrix (in 2D applications), see Section 2.5.3 (although geometrically the grid itself is not necessarily square). This explains to some extent why their popularity is currently in decay in the academic community (Alcrudo 2004), as unstructured grids lend themselves better to the modelling of environmental flows. Software packages based on FD methods, however, are popular with a number of UK consultants, due mainly to their compatibility with high resolution digital terrain models and digital bathemetric models created from LiDAR and sonar surveys.

Finite element methods

In finite element methods, the solution space in divided into a number of elements in 2D. In each element, the unknown variables are approximated by a linear combination of piecewise linear functions called trial functions. There are as many such functions as there are vertices defining the element, and each takes the value of one at one vertex and the value of zero at all other vertices. A global function based on this approximation is substituted into the governing partial differential equations. This equation is then integrated with weighting functions and the resulting error is minimised to give coefficients for the trial functions that represent an approximate solution (Wright 2005). A number of methods to do this exist, including the *Galerkin* method (see for example Ottosen and Petersson 1992).

Finite element methods benefit from a rigorous mathematical foundation (Alcrudo 2004) that allows a better understanding of their accuracy (Hervouet 2007); however, the technique has not been used as much as other approaches in commercial software, perhaps because it is less accessible conceptually and produces models that result in large run-times. Also, generating meshes can be time-consuming when a suitable mesh generation tool is not available (Sauvaget *et al.* 2000).

Finite volume methods

In the finite volume method, space is divided into so-called finite volume which are 2D (in this context) regions of any geometric shapes. The shallow water equations (in conservative form) are integrated over each control volume to yield equations in terms of fluxes through the control volume boundaries. Flux values across a given boundary (calculated using interpolated variables) are used for both control volumes separated by the boundary, resulting in the theoretically perfect mass and momentum conservativeness of the approach (a flux into a finite volume through a boundary is always equal to a flux out of a neighbouring one through the same boundary). In 1D, finite volume methods are equivalent to finite difference methods.

Finite volume methods are increasingly popular and have become the most widely used method in the area of Shallow Water flow modelling (see for example Sleigh *et al.* 1998, Caleffi *et al.* 2003, DHI 2007b, Villanueva and Wright 2005, Alcrudo and Mulet YEAR, Kramer and Stelling 2008). This can be explained by their advantages in terms of conservativeness, geometric flexibility and conceptual simplicity (Alcrudo 2004)

2.5.2 Further introduction to numerical schemes

A property common to all classes of numerical methods is that the local accuracy of the approximation is controlled by the grid resolution and by the magnitude of local gradients in the process being modelled (this is consistent with the definition of a derivative, the limit of a finite difference approximation over an interval Δx as Δx approaches zero). Consequently grid refinement is usually the most obvious way to improve the accuracy of a numerical model. A *convergent* solution is defined as a solution that becomes independent of grid resolution as the grid resolution is increased (Wright 2005).

One difficulty in the numerical resolution of shallow water equations is prediction of the location (celerity) of flood wave fronts and discontinuities (shocks). This is an area where considerable progress has been achieved over the recent two decades, mainly through the use of the so-called *shock-capturing* methods. Some of the well-known shock-capturing methods (see Toro 2001) used in inundation modeling include the MacCormack method (Liang *et al.* 2007), the Lax-Wendroff method, Total-Variation Diminishing (TVD) schemes, Monotonic upstream-centered Schemes for Conservation Laws (MUSCL) based on the Godunov approach, and Essentially Non-Oscillatory (ENO) schemes. Schemes belonging to the class of approximate Riemann solvers (Roe 1981, Toro 1999) are also increasingly popular.

An important consideration in numerical methods is the approach used to proceed through the calculation in time. The solution is normally obtained in time step increments. However, numerical schemes can be divided in two major categories depending on the approach used to discretise the shallow water equations through time. In *implicit schemes*, the discretisation approach applied to the space gradients involves values at both the previous time step (n) and the new time step (n+1). In *explicit schemes*, it involves values from the previous time step only. Implicit schemes are of greater theoretical accuracy. However the approach also implies that at each new step, the solution cannot proceed through the computational grid one node (or finite volume) at a time, and that a system of algebraic equations covering the entire computational domain must be solved. Explicit schemes (which represent the vast majority of newly developed schemes) are simpler to implement. However, they are subject to some form of time-step limitation (for stability) analogous to the *Courant-Friedrichs-Lewy condition* ($u.\Delta t/\Delta x<1$). Implicit schemes are not subject to such stringent limitations, but time steps are nevertheless limited by considerations of accuracy.

Two major areas of ongoing research in numerical modelling of the shallow water equations are related to a) the treatment of source terms and b) the modelling of wetting and drying. Source terms (*H* in Equation 8) arising from the bed slope dominate in applications to real floodplains, so that the discretisation approaches for the flux term and the source terms must ensure an appropriate balance (see for example Garcia-Navarro and Vazquez-Cendon 2000), otherwise numerical schemes can fail simple tests involving a complex bottom geometry and no movement, where spurious non-zero velocities can be calculated. The modelling of *wetting and drying* (prediction of the boundaries of inundation) is a challenge in inundation modelling, because flood depths are usually very small along most floodplain inundation boundaries. Model instabilities occur very easily, often due to the fact that friction slope formulae (see for example

Equation 6) diverge for very small flow depths. A number of approaches have been proposed (see for example Begnudelli and Sanders 2006, or Bates and Horritt 2005 for a comprehensive review of the issue), all of which are a compromise between stability, accuracy and mass conservation.

2.5.3 Computational grids

The numerical methods outlined above are implemented on a discretised representation of space called either a *mesh* or *grid*. A grid is a collection of points (or *vertices*) where the variables defining the flow condition (velocity, depth or water level) are computed through solution of the systems of algebraic equations obtained from the discretisation process as outlined in Section 2.5.1. The *resolution* of the grid refers to the distance between the vertices. Closely positioned vertices give a fine grid and widely spaced vertices give a coarse grid. The resolution may also vary in space. The computational efficiency of a numerical model is directly related to the number of equations that need to be solved and therefore to the resolution of the grid.

A *structured* grid is (originally) a grid that can be conceptually represented on a rectangular matrix (the numerical program can effectively make use of rectangular matrices to store the flow variables involved in the computation). Any point in the matrix is physically connected to the four points on either side. A structured grid where the vertices are physically at regular intervals apart is called a structured *square* grid (Figure 2.1a). A *boundary-fitted* grid is a structured grid that makes use of irregular intervals between vertices (Figure 2.1b).

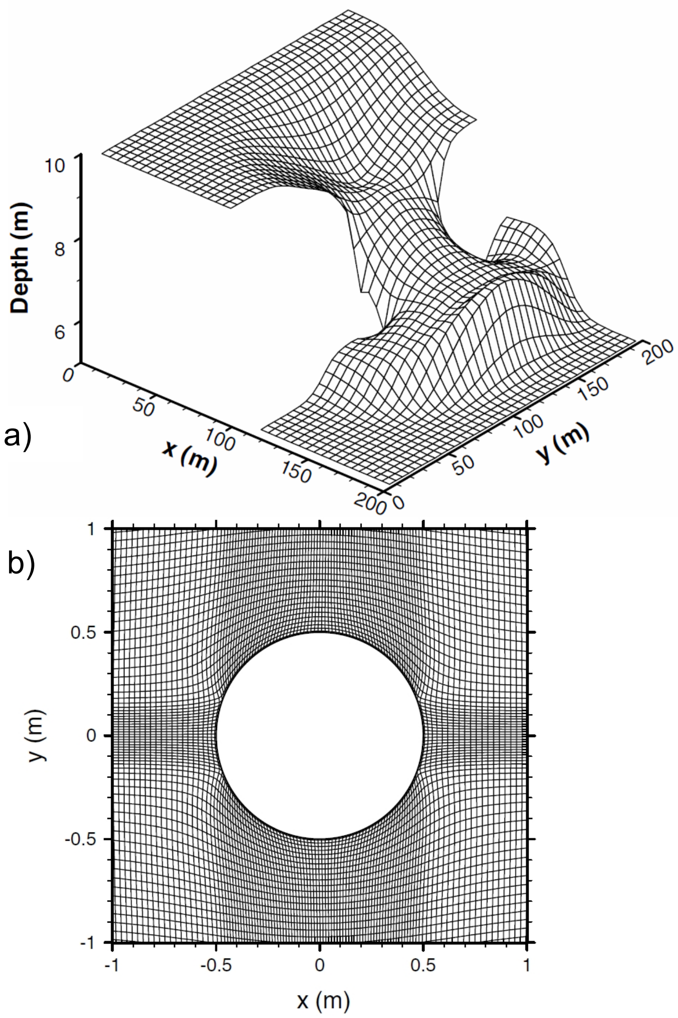

Figure 2.1: a) Dam-break simulation on a structured square grid from Liang *et al.* (2006); b) Boundary-fitted grid from Liang *et al.* (2007)

An *unstructured* grid is a grid that cannot be represented on a rectangular matrix (Figure 2.2). The points that constitute such a grid are kept as lists of (x,y,z) coordinates and details on how the points are connected to each other are recorded in a database. The flow variables computed by the model are also stored in the form of lists. The attraction of unstructured grid models lies in the possibility to follow irregular floodplain contours, and to apply a non-uniform resolution. It can be refined locally to take into account fine features in the flow, while keeping a low resolution in areas where refinement is not needed, thereby ensuring optimal use of computer power. However, the finer areas usually dictate that a smaller time step be used which can increase computation time.

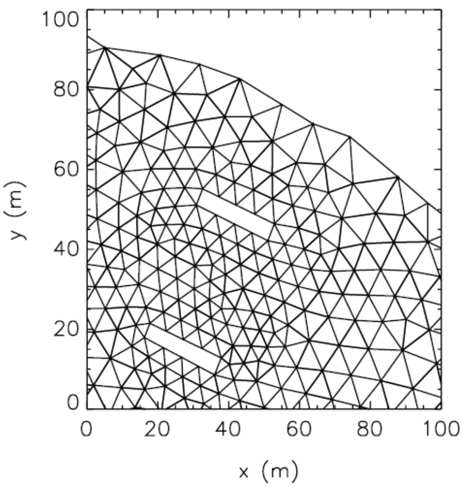

Figure 2,2: Unstructured mesh from Horritt *et al.*(2006)

The choice of discretisation strategy is linked to the choice of grid type. Finite difference methods are suited to structured grids only, whereas most finite element and finite volume methods have been designed with both structured and unstructured grids in mind.

Structured square grids have an obvious advantage over unstructured grids in that the construction of the physical geometry of the grid is straightforward and entirely defined by a small number of user-defined parameters, for example resolution, lower left corner coordinates, and dimensions (alternatively, an irregular GIS defined outline can also be used). The issue of grid generation for unstructured grids is much more complicated, and the process can be time-consuming if a large amount of human intervention is necessary (Sauvaget *et al.* 2000). Automatic grid generation techniques are not yet used to their full potential in the context of floodplain flow modelling. However, significant advances in this field in recent years (see for example Owen *et al.* 2003) are beginning to be used in such applications (for example Begnudelli and Sanders 2006) including in some commercially available software (such as InfoWorks-RS 2D, see Gutierres Andres *et al.* 2008). “Smart” grid generation techniques that are specifically designed for floodplain flow modelling, and that integrate physical features of the floodplains digitised in the form of break-lines or building outline polygons, are being implemented. Some research algorithms make mesh resolution locally dependent on vegetation features (such as Cobby *et al.* 2003). Such advances are, however, still to be used in engineering practice.

Modelling of inundation in urban areas faces specific difficulties. Urban flood flow pathways are typically narrow in size and their modelling in detail requires a grid resolution such that computation times are excessive for most applications. It is therefore preferable to apply coarse grids combined with some sort of sub-grid treatment of the urban environment. While the limitations of the approach in using roughness alone to account for the overall effects of buildings on the flow have been shown (Néelz and Pender 2007), approaches where an attempt is made to model the directional effect of the urban area on the flow are beginning to be proposed (see Sanders *et al.* 2008). Other recent advances involving a sub-grid scale treatment in coarse models include those by Yu and Lane (2005), Morris *et al.* (2006) and Fewtrell *et al.* (2008).

Finally, it is worth mentioning the so-called *quadtree* grids which are structured square grids that can be locally refined (Liang *et al.* 2008, Liang and Borthwick 2009). No commercial application of this technique exists at the present time.

2.6 Model boundaries and parameterisation

2.6.1 Boundary conditions

For unsteady flow simulations, boundary conditions are required at each boundary node for the duration of the simulation. For 2D hydraulic models where flow conditions on the boundary are subcritical, two boundary conditions are required at the upstream (inflow) and downstream (outflow) boundaries. At boundary nodes where no flow is expected, the boundary condition is simply a “no flow” condition. For supercritical conditions, two boundary conditions are required at the upstream boundary. Boundary conditions can be values of flow or water level obtained from measured data, hydrological analysis, or others models, such as an embankment breach modelling, or a sewer surcharging model. The flow can also enter the domain as a source, which is an approach typically used to model direct rainfall.

2.6.2 Initial conditions

Initial conditions consist of values of predicted variables (water level and velocity) at each node on the computational grid at the start of the simulation. It is normal practice to generate initial conditions using steady flow simulations or assume zero values initially and then refine these by using a “warm up” period for the unsteady simulations. The nature of the shallow water equations means that the initial conditions cease to influence the predicted values relatively quickly into the simulation. Most 2D hydraulic modelling packages offer a “hot start” facility where the results from previous simulations can be fed into a new model run as initial conditions.

2.6.3 Terrain data

A 2D computer model of inundation flow invariably relies on the availability of a so-called Digital Elevation Model or Digital Terrain Model (conventions on the use of such terminology are not consistent, but we suggest that DEM refers to a representation of the Earth’s surface plus above ground features such as buildings and other structures, whereas DTM refers to a representation of the “bare” earth). In recent years, DEM and DTM have benefitted from significant advances in remote-sensing, involving the automated, broad-area mapping of topography from satellite and, more importantly, airborne platforms. This in turn has stimulated the use of 2D inundation models. Three techniques which currently show potential for flood modelling are aerial stereo-photogrammetry, airborne laser altimetry or LiDAR and airborne Synthetic Aperture Radar interferometry (FLOODsite project 2008). LiDAR in particular has attracted much attention in the hydraulic modelling literature (Bates *et al.*, 2003, French, 2003, Smith *et al.* 2005). A major LiDAR data collection programme is underway in the UK, where so far more than 20 per cent of the land surface area in England and Wales has been surveyed. In the UK, helicopter-based LiDAR survey is also beginning to be used to monitor in detail (at 0.2 m spatial resolution) critical topographic features such as flood defences and embankments. LiDAR systems operate by emitting pulses of laser energy at very high frequency (around 5-100 KHz) and measuring the time taken for these to be returned from the surface to the sensor. Global Positioning System data and an onboard Inertial Navigation System are used to determine the location of the plane in space and hence the surface elevation. As the laser pulse travels to the surface, it spreads out to give a footprint of around 0.1 m^2 for a typical operating altitude of 800 m. On striking a vegetated surface, part of the laser energy will be returned from the top of the canopy and part will penetrate to the ground. Hence, an energy source emitted as a pulse will be returned as a waveform, with the first point on the waveform representing the top of the canopy and the last point (hopefully) representing the ground surface. The last returns can then be used to generate a high resolution 'vegetation-free' DEM, while other returns provide information on the vegetation cover. Buildings will normally be identified by last returns. They can either be kept as part of a DEM, or automatically extracted using specific algorithms (see for example Zhang *et al*. 2003) to produce a DTM. Ordnance Survey products, such as Mastermap, can also be used to aid this process (Mason *et al.* 2007).

2.6.4 Parameterisation

Parameterisation in 2D flood flow modelling is usually reduced to the setting of the friction coefficient (such as Manning's n in Equation 9) and the viscosity coefficient (in Equation 10), although as already mentioned in Section 2.3, viscosity is usually considered a secondary parameter and is often ignored. When not ignored, viscosity may be dealt with using a constant viscosity coefficient (see for example Sauvaget *et al*. 2000, DHI 2007a), the Smagorinsky viscosity formulation (Syme 1991, DHI 2007a), or the two equation k–e model (Namin 2004). No methodology exists to calibrate viscosity in flood inundation models (because calibration data at an adequate level of detail do not exist and are unlikely to ever exist). It should also be mentioned that the viscosity coefficient is sometimes used to introduce additional artificial viscosity to the flow, to enhance model stability.

The parameterisation of bed friction is a much more important issue, because the prediction of flow (velocity and flood wave celerity) using the shallow water equations is crucially dependent on the friction parameter values adopted in the model. Applications of 1D models benefit from decades of hydrometric data collection, user experience in model calibration and validation, and flood wave propagation (at least in the case of in-bank floods) is now predicted by 1D models with an accuracy that can be considered excellent for many engineering applications. Nevertheless the issue as to whether models should be parameterised using engineering judgement informed by experience, or simply by calibration, or even by an *ad hoc* combination of both is still debated in the literature (Beven 2000, Cunge 2003).

The parameterisation of friction in 2D models benefits to some extent from the knowledge and experience available in 1D modelling, although the formulation of friction is different in 2D models, because a) bed friction only concerns the interaction of the flow with the river bottom while in 1D models it concerns the entire wetted perimeter, and b) viscosity is explicitly represented in the 2D shallow water equations whereas it is effectively taken into account as part of the friction parameterisation in 1D models. Theoretically this should result in lower values (assuming that lower values are used for less rough beds, as is the case with Manning's n) of friction in 2D models compared with 1D models (Samuels 2006, Morvan *et al.* 2008). The essential point is that friction parameters are scale-dependent effective values that compensate for varying conceptual errors in the model.

The problem of parameterisation needs to be approached in a fundamentally different way in 2D floodplain models. Studies to predict flood levels in models of compound channels (river and floodplain systems) have shown results to be sensitive primarily to the channel friction values used, with the sensitivity to floodplain friction values being much less significant (see for example Pappenberger *et al.* 2005). This reflects the fact that many floodplains act as lateral storage reservoirs where water depths and velocities remain small compared to those in the main channel (this is more commonly the case in the UK than for example in Mediterranean regions of Europe). The main consequence is that it is not straightforward to calibrate floodplain friction using measured flood levels (or inundation extent maps) (Hunter *et al.* 2005). A more compelling argument for not adopting this approach is the problem of *equifinality* introduced by Aronica *et al.* (1998) and Beven (2006), which provides a conceptual framework for dealing with the non-uniqueness of calibrated parameter values in over-parameterised problems. In the above context, it implies that an agreement between model predictions and any observed flood level or inundation extent is achievable by calibrating channel friction values only. In the distinct context where floodplain flow results from some form of failure of flood defences (and continues until it reaches the same level as the source or the latter recedes), correct model predictions are then likely to depend on the correct prediction of flood discharge (flowing through or over the failed defence) much more than on the floodplain friction parameterisation. As volume inflow is extremely difficult to estimate in such circumstances, any observation data in the form of inundation extent or water levels only provide part of the data set necessary to undertake friction parameterisation. In addition, these data are likely to have been collected at a time when the flood has settled on the floodplain (in a state that depends only marginally on the dynamics of inundation).

The implications of the above are that inundation extent (Néelz *et al*. 2006) and floodplain water level measurements alone cannot usually be used to calibrate 2D floodplain models in the same way as river levels are used to calibrate 1D river models (see also Hunter *et al.* 2005, Werner *et al.* 2005). In the same way as calibrating 1D models usually involves tuning friction parameter values to yield an optimal match between predicted and measured water level hydrographs, the approach for 2D floodplain models should at the very least concentrate on the prediction of features of the flow that depend primarily on the processes modelled by the 2D solver (perhaps velocities). But as implied above, a major difficulty will be that floodplain flows usually depend to a large extent on processes external to the floodplain, and accurate measurements of discharges versus time at the boundaries of floodplains in real events (for example through a breach or over an embankment crest); considerably more research is thus required before such inflows can be reliably predicted. An additional difficulty if measured velocities are to be used is that these must be measured in a form that is consistent with what models predict, that is, depth-averaged velocities.

The above paragraphs focus on the modelling of floodplains only or on the modelling of floodplains in 2D as part of combined 1D/2D models. Approaches to calibration for fully-2D models where floodplains as well as river channels are modelled in 2D is somewhat different (see for example Sauvaget *et al*. 2000). However, the issues mentioned above apply equally to the calibration of floodplain friction in these models.

Elaborate approaches to floodplain friction parameterisation have been suggested in recent years. These approaches make use of the wealth of information provided by remote-sensing data such as LiDAR, from which spatially-distributed details on vegetation thickness and density can be extracted (Asselman *et al.* 2002, Cobby *et al.* 2003, Mason *et al.* 2003). However, output variables such as inundation extent and point water levels may not be sensitive to distributed friction values on river floodplains to any discernible extent, as demonstrated by Werner *et al.* 2005. This suggests that a methodology for floodplain friction parameterisation at a coarse scale may be more appropriate than the use of such technologies if floodplain water levels are of interest, although in applications where detailed predictions of flow patterns (including velocities) are sought, then clearly distributed friction values are relevant. Other types of datasets such as high-resolution land-use maps (such as Mastermap in the UK) may be useful in a similar way, subject to the same reservations. Even if friction phenomena on different surfaces (roads and so on) and through different types of vegetation were adequately understood and modelled, there may remain the issue of modelling very localised processes involving head losses such as those caused by hedges and fences. These may be better taken into account in a model parameterised at a coarse scale where they would effectively be treated as sub-grid processes in the same way as bottom friction would.

2.7 Linking 1D and 2D models

As already mentioned, almost limitless possibilities exist in principle to combine 1D and 2D modelling approaches. In particular, a number of commercial software packages include the possibility to link a 1D river model to 2D floodplain grids. This has become popular in recent years because it allows modellers to take advantage of the respective benefits offered by 2D floodplain models and 1D river models. Several techniques exist to date to link 1D and 2D models. The most widely used technique for 1D river and 2D floodplain linking is the *lateral* link, where the exchange flows are typically modelled using broad crested weir equations or depth-discharge curves (Lin *et al.* 2006, Liang *et al*. 2007b, Evans *et al.* 2007, DHI 2007a, WBM-BMT 2008), based on water level differences. A limitation of the approach is that the complicated momentum exchange processes that characterise the river-floodplain boundary are not modelled (due to the fact that these processes intimately depend on complex 3D flow patterns in the river, which by definition are not resolved in a 1D river model). Progress towards improved model representation is reported in Liang *et al*. (2007b).

Other linking approaches include the longitudinal link, which one may use to model a watercourse partly in 1D (upstream) and partly in 2D (downstream), or to connect the downstream extremity of a 1D model to a 2D grid (Evans *et al.* 2007, DHI 2007a, Liang *et al.* 2007b). In this approach the flow from the 1D enters the 2D model as a “source”, and the water level in the 2D model at the junction is used as a downstream boundary condition in the 1D model. Some combined 1D/2D models also offer the possibility to use small 1D components to represent pipes or culverts within an otherwise 2D model (see WBM-BMT 2008).

Combined 1D/2D modelling approaches where a 1D sewer system model can be linked to a 2D floodplain models are also commercially available (see for example DHI 2007a).

Finally the approach consisting in coupling a 1D river model and a 2D floodplain model using a *vertical link* should be mentioned (Bates *et al.* 2005, Verwey 2001, Stelling and Verwey 2005). This consists in representing the floodplain using an uninterrupted 2D grid overlying the 1D river model. The 1D model operates on its own until the river level reaches bankfull level, at which point the water above this level is transferred to the 2D model.

2.8 Commercial software packages and research codes

Table 2.2 provides a summary of the software packages included in this review, including, according to the column number in the table:

1. The package name.
2. An indication of how much physics are modelled, that is, whether the full shallow water equations (SWE) are used or otherwise.
3. Some basic information about the numerical scheme.
4. Whether the code has shock-capturing capabilities.
5. The name of the developer.

6. Whether the package is available commercially, is an “internal” proprietary package or is an academic research code.
7. Whether the package includes the possibility to link 2D and 1D modelling approaches.

Table 2.2: Summary of software considered in this report

(1) Name	(2) Physics	(3) Further information on numerical scheme	(4)Shock capturing	(5) Developer	(6) Status	(7) Linkages
FINITE DIFFERENCE SCHEMES						
TUFLOW	SWE	Alternating Direct. Implicit	No	BMT-WBM	Commercial	Own 1D river and pipes solver
DIVAST	SWE	Alternating Direct. Implicit	No	Cardiff Univ.	Research	As part of ISIS 2D
DIVAST-TVD	SWE	Explicit TVD- MacCormack	Yes	Cardiff Univ.	Research	
ISIS 2D	SWE	Alternating Direct. Implicit	No	Halcrow	Commercial	Own 1D river solver
MIKE 21	SWE	Alternating Direct. Implicit	No	DHI	Commercial	As part of MIKE FLOOD
MIKE FLOOD	SWE	MIKE 21	No	DHI	Commercial	Own 1D river (MIKE 11) and urban drainage (MIKE URBAN) solvers
SIPSON/UIM	SWE	Alternating Direct. Implicit	No	U. of Exeter	Research	Own multiple linking element
SOBEK	SWE	Implicit - Staggered grid	Yes	DELTARES	Commercial	Own 1D river solver, vertical link
JFLOW	Diffusive wave	Explicit	No	JBA	Internal	
FINITE ELEMENT SCHEMES						
TELEMAC 2D	SWE		No	EDF	Commercial	
FINITE VOLUME SCHEMES						
TELEMAC 2D	SWE	Tbc	Yes	EDF	Commercial	
MIKE 21 FM	SWE	Godunov based	Yes	DHI	Commercial	As part of MIKE FLOOD
MIKE FLOOD	SWE	MIKE 21 FM	Yes	DHI	Commercial	Own 1D river (MIKE 11) and urban drainage (MIKE URBAN) solvers + MOUSE (?)
InfoWorks-RS	SWE	Roe's Riemann solver	Yes	Wal'ford Softw	Commercial	Own 1D river solver
InfoWorks-CS	SWE	Roe's Riemann solver	Yes	Wal'ford Softw	Commercial	Own 1D urban drainage solver
HEMAT	SWE	Roe's Riemann solver	Yes	Iran Wat. Res. Cent. & Cardiff	Research	
BreZo	SWE	Explicit- R Riemann solver	Yes	U. of California	Research	
TRENT	SWE	Explicit- R Riemann solver	Yes	Nottingham U.	Research	
OTHERS						
LISFLOOD-FP	Norm. Flow in x and y dir.	Explicit	No	U. of Bristol	Research	1D kinematic wave treatment. Vertical link.
RFSM	Gravity only	Volume filling algorithm	No	HR-Wal'ford	Internal	Linked to other components of national FRA
Flowroute	Diffusive wave			Ambiental	Internal	No technical information published.
Grid-2-Grid				CEH		No technical information published.
Floodflow				Microdrainage		No technical information published.

2.9 Summary

This evaluation of model packages highlighted the following aspects of performance that should be confirmed through benchmarking, using case studies appropriate to the type of decisions required by the Environment Agency.

1. Where estimates of flood hazard are required, a modelling package based on the shallow water equations should provide predictions of flood water velocity that are closer to reality than those obtained from models based on simplified equations.
2. Where one is interested in predicting inundation extent at a broad scale, the performance of models based on simplified equations should be compared with that of models based on the shallow water equations applied on a coarse numerical grid.
3. For a range of practical applications required by the Environment Agency, the choice of numerical scheme should be a secondary consideration to the physical processes included in model equations.
4. The exception to Point 3 may be where hydraulic conditions alternate between super and subcritical flows; such circumstances can occur close to embankment failures, in dam break flows following reservoir failures and during inundation of urban areas. In such circumstances the literature suggests that shock capturing schemes will perform better. This requires to be confirmed.
5. 2D hydraulic modelling packages using a variety of grid methods to represent problem geometry are available. There is no clear evidence that these different techniques possess any particular advantage for Environment Agency problems at a practical level, although there may be a preference for structured grids due to the ease with which data from this configuration can be transferred to and from GIS software. This requires to be confirmed.
6. The capacity to link to 1D modelling packages is essential for many Environment Agency applications as it ensures best use of available models in terms of both theoretical application and re-use of existing resources. Our literature review has highlighted a number of alternative methods for linking 1D and 2D models and an evaluation of these is required through a systemic benchmarking exercise.

3 Questionnaire analysis

3.1 Questionnaire survey

An email questionnaire survey was used to collect supplementary data on:

- Modelling packages most frequently used by the Environment Agency and its contractors on flood risk management-related projects.
- The range of tasks these packages are used on.
- The comparative resource requirements in terms of man hours for 2D versus 1D modelling tasks.
- User's experience in using the packages on flood risk management projects.
- Hardware profiles currently used by those undertaking 2D modelling in support of flood risk management.
- Future software development plans of those organisations that develop and maintain their own 2D modelling packages.

A list of the 2D hydraulic modelling packages included in the survey is provided below and a copy of the questionnaire is provided in Appendix A.

BreZo, DIVAST, DIVAST TVD, FloodFlow, Flowroute, Grid-2-Grid, HEMAT, Hydro AS-Z2, InfoWorks, 2D RS/CS, ISIS 2D, JFLOW, JFLOW GPU, LISFLOOD-FP, Mike-21, RFSM, RIC-Nays, SOBEK, TELEMAC, TRENT and TUFLOW.

The questionnaire was distributed to specialist Environment Agency modelling staff, consultants on the Environment Agency's Strategic Flood Risk Management Framework, other individuals with specialist knowledge of value to the information-gathering process. A copy of the distribution list is provided in Appendix B.

A total of 21 completed questionnaires were returned, giving an 85 per cent return rate. This is considered satisfactory for the data-gathering purposes of this project.

3.2 Analysis of questionnaire results

3.2.1 Packages used

Figure 3.1 provides a summary of the packages currently used on Environment Agency flood risk management projects and their use. At the present time the top four are:

1. TUFLOW, WBM Pty.
2. InfoWorks RS/CS 2D, Wallingford Software Ltd.
3. Mike 21/Flood, DHI.
4. JFLOW, JBA Associates.

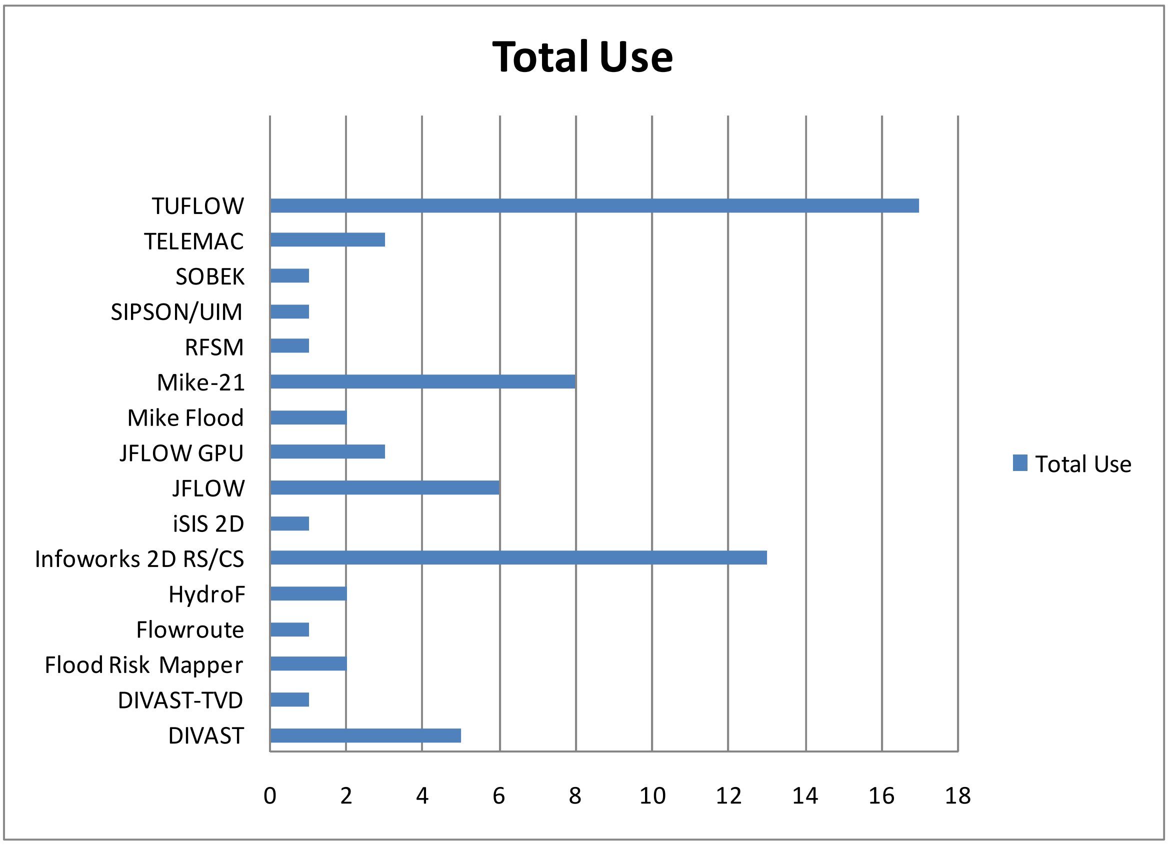

Figure 3.1: Number of respondents using each 2D flood inundation modelling package identified by questionnaire survey

3.2.2 Current use of 2D modelling packages

The current uses of 2D flood inundation modelling packages, as reported by those returning questionnaires, is summarised in Figure 5.2. This shows that 2D modelling packages are now employed across the full range of the Environment Agency's modelling requirements. Note that:

1. The frequency of use reported will depend upon the Environment Agency's priorities at the time of the questionnaire survey and one would expect this to change with time; for example, modelling of dam break scenarios will increase in frequency as the recommendations of the Pitt Review and the Water Resources Act (2003) are implemented.

2. It is surprising that flood warning has been identified as a potential use of 2D packages given their relatively long runtimes relative to other model types. It is likely that those reporting this are employing 2D models to improve faster 1D models or to train model emulators that are then used to provide simulations for flood warning purposes; alternatively, they may be being used to extend ratings at natural gauging locations where water spills from channel to floodplain.

3. Water quality and sediment transport predictions were also reported by some contractors. These have been included in Figure 3.1, as health issues from exposure to contaminated water and sediment is an increasingly important element of flood risk management. 2D flood inundation models have the potential to simulate the movement of both polluted water and contaminated sediments and these applications are likely to be more important in the future.

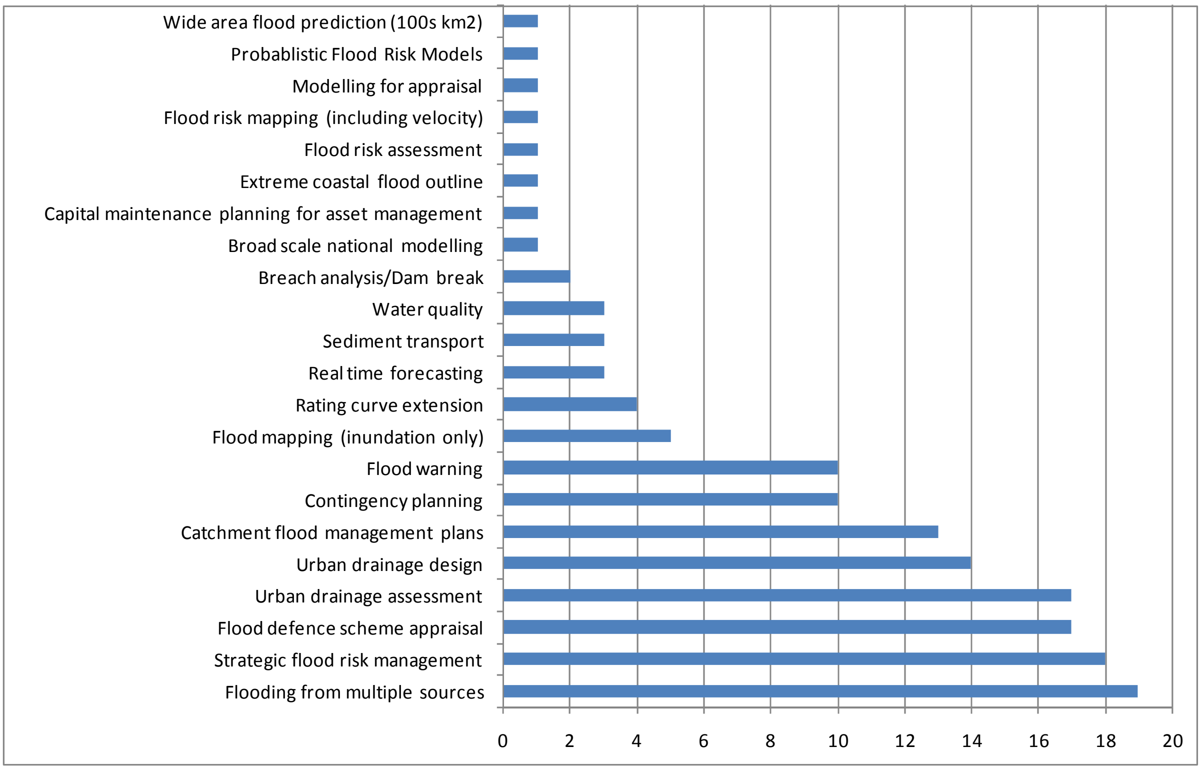

Figure 3.2: Flood risk management tasks benefitting from 2D flood inundation modelling

3.2.3 Resources required to set-up and run 2D models relative to 1D models

The questionnaire survey collected the views of Environment Agency staff and their contractors on the relative staff costs of setting up and running 2D flood inundation models compared with their 1D modelling equivalents. As it is extremely rare for 1D and 2D modelling packages to be applied to the same problem, the responses are based on judgement and experience rather than on hard data. The responses are summarised below.

Table 3.1: Comparison of resource required for 2D modelling relative to 1D modelling

Activity	Staff resource relative to 1D modelling package
Data collection	Less
Model set up	Less
Resolving data issues	Less
Model calibration	More
Model validation	Comparable
Setting up production runs	Comparable
Production runs	More
Reporting	Less
Staff training	More
Resolving software issues	Comparable

On balance it can be concluded that less staff resource is required to set up and run 2D hydraulic modelling packages compared to the 1D versions.

3.2.4 Package ratings

The questionnaire also collected information on the experience of Environment Agency staff and their consultants on running the 2D hydraulic modelling packages identified in Table 2.2. This was achieved by asking users to score package performance against the key indicators listed below. The scoring ranged between five (excellent) to one (poor). All packages identified in Section 3.2.1 received good ratings commensurate with their use on future Environment Agency projects, see Table 3.1. If business needs dictate an early decision on software investment, one way forward may be to invest in a multi-user licence for TUFLOW as this was the most commonly used package amongst Environment Agency consultants and staff responding to the questionnaire.

3.2.5 Budget costs

We obtained budget quotations from the vendors of TUFLOW, InfoWorks, Mike-Flood, ISIS 2D and JFLOW for:

1. Cost of a single licence.
2. Discount if 10 licences were purchased.
3. Discount if 50 licences were purchased.
4. Any additional costs associated with network implementation of multiple licences.
5. Annual cost of maintenance and support agreements for Options 1 to 3 above.
6. Length of recommended training courses to ensure user competence and cost for attendance at such a course for up to 10 attendees.

A wide range of options exist for obtaining value for money and all vendors were open to direct negotiation on costs. In broad terms, 10 licences would cost between £15,000 and £25,000, maintenance costs are typically between 10 and 20 per cent of licence costs. The recommended duration of training courses is two to three days at a cost of around £2,000 per day for ten participants.

Table 3.1: User ratings for most frequently used 2D hydraulic modelling packages (five is excellent, one is poor)

	TUFLOW		InfoWorks		Mike		JFLOW	
Criteria	**Ave. Rating**	**No. Resp.**	**Ave. Rating**	**No. Resp.**	**Ave. Rating**	**No. Resp.**	**Ave. Rating**	**No. Resp.**
User manual and technical reference	4.2	15	4.0	9	4.0	5	2.7	3
Technical support (including training)	4.0	15	4.2	9	4.0	5	4.0	3
Data compatibility	4.3	15	4.1	9	4.0	5	4.7	3
Flexibility of data input	4.0	15	4.1	8	3.8	5	1.7	3
Model setup	3.0	15	3.9	8	4.0	5	4.0	3
Adding structures	3.2	14	4.1	8	4.0	5	1.3	3
Run time	3.2	15	3.7	9	3.8	5	3.7	3
Stability	3.9	15	4.1	9	4.2	5	3.0	3
Presentation of flood depth and velocity predictions	3.6	14	4.0	9	4.4	5	0.7	3
Visualisation tools	2.6	14	4.6	9	4.8	5	3.0	3
File management	3.5	15	4.2	9	4.2	5	3.7	3
Sensitivity testing	3.1	13	3.3	7	4.0	3	3.3	3
Uncertainty analysis	2.8	10	2.5	4	1.7	3	4	2

4 Development of an outline specification for 2D model benchmarking

4.1 Objectives

The objectives of the benchmarking exercise are to provide:

1. An evidence base to ensure that 2D hydraulic modelling packages used for flood risk management, by the Environment Agency and its consultants, are capable of predicting the variables upon which flood risk management decisions are based.

2. A data set against which such packages can be evaluated by their developers.

To ensure these objectives can be met, the benchmarking data set must be easily accessible and well documented.

4.2 Inclusion of two-dimensional hydraulic modelling packages in benchmarking tests

Based on our analysis of questionnaire responses and targeted discussions with the Environment Agency's Strategic Flood Risk Management Framework contractors, we recommend that the following 2D hydraulic modelling packages should be included in the Stage 2 benchmarking exercise.

- InfoWorks 2D
- TUFLOW
- Mike 21
- JFLOW
- ISIS 2D

The first four packages in the list above are widely used on Environment Agency projects at the present time and there is no immediate reason why this will change. ISIS 2D is included as the widespread use of ISIS 1D in the Environment Agency suggests that ISIS 2D may also be popular in the future. However, the Phase 2 process will seek to include a range of additional software to cover a broad range of 2D model types. These will include other packages that are important to the Environment Agency (such as RFSM), and those frequently used by developers (such as Microdrainage Floodflow). Additionally, the tests will be available to all software developers and all the model manufacturers identified in Table 2.2 will be invited to participate along with any others subsequently identified.

4.3 Flood sources

Another factor to be considered in the selection of benchmark cases is the source of floodwater as this can determine important test parameters such as flood volume, rate of flood rise and the nature of the flood inflow. The most significant flood sources are listed below along with comments on their inundation characteristics.

4.3.1 Fluvial

With fluvial inundation on an undefended floodplain, the inundation occurs relatively slowly and there is normally a downward slope parallel to the river which means that the water will flow along the floodplain. Such inundation events are relatively easy to simulate using a 2D hydraulic modelling package, although linear features, such as roads, walls, hedges and embankments may add complications.

When the floodplain is defended and overtopping occurs this generally starts slowly, and is unlikely to become large unless defence failure occurs. The flood water is usually expected to pond on the defended floodplain rather than to flow back into the river. As with the undefended case the floodplain inundation is relatively easy to simulate using a 2D hydraulic modelling package, although in this case there may be areas of supercritical flow close to the overtopped defence. The extent of these areas is likely to be smaller than the typical numerical grid size and therefore not something that would be resolved by the 2D hydraulic model.

Fluvial inundation due to an embankment failure by breaching is a significantly more difficult case to model as supercritical flow conditions may exist for a considerable distance beyond the breach location. Boundary conditions are also highly uncertain as they depend on the breach location and the speed with which the breach develops.

4.3.2 Coastal flooding

The characteristics of coastal flooding are generally similar to fluvial flooding, with each of the three cases described above also relevant, although the rate of rise of storm surges can be significantly greater than a typical fluvial flood resulting in more rapid inundation events. Volume input arising from wave overtopping is an additional feature of coastal flooding that should be included in computer simulations, although the volume is generally significantly smaller than that arising from overtopping of embankment failure.

4.3.3 Sewer

The volume of water involved in sewer flooding is generally less than for fluvial and coastal floods. Such floods are characterised by multiple sources of surcharging, rapid increases in water level and relatively shallow flows along flow paths that are difficult to define *a priori*. Flood depths can become significant where a number of flow paths converge at a single low-lying location. Additionally, differences in capacity of the pipe system can result in flooding problems being transferred to locations remote from the original source. A further complication with such flood events is that elements of the drainage system are designed to different standards and can therefore lead to surcharging at a variety of rainfall intensities. For sewer flooding, modelling package capability to simulate dewatering operations through the simulation of pumping operations can be useful.

Table 4.1: Mapping of benchmark test case to model type and Environment Agency application

Application	Predictions required	Suitable model type	Relevant benchmark test
Large scale[1] flood mapping	i. inundation extent	1D, $1D^{+}$, $2D^{-}$, 2D	1 and 2
Catchment Flood Management Plan	ii. inundation extent iii. maximum depth	1D, $1D^{+}$, $2D^{-}$, 2D	1, 2 and 7
Flood Risk Assessment	i. inundation extent ii. maximum depth	1D, $1D^{+}$, $2D^{-}$, 2D	1, 2, 3 and 7
Strategic Flood Risk Assessment	i. inundation extent ii. maximum depth iii. maximum velocity	1D or 2D depending on level of flood hazard.	1, 2, 3 and 7
Flood Hazard Mapping	i. inundation extent ii. maximum depth iii. maximum velocity	2D	1, 2 3, 4, 7 and 8
Contingency planning for real-time flood risk management	i. temporal variation in inundation extent ii. temporal variation in depth iii. temporal variation in velocity	2D	1, 2 3, 4, 7 and 8
Reservoir Inundation Mapping	i. temporal variation in inundation extent ii. temporal variation in depth iii. temporal variation in velocity	2D	1, 2, 3, 4, 5, 6, 7 and 8

1 Large scale can extend to catchments of 100s km^2

4.3.4 Surface water

Surface water flooding is caused by high intensity rainfall directly onto the catchment. The issues in simulating surface water flooding are generally similar to sewer flooding with the additional requirements that the package must be able to a) accept input as a distributed rainfall field directly onto the model grid and b) handle the prediction of very shallow flows (depths of less than a few centimetres). Surface water flooding seldom occurs in isolation and an essential feature of modelling its significance is being able to simultaneously simulate inflows from other sources, such as surcharging drainage systems and water courses.

4.3.5 Groundwater

Groundwater flooding is generally characterised by very slow increases in flow and water level. When groundwater flooding occurs it can persist for long durations. It is not normally a type of flooding the one would wish to simulate using a 2D hydraulic modelling package but this could be appropriate when it occurs along with other sources.

4.3.6 Dam break and flash floods

Very rapid events characterised by complex hydraulics and changes of flow regime from subcritical flow to supercritical flow and back again. Simulating floods of this nature can be difficult with 2D hydraulic packages.

4.4 Approaches to benchmarking

There are a range of possible approaches to benchmarking including comparing hydraulic model predictions with analytical solutions, field data, physical model data and other model predictions of real or hypothetical flood events. Below we discuss the relative merits of each of these approaches.

4.4.1 Analytical solutions

One approach to benchmarking is to undertake simulations of test cases where analytical solutions already exist. In the case of 2D inundation models this is useful for code testing and debugging; however, analytical solutions are only available for relatively simple geometries and boundary conditions. Consequently, they are of limited value for assessing modelling package performance in a practical sense, where the package's ability to simulate flow over large complex digital terrain models is an essential characteristic. Potential benchmarking case studies in this category include:

1. Transcritical flow over a bump reported in Liang *et al.* (2006), Begnudelli and Sanders (2006), Caleffi *et al*. (2003), Liang and Borthwick (2009).
2. Dam break as derived by Stocker (1957) and used in Namin *et al*. (2004), Begnudelli and Sanders (2006) and Guitierres Andres *et al.* (2008). The test can be undertaken with both initially wet and dry beds. Gutierres Andres *et al.* (2008) also used a circular dam break for which a pseudo-analytical solution exists from LeVeque (2002).

4.4.2 Simulation of simplified hydraulic processes

Previously applied tests in this category include:

1. Qualitative tests, such as those described in the TELEMAC validation document (EDF 2000) including: simulating flow around bridge piers (tests for asymmetry and vortex generation) and wave propagation in a channel with a series of sills (tests package's ability to cope with discounted domains and that back water curves from individual reaches are simulated correctly).
2. Uncovering of a beach applies equally to coastal and fluvial modelling and essentially tests the package's ability to simulate flooding and drying while conserving mass within the model.
3. Water at rest over an irregular terrain (Gutierres Andres *et al.* 2008), some of which emerges above the water level. The expectation is that the water surface remains flat, which is not always the case and depends on the numerical method employed.
4. Transcritical flow over an irregular channel bed was used by Liang *et al.* (2006); a constant discharge is applied in a channel with an irregular profile (although uniform in the transverse direction). There are critical transitions at several locations down the channel and the discharge at each section is expected to remain constant and uniform.

4.4.3 Field data

Alternatively, computer models can be benchmarked against data from an observed flood inundation event, for example the Malpasset dam break detailed by Hervouet (2007) and used by Liang *et al.* (2007). However, this poses a number of problems:

1. Available data is usually limited to observations of flood extent and maximum water level collected by surveying wrack and water marks after the flood has subsided, limiting assessment of model performance to a comparison of maximum inundation, although recent developments in the use of Synthetic Aperture Radar and aerial photography have enabled comparisons of temporal variations in flood extent, see Bates *et al.* (2006), Néelz *et al.* (2006).

2. Field data sets that include measurements of velocity are extremely rare and where such data does exist, it is limited to point locations.

3. The magnitude of errors in observed data can be significant. This is particularly true where the data is collected post flood. In such cases, data errors are likely to be at least as large as the difference between models constructed using different modelling packages.

4. There are usually large uncertainties in appropriate values for upstream and downstream boundary conditions for observed events. The contribution of inflow from minor tributaries, groundwater and surface water flooding components may also be unknown.

5. Information on important topographic details (walls, drainage pathways, hedges, fences and so on) is often not captured in the floodplain DTM. These can have a profound influence on flow routes and inundation patterns and are extremely difficult and costly to collect. The performance of such 'assets' is difficult to predict under flood conditions, as they were not purpose built so defences may 'fail' at any stage of an event.

6. The details of the operation of flood defence infrastructure, construction of temporary defences, infrastructure failure and debris blockage are other unknowns that can have a significant impact on flood inundation.

Benchmarking using field data is more often a test of how much one knows about the event and in how much detail one models it, than a test of the modelling package. As discussed below, however, there is merit in using field-scale cases for benchmarking providing one accepts that the purpose of the exercise is to evaluate modelling package performance against predetermined criteria, rather than an exercise in accurately modelling a particular flood.

4.4.4 Physical model data

Physical model data presents an alternative to measured field data and to some extent overcomes the issues associated with errors in observed data, as measurements are considerably easier in a controlled laboratory environment. "Easier" is relative to field data collection as the accurate data collection in physical model experiments can also be problematic due to difficulties with instrument access, reliability and scale effects when measuring water velocities. A further limitation of using laboratory data for 2D hydraulic model benchmarking is its small scale, which can cause significant numerical problems due to extremely small flow depths and a disproportionately large influence of bed friction. A significant library of possible physical model test cases has been collected by the CADAM project (CADAM 2000, includes a 1:100 scale model of a reach of the Toce river valley, and a dam break simulation in a rectangular channel with a 45^o bend), the IMPACT project (IMPACT 2005, includes the isolated building cases used by Soares-Frazao and Zech 2002, the model city case used by Alcrudo *et al.* 2003 and dam break flow over a triangular bottom sill, Soares-Frazao *el al.* 2002), and Delft University of Technology dyke break experiment (Stelling and Duinmeijer 2003).

4.4.5 Optimising 2D model benchmarking procedure

The cost of benchmarking in the second phase of this project will increase with the number of test cases recommended. We therefore recommend seven benchmark test cases, designed to use all of the opportunities for model benchmarking discussed and to evaluate software performance against one or more of the Environment Agency's modelling requirements listed in Table 4.1. In addition, a sub-set of the test cases are designed to evaluate code functionality when working with real world data.

4.5 Benchmarking test cases

In addition to evaluating package performance in simulating the hydraulics of inundation the benchmarking exercise will need to capture information on ancillary software necessary to prepare input data and analyse model output, for example, MapInfo and ArcGIS. This is important as it may have significant cost implications for the Environment Agency's in-house investment through licence and training costs.

4.5.1 Test 1 – Uncovering of a beach

Description

This test consists of a sloping topography with a depression as illustrated in Figure 4.1. An inflow boundary condition is applied at the low end, causing the water to rise to the level indicated by a thick blue line. The inflow is then replaced by a sink term until the water level becomes as indicated by the thin blue line. A similar test has been used by EDF (2000) for validation of the TELEMAC package.

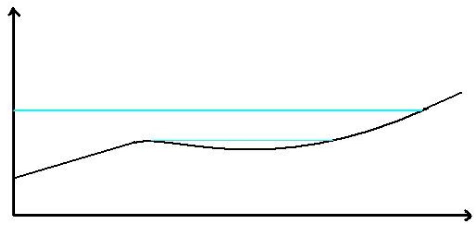

Figure 4.1: Sloping topography with depression

Modelling performance tested

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

Required output from test

i. Time increment used, grid resolution and total simulation time.
ii. Final water volume.
iii. Water level in the pond.
iv. Standard deviation of elevation in inundated cells in final state (which should be zero).

4.5.2 Test 2 – Depression filling

Description

The DTM shown in Figure 4.2 consists of a series of depressions of equal volume with an under-lying slope of 0.001 west to east and north to south. The inflow boundary condition is a symmetrical flood hydrograph with a peak flow of 10 m^3 per second and time base of six hours entering the DTM at the northwest corner.

Modelling package performance tested

The test has been designed to evaluate each package's capability to determine inundation extent and final flood depth.

Required output from test

i Time increment used, grid resolution and total simulation time.
ii Contour plot showing final inundation extent and predicted flood depth over DTM.
iii Numerical prediction of flood depth at the centre of each cell.

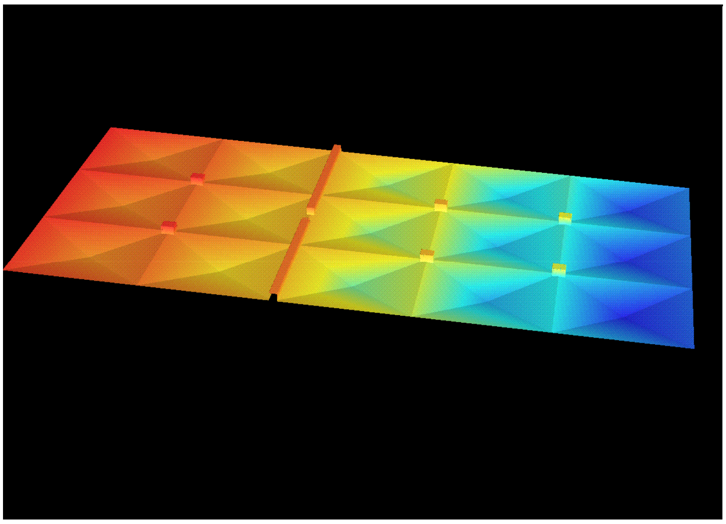

Figure 4.2: DTM for depression Filling

4.5.3 Test 3 – Crossing channels

Description

The DTM shown in Figure 4.3 is one km by one km and consists of two 300 mm deep channels running north to south and west to east. The slope on the north to south channel is 0.001 and the west to east channel is horizontal. In the north-south channel, there is a small 100 mm barrier to flow downstream of the location where the channels cross. Two separate tests will be conducted with different boundary conditions. Test 3(a) will use an inflow hydrograph entering the north-south channel at the northern end. The symmetrical hydrograph has a peak flow of 10 m^3/s and a time base of 45 minutes. Test 3(b) will use a distributed rainfall input of 20 mm/hour for one hour over the northern most 35 per cent of the DTM.

Modelling package performance tested

The case tests the package's capacity to simulate the movement of flood water flowing at relatively low depths in shallow channels. This capability is important when simulating sewer or surface water flooding in urbanised floodplains. The barrier to flow in the north-south channel is designed to differentiate the performance of 2D cellular packages (without inertia terms) and 2D hydrodynamic packages (with inertia terms). With inertia terms, the flood water will pass over the barrier and continue in a north-south direction; without inertia terms, the water will spread in a lateral west-east direction.

Required output from test

i. Time increment used, grid resolution and total simulation time.
ii. Graphical plots and numerical predictions of velocity and water level versus time at four locations (two either side of the crossing point) on the centre line of each channel.
iii. Contour plot of maximum inundation extent and depth over the DTM.

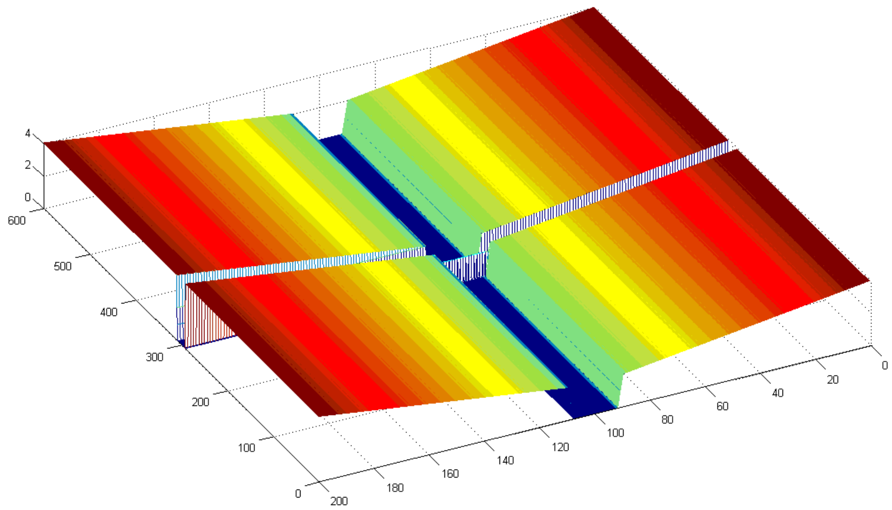

Figure 4.3: DTM including crossing channels

4.5.4 Test 4 – Rate of flood propagation over extended floodplains

Description

This test is designed to simulate the rate of flood wave propagation over a relatively wide floodplain following a defence failure. The DTM is one km by one km as shown in Figure 4.4. The floodplain surface is horizontal and two inflow boundary conditions will be used. The first to simulate fluvial flooding will be an inflow hydrograph through the breach location with a peak flow of 10 m^3/s and time base of six hours, the second to simulate tidal flooding will be two inflow hydrographs with peaks of 5 m^3/s and time based of four hours with their peaks separated by 12 hours.

Modelling package performance tested

This tests the package's capacity to simulate the speed of movement of the flood wave and the velocities at the leading edge of the advancing flood boundary and is relevant to fluvial and coastal inundation resulting from breached embankments.

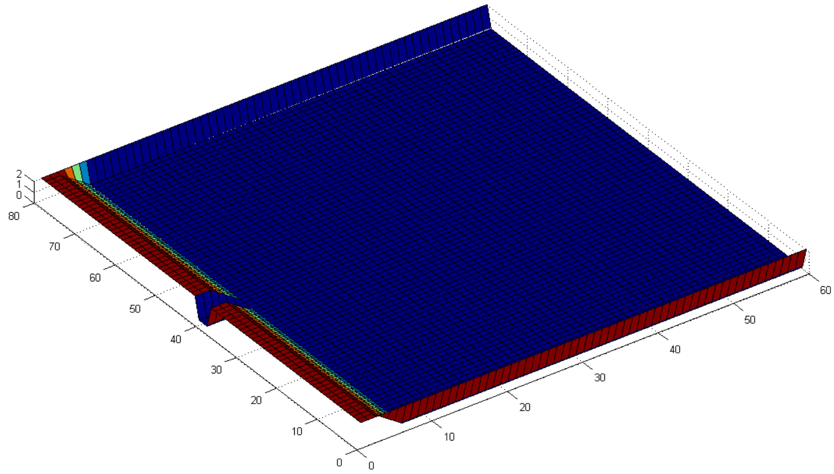

Figure 4.4: Extended floodplain DTM

Required output from test

i. Time increment used, grid resolution and total simulation time.
ii. Contour plots of inundation extent and depth at three suitable times during the advance of the flood wave.
iii. Plots of the 2D velocity field at three suitable times during the advance of the flood wave and coincident with those used in ii above.
iv. Plots of velocity versus time at four equally spaced locations in line with the breach location.

4.5.5 Test 5 – Valley flooding following dam failure

Description

This test is designed to simulate flood wave propagation down a river valley following failure of a dam. The DTM is two km by 10 km and the valley slopes downstream on a slope of 0.01. The inflow hydrograph at the upstream end will be designed to account for a typical failure of a clay core embankment dam and to ensure that both supercritical and subcritical flows will occur in different parts of the flow field.

Modelling package performance tested

This tests the package's capacity to simulate major flood inundation and predict flood hazard arising from dam failure.

Required output from test

i. Time increment used, grid resolution and total simulation time.
ii. Contour plots of inundation extent and depth at three suitable times during the advance of the flood wave.
iii. Plots of the 2D velocity field at three suitable times during the advance of the flood wave and coincident with those used in ii above.
iv. Plots of velocity versus time at four equally spaced locations in line with the breach location.

4.5.6 Test 6 – Dam break

Description

This dam-break test case has been selected from the data available from the IMPACT project (IMPACT, 2004). The purpose is to validate 2D hydrodynamic packages against a data set involving transient flow in complex topographies. Downstream of the dam is an idealised representation of a single building, Figure 4.5.

Modelling package performance tested

The fact that the building is neither centred in the channel, nor aligned with the flow direction means successful simulation requires the package to correctly simulate hydraulic jumps and the wake zone behind the building (Soares-Frazao and Zech, 2007).

Required output

i. Time increment used, grid resolution and total simulation time.
ii. Contour plots of inundation extent and depth at one, three and 10 seconds after the dam break.
iii. Plots of the water level versus time at locations G1 to G6 in Figure 4.5. These to be compared with measured values from the physical model.

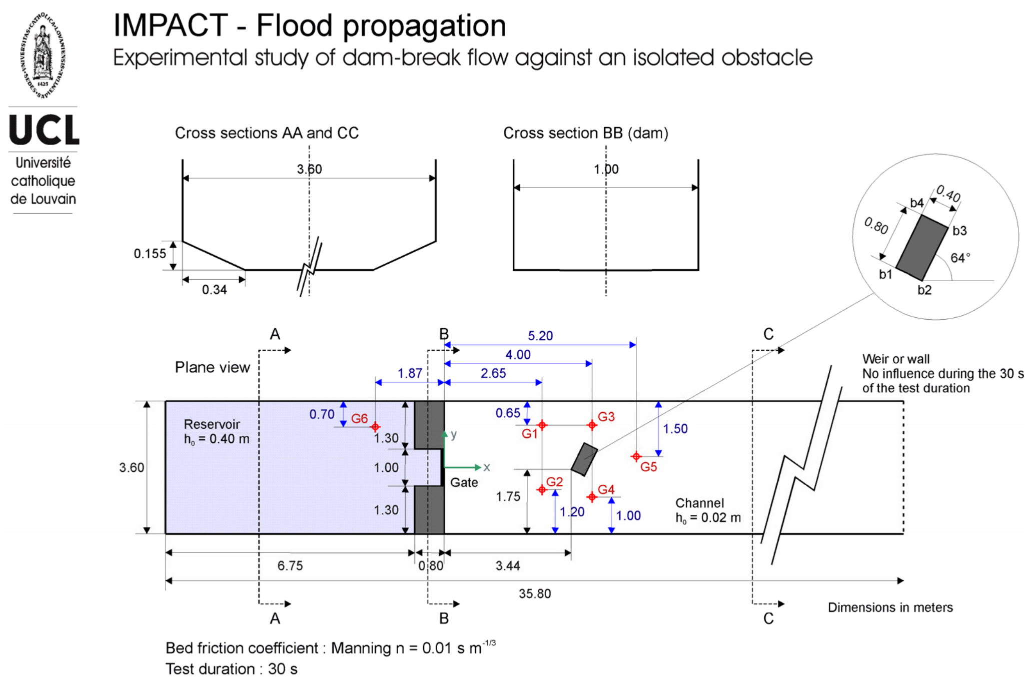

Figure 4.5: Dam-break test case

4.5.7 Test 7 – Upton-upon-Severn

Description

The site to be modelled is approximately six km long by 1.5 km wide, Figure 4.6. This test will evaluate the package's capacity to simulate fluvial flooding in a relatively large river using existing field data for the November 2000 flood in the River Severn. The test can also be used to evaluate 1D to 2D model linking within the packages. Boundary conditions are an inflow hydrograph for the River Severn, tributary inflows hydrographs, and a downstream rating curve. This example poses a relatively challenging test as the model needs to adequately identify and simulate flooding along separate floodplain flow paths, where Upton-upon-Severn is located on raised ground which functions as an island for part of the flood event. The site has been subjected to flooding on a number of occasions but it is not the intention to replicate an observed flood for this exercise, hence the upstream and tributary boundary conditions have been designed to provide a suitable benchmarking case.

Modelling package performance tested

This test case evaluates the package's capability to simulate exchange of flood volume between the main channel and the floodplain and fluvial flooding on a largely rural floodplain for flood mapping and flood risk assessment purposes.

Figure 4.6: Upton-on-Severn test site

Required outputs from test

i. Time increment used, grid resolution and total simulation time.
ii. Contour plots of inundation extent and depth at six suitable times during the rising (three plots, including one when the flood extent has reached its maximum extent) and falling limb (three plots) of the flood.
iii. Plots of the 2D velocity field at six suitable times during the rising (three plots) and falling limb (three plots) of the flood and coincident with those used in ii above.
iv. Plots of water level versus time predictions at eight locations distributed across the floodplain.

4.5.8 Test 8 – Greenfield, Glasgow

Description

This test will evaluate the package's capacity to simulate sewer and surface water flooding in an urbanised area at relatively shallow flow depth. The DTM approximately 0.5 km by one km is shown in Figure 4.7. For Test 8(a) the inflow boundary condition is an inflow hydrograph arising from the simulation of culvert blockage and entering at the north-east corner of the DTM. The details of culvert blockage are to be designed to create a symmetrical hydrograph with peak flow of approximately 10 m^3/s and a time base of 45 minutes discharging in the 2D domain. In Test 8(b) the inflow to the 2D domain arises from surcharging of an underlying sub-surface sewer system. The boundary conditions for the sewer model will be designed to create a surcharge hydrograph with a peak flow of 5 m^3/s and a time base of one hour; coincident with this, a distributed rainfall event of 15 mm/hour for one hour will occur over the whole DTM.

Modelling package performance tested

The relatively shallow flow depths pose a challenge to some packages as they generate spurious numerical oscillations. Further, while we would expect most packages to predict the final extent in the south-west corner with sufficient accuracy, prediction of the routes travelled by the flood and the velocities with which the water flows through the DTM can be evaluated.

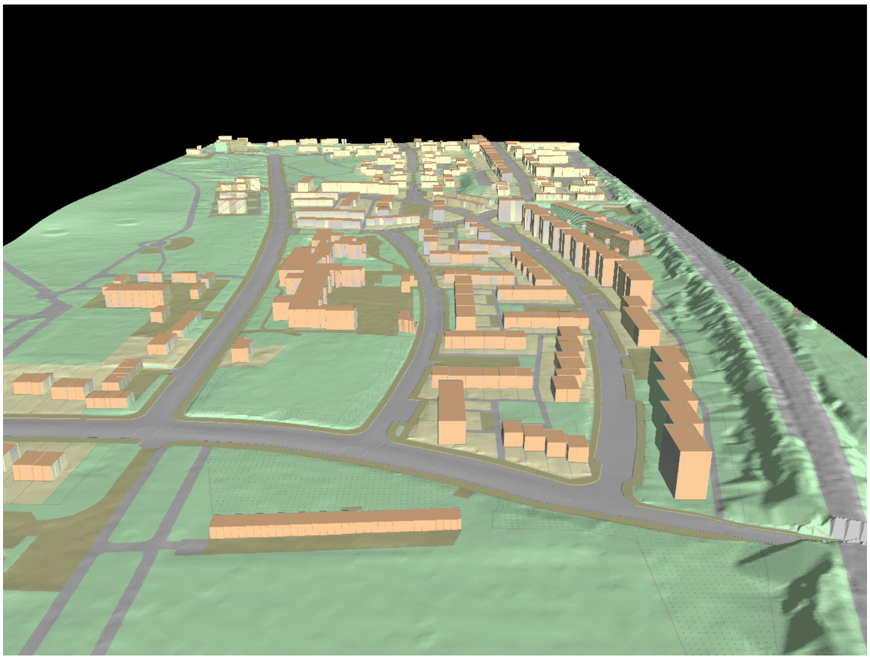
Figure 4.7: Urbanised area DTM

Required output

i. Time increment used, grid resolution and total simulation time.
ii. A contour plot of final inundation extent and depth.
iii. Plots of velocity versus time and water level versus time at five locations on the road network defining the flow paths though the DTM.
iv. Plots of flow (integrated across the flow path defined by the road) versus time at five locations on the road network defining the flow paths through the DTM.

5 Conclusions

1. Two-dimensional hydraulic models are widely used by the Environment Agency's contractors for the full range of flood sources and potential model applications detailed in Section 1. In most cases these models are suitable for the uses to which they are being applied; however, the theory upon which 2D and 2D- packages are based suggests that predictions using these alternative approaches will differ where acceleration terms are significant. To translate this theoretical analysis into practical guidance, it is recommended that the benchmarking detailed in Chapter 4 is undertaken at the earliest opportunity.

2. The benchmarking test case studies recommended here have been designed to focus on testing the practical application of 2D hydraulic modelling packages and Table 4.1 indicates how these map onto Environment Agency modelling needs in flood risk modelling and management. The upcoming requirement to simulate inundation extent for dam break flooding suggests that packages' capability to model super and subcritical flows may become more significant than at present. Benchmarking Test 6 has been designed to discriminate between the performance of each package for this application.

3. The results from the questionnaire survey indicate that the packages most commonly used on Environment Agency contracts (TUFLOW, InfoWorks, Mike-Flood and JFLOW) possess the features necessary to satisfy Environment Agency requirements and that a reasonable level of technical support is available from each vendor. We would therefore advise against selecting a single 2D hydraulic modelling package for Environment Agency contracts, as value for money will be achieved best from competitive tendering allowing contractors freedom of choice with regard to 2D modelling package.

4. In terms of the use of existing models within the Environment Agency, there is evidence from the questionnaire analysis and other sources that expertise currently exists within the Environment Agency in the application of the most commonly used 2D hydraulic modelling packages. Therefore, provided package use remains confined to around six packages, it will remain possible to continue making best use of previous investment in model development.

5. Quotations from vendors indicate that a wide range of options exist for obtaining value for money when purchasing package licences. A number of vendors are open to direct negotiation on costs. In broad terms, 10 licences would cost between £15,000 and £25,000, maintenance costs are typically between 10 and 20 per cent of licence costs. The recommended duration of training courses is two to three days at a cost of around £2,000 for ten participants.

6. The Environment Agency should complete the second phase of benchmarking described in Section 4 prior to deciding on which 2D inundation modelling package to adopt for in-house use. However, if business needs dictate an early decision, the range of application and popularity of the existing TUFLOW software (marketed by BMT-WBM) suggests that the purchase of a multi-user licence for this package would be a relatively safe short-term investment. Such an investment would also require the purchase of MapInfo licences for data set up and result visualisation and access to the freeware SMS for visualisation of 2D results.

References

ALCRUDO. F., GARCIA, P., BRUFAU, P., MURILLO, J., GARCIA, D., MULET, J., TESTA, G. AND ZUCCALA, D., 2003 *The Model City Flooding Experiment*. IMPACT project technical report.

ALCRUDO, F., 2004 *A state of the art review on mathematical modelling of flood propagation.* IMPACT project.

ALCRUDO, F. AND MULET, J., 2005. *Urban inundation models based on the Shallow Water equations. Numerical and practical issues*. Finite Volumes for Complex Applications IV: Problems and Perspectives. Wiley-ISTE.

ALCRUDO, F. AND MULET, J., *Conclusions and Recommendations from the IMPACT Project WP3: Flood Propagation.* IMPACT project. http://www.impact-project.net/wp3_technical.htm

ARONICA, G., HANKIN, B., BEVEN, K.J., 1998. Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. *Advances in Water Resources*, 22 (4), 349-365.

ASSELMAN, N.E.M., MIDDELKOOP, H., RITZEN, M.R. AND STRAATSMA, M.W., 2002. *Assessment of the hydraulic roughness of river floodplains using laser altimetry. The structure, function and management implications of fluvial sedimentary systems* IHAS Publication, 276, 381-388.

BARRE DE ST-VENANT, A.J.C., 1871. Théorie du mouvement non-permanent des eaux avec application aux crues des rivières et à l'introduction des marées dans leur lits. *Compt. Rend*., 73 (147-154), 237-240.

BATES, P.D., 2004. Remote sensing and flood inundation modelling. *Hydrological Processes*, 18, 2593-2597.

BATES, P.D., MARKS, K.J. AND HORRITT, M.S., 2003. Optimal use of high-resolution topographic data in flood inundation models. *Hydrological Processes*, 17, 5237-557.

BATES P.D. AND HORRITT M.S., 2005. Modelling wetting and drying processes in hydraulic models. In Bates, P.D., Lane, S.N., Ferguson, R.I. (editors), *Computational Fluid Dynamics: Applications in Environmental Hydraulics.* Wiley, Chichester.

BATES P.D., HORRITT M.S., WILSON M.D. AND HUNTER N.M., 2005. *LISFLOOD-FP. User manual and technical note.* University of Bristol.

BATES P.D., WILSON M.D., HORRITT M.S., MASON D.C., HOLDEN N. AND CURRIE A., 2006. Reach scale floodplain inundation dynamics observed using airborne synthetic aperture radar imagery: Data analysis and modelling. *Journal of Hydrology*, 328(1-2), 306-318.

BEGNUDELLI, L. AND SANDERS, B.F., 2006. Unstructured grid finite-volume algorithm for shallow-water flow and scalar transport with wetting and drying. *Journal of Hydraulic Engineering*, 132(4), 371-384.

BEVEN, K.J., 2000. Uniqueness of place and process representations in hydrological modeling. *Hydrology and Earth System Sciences* 4 (2), 203-213.

BEVEN, K.J., 2006. A manifesto for the equifinality thesis. *Journal of Hydrology*, 320 (1-2), 18-36.

BEVEN, K.J., YOUNG, P, LEEDAL, D. AND ROMANOWICZ, R., 2008. Computationally efficient flood water level prediction (with uncertainty). In *Flood Risk Management: Research and Practice* – Samuels et al. (editors). Taylor and Francis Group, London.

BMT-WBM, 2008 *TUFLOW User Manual*.

BRADBROOK, K.F., LANE, S.N., WALLER, S.G. AND BATES, P.D., 2004. Two dimensional diffusion wave modelling of flood inundation using a simplified channel representation. *Journal of River Basin Management*, 2 (3), 1-13.

BRADBROOK, K. F., WALLER, S. G. AND MORRIS, D., 2005. National floodplain mapping: datasets and methods - 160,000 km in 12 months. *Journal of Natural Hazards*, 36(1-2), 103-123.

BRUFAU, P., GARCÍA-NAVARRO, P. AND VÁZQUEZ-CENDÓN, M.E., 2002. A numerical model for the flooding and drying of irregular domains. International Journal for Numerical Methods in Fluids, 39, 247-275.

CADAM, 2000. *Concerted action on dam-break modelling*. Final report.

CALEFFI, V., VALIANI, A., AND ZANNI, A., 2003. Finite volume method for simulating extreme flood events in natural channels. *Journal Hydraulic Research*, 41(2), 167-177.

COBBY, D.M., MASON, D.C., HORRITT, M.S. AND BATES, P.D., 2003. Two-dimensional hydraulic flood modelling using a finite-element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry. *Hydrological Processes*,17, 1979-2000.

CUNGE J., 2003. Of data and models. *Journal of hydroinformatics*, 5 (2), 75-98. Comments by Hall J. and response by Cunge J. in 6(1), 2004.

Danish Hydraulic Institute (DHI), 2007a. *MIKE Flood User Manual*. Copenhagen, Denmark.

Danish Hydraulic Institute (DHI), 2007b. *MIKE 21 & MIKE 3 Flow model FM.* Copenhagen, Denmark.

EDF (Electricité de France), 2000. TELEMAC 2D Validation document [online]. Available from: http://www.telemacsystem.com/internat/validtel2d50/sld001.htm

FEWTRELL, T., BATES, P.D., HORRITT, M.S. AND HUNTER, N.M., 2008. Evaluating the effect of scale in flood inundation modelling in urban environments. *Hydrological Processes*, 22, 5107-5118.

EVANS, E.P., WICKS, J.M., WHITLOW, C.D., AND RAMSBOTTOM, D.M., 2007. The evolution of a river modelling system. *Proceedings of the Institution of Civil Engineers, Water Management,* 160 (WM1), 3-13.

FLOODsite Project, 2008. *Task 8 - Flood Inundation Modelling; Model Choice and Proper Application.* Report.

FRENCH, J.R., 2003. Airborne LiDAR in support of geomorphological and hydraulic modelling. *Earth Surface Processes and Landforms*, 28 (3), 321-335.

GARCIA-NAVARRO, P. AND VAZQUEZ-CENDON, M., 2000. On numerical treatment of the source terms in the shallow water equations. *Computer & Fluids*, 29(8), 951-979.

GOULDBY, B., SAYERS, P., MULET-MARTI, J., HASSAN, M. AND BENWELL, D., 2008. A methodology for regional scale flood risk assessment. *Proceedings of the Institution of Civil Engineers. Water Management*, 161 (WM3), 169-182.

GUTIERRES ANDRES, J. AND RAYNER, C., 2007. *A comparison of 1D and 2D flooding analysis from the Brechin case study.* WaPUG autumn conference.

GUTIERRES ANDRES, J., LHOMME J., WEISBERGER, A., COOPER, A., AND GOULDBY, B., 2008. Testing and application of a practical new 2D hydrodynamic model. In *Flood Risk Management: Research and Practice* – Samuels et al. (editors). Taylor and Francis Group, London.

HERVOUET, J.M., 2007. *Hydrodynamics of Free Surface Flows*. First Edition, John Wiley and Sons, Press 2007, ISBN-13: 978-0-470-03558-0.

HR WALLINGFORD, 2003. *Reducing Uncertainty in River Flood Conveyance: Interim Report 3, Review of Methods for Estimating Conveyance*. Project W5A-057, HR Wallingford Ltd.

HORRITT, M.S., 2005. Parameterisation, validation and uncertainty analysis of CFD models of fluvial and flood hydraulics in the natural environment. In Bates, P.D., Lane, S.N., Ferguson, R.I. (editors), *Computational Fluid Dynamics: Applications in Environmental Hydraulics.* Wiley, Chichester.

HORRITT, M.S. AND BATES, P.D., 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation, *Journal of Hydrology*, 268 (1-4), 87-99.

HUNTER, N.M., BATES, P.D., HORRITT, M.S. AND WILSON, M.D., 2006. Improved simulation of flood flows using storage cell models. *Proceedings of the Institution of Civil Engineers, Water Management*, 159 (1), 9-18.

HUNTER, N.M., HORRITT, M.S., BATES, P.D., WILSON, M.D. AND WERNER, M.G.F., 2005. An adaptive time step solution for raster-based storage cell modelling of floodplain inundation. *Advances in Water Resources*, 28, 975-991.

HUNTER, N.M., BATES, P.D., HORRITT, M.S., DE ROO, A.P.J., AND WERNER, M.G.F., 2005. Utility of different data types for calibrating flood inundation models within a GLUE framework. *Hydrology and Earth System Sciences*, 9 (4), 412-430.

HUNTER, N.M., BATES, P.D., HORRITT, M.S. AND WILSON, M.D., 2007. Simple spatially-distributed models for predicting flood inundation: A review. *Geomorphology*, 90 (3-4), 208-225.

HUNTER, N.M., BATES, P.D., NEELZ, S., PENDER, G., VILLANUEVA, I., WRIGHT, N.G., LIANG, D., FALCONER, R.A., LIN, B., WALLER, S., CROSSLEY, A.J. AND MASON, D.C., 2008. Benchmarking 2D hydraulic models for urban flooding. *Proceedings of the Institution of Civil Engineers. Water Management*, 161 (1),13-30.

IMPACT, 2005 *Investigation of Extreme Flood Processes and Uncertainty*. Final Technical Report.

JULIEN, P., 2002. *River mechanics*. Cambridge University Press.

KRAMER, S.C. AND STELLING, G.S., 2008. A conservative unstructured scheme for rapidly varied flows. *International Journal for Numerical Methods in Fluids*, 58 (2), 183-212.

LANE, S., 2005a. A framework for model verification and validation of CFD schemes in natural open channel flows. In Bates, P.D., Lane, S.N., Ferguson, R.I. (editors), *Computational Fluid Dynamics: Applications in Environmental Hydraulics*. Wiley, Chichester.

LANE, S., 2005b. Modelling reach-scale fluvial flows. In Bates, P.D., Lane, S.N., Ferguson, R.I. (editors), *Computational Fluid Dynamics: Applications in Environmental Hydraulics.* Wiley, Chichester.

LEVEQUE, R.J., 2002. *Finite Volume Methods for Hyperbolic Problems*. Cambridge: Cambridge University Press.

LAMB, R., MANTZ, P., ATABAY, S., BENN, J. AND PEPPER, A., 2006. *Recent advances in modelling flood water levels at bridges and culverts.* Defra Flood and Coastal Risk Management Conference.

LHOMME, J., BOUVIER, C., MIGNOT, E., PAQUIER, A., 2005. *One-dimensional GIS-based model compared to two-dimensional model in urban floods simulation*. Tenth International Conference on Urban Drainage, Copenhagen/Denmark,

LIANG, D., FALCONER, R., AND LIN, B., 2006. Comparison between TVD-MacCormack and ADI-type solvers of the shallow water equations. *Advances in Water Resources*, 29, 1833-1845.

LIANG, D., LIN, B., AND FALCONER, R., 2007a. A boundary-fitted numerical model for flood routing with shock-capturing capability. *Journal of Hydrology*, 332, 477-486.

LIANG, D., FALCONER, R., AND LIN, B., 2007b. Linking one- and two-dimensional models for free surface flows. *Proceedings of the Institution of Civil Engineers, Journal of Water Management,* 160(3), 145-151*.*

LIANG, Q., DU, G., HALL, J. AND BORTHWICK, A., 2008. Flood inundation modelling with an adaptive quadtree grid shallow water equation solver. *Journal of Hydraulic Engineering*, ASCE, 34 (11), 1603-1610.

LIANG, Q. AND BORTHWICK, A., 2009. Adaptive quadtree simulation of shallow flows with wet–dry fronts over complex topography. *Computer & Fluids*, 38, 221-234.

LIN, B., WICKS, J. M., FALCONER, R. A. AND ADAMS, K., 2006. Integrating 1D and 2D hydrodynamic models for flood simulation. *Proceedings of the Institution of Civil Engineers, Water Management*, 159 (1), 19-25.

MASON, D. C., HORRITT, M.S., HUNTER, N.M. AND BATES, P.D., 2007. Use of fused airborne scanning laser altimetry and digital map data for urban flood modelling. *Hydrological Processes*, 21, 1436-1477.

MASON, D.C., COBBY, D.M., HORRITT, M.S. AND BATES, P.D., 2003. Floodplain friction parameterization in two-dimensional river flood models using vegetation heights from airborne scanning laser altimetry. *Hydrological Processes,* 17, 1711-1732.

MORVAN, H.P., KNIGHT, D.W., WRIGHT, N.G., TANG, X.N. AND CROSSLEY, A.J., 2008. The concept of roughness in fluvial hydraulics and its formulation in 1-D, 2-D and 3-D numerical simulation models. *Journal of Hydraulic Research*, 46(2), 191-208.

MORRIS, A., INGRAM, D. AND MINGHAM, C., 2006. *Two-dimensional flood simulation using the cartesian cut-cell method.* Seventh International Conference on Hydroinformatics, HIC 2006, Nice, France.

NAMIN, M., LIN, B. AND FALCONER, R.A., 2004. Modelling estuarine and coastal flows using an unstructured triangular finite volume algorithm. *Advances in Water Resources*, 27(12), 1179-1197.

NÉELZ, S., PENDER, G., VILLANUEVA, I., WILSON, M.D., WRIGHT, N., BATES, P.D., MASON, D. AND WHITLOW, C., 2006. Using remotely sensed data to support flood modelling. *Proceedings of the Institution of Civil Engineers, Journal of Water Management*, 159 (1), 35-43.

NÉELZ, S. AND PENDER, G., 2007. *Parameterisation of square-grid hydrodynamic models of inundation in the urban area*. Proceedings of the 32nd IAHR congress.

OTTOSEN, N.S. AND PETERSSON, H., 1992. *Introduction to the Finite Element Method.* Prentice Hall.

OWEN, S.J. AND SHEPHARD, M.S., 2003. Trends in Unstructured Mesh Generation. *Special Issue: International Journal for Numerical Methods in Engineering*, 58 (2),159-160.

PAPPENBERGER, F., BEVEN, K.J., HORRITT, M.S., AND BLAZKOVA, S., 2005. Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations, *Journal of Hydrology*, 302 (1-4), 46-69.

PENDER, G., 2006. Briefing: Introducing Flood Risk Management Research Consortium. *Proceedings of the Institution of Civil Engineers, Water Management*, 159 (WM1), 3-8.

RESCDAM, 2000. *The use of physical models in dam-break flood analysis. Rescue actions based on dam-break flood analysis*. Final report of Helsinki University of Technology, Helsinki, Finland.

RODI, W., 1980. *Turbulence Models and their Application in Hydraulics*. IAHR, Delft.

ROE, P., 1981. Approximate Riemann solvers, parameter vectors and difference schemes. *Journal of Computational Physics*, 43, 357-372.

SAMUELS, P., 2006. E-mail to the IAHR Rivers-list [online], available from: http://www.iahr.org/newsweb/

SAMUELS, P., BRAMLEY, M. AND EVANS, E., 2002. *A New Conveyance Estimation System.* Defra Flood and Coastal Risk Management Conference.

SANDERS, B.F., SCHUBERT, J.E., GALLEGOS, H.A., 2008. Integral formulation of shallow-water equations with anisotropic porosity for urban flood modelling. *Journal of Hydrology*, 362, 19-38.

SAUVAGET, P., DAVID, E., DEMMERLE, D. AND LEFORT, P., 2000. Optimum design of a large flood relief culvert under the A89 motorway in the Dordogne-Isle confluence floodplain. *Hydrological Processes*, 14 (13), 2311-2329.

SCHUBERT, J.E., SANDERS, B.F., SMITH, M.J. AND WRIGHT, N.G., 2008. Unstructured mesh generation and landcover-based resistance for hydrodynamic modeling of urban flooding. *Advances in Water Resources*, 31 (12), 1603-1621.

SHEWCHUK, J.R., 1996. Triangle: engineering a 2D quality mesh generator and Delaunay triangulator. Applied computational geometry: towards geometric engineering. In: Lin, M.C., Manocha, D. (editors), *Lecture Notes in Computer Science*, Springer-Verlag, 1148, 203-222.

SLEIGH, P.A., BERZINS, M., GASKELL, P.H. AND WRIGHT, N.G., 1998. An unstructured finite-volume algorithm for predicting flow in rivers and estuaries. *Computers and Fluids*, 27(4), 479-508.

SLEIGH, P.A. AND GASKELL, P.H., 1999. *A two-dimensional unstructured solution algorithm applied to the simulation of dam-break waves.* Proceedings of the IAHR 28th Congress, Graz, Austria.

SMITH, M.J., EDWARDS, E.P., PRIESTNALL, G. AND BATES P.D., 2005. *Creation of Digital Elevation Models for Flood Inundation Modelling.* Research report, Flood Risk Management Research Consortium, UK.

SOARES-FRAZAO, S. AND ZECH, Y., 2002. *Dam-break flow experiment: The isolated building test case.* IMPACT project technical report.

SOARES-FRAZAO, S., DE BUEGER, C., DOURSON, V. AND ZECH, Y., 2002. Dam-break wave over a triangular bottom sill. *Proceedings River Flow 2002 Conference*, Louvain-la-Neuve, Belgium, Balkema, 1, 437-442.

STELLING, G., AND DUINMEIJER, S.P.A., 2003. A staggered conservative scheme for every Froude number in rapidly varied shallow water flows. *International Journal of Numerical Methods Fluids* ,43,1329–1354.

STELLING, G.S. AND VERWEY, A., 2005. *Numerical flood simulation, Encyclopedia of Hydrological Sciences*, John Wiley & Sons Ltd., UK.

STOCKER, J.J., 1957. *Water Waves. Pure and Applied Mathematics*, Vol. 9, The Mathematical Theory and Applications, Institute of Mathematical Sciences, New York University, U.S.A.

SYME, W.J., 1991. *Dynamically linked two-dimensional/one-dimensional hydrodynamic modelling program for rivers, estuaries and coastal Waters*. M.Eng.Sc. Thesis, Dept of Civil Engineering, University of Queensland, Australia.

SYME, B., 2006. *2D or not 2D? – An Australian perspective.* Defra Flood and Coastal Risk Management Conference.

TORO, E.F., 1999. *Riemann Solvers and Numerical Methods for Fluid Dynamics*, Second edition, Springer-Verlag.

TORO, E.F., 2001. Shock-capturing methods for free-surface shallow flows. John Wiley, New-York.

VERWEY, A., 2001. *Lates developments in floodplain modelling – 1D/2D integration*. The Institution of Civil Engineers, Australia, Conference on Hydraulics in Civil Engineering, Hovart.

VILLANUEVA, I. AND WRIGHT, N.G, 2005. *Report on validation of TRENT solver, part I: laboratory tests.* Nottingham University.

VREUGDENHIL, C.B., 1994. *Numerical methods for shallow flows.* Kluwer Academics Publishers.

WERNER, M.G.F., HUNTER, N.M. AND BATES, P.D., 2005. Identifiability of distributed floodplain roughness values in flood extent estimation. *Journal of Hydrology*, 314 (1-4), 139-157.

WICKS, J., SYME, W., HASSAN, M.A.A.M., LIN, B. AND TARRANT, O., 2004. *2D modelling of floodplains – is it worth the effort?* 39th Defra Flood and Coastal Management Conference 2004, University of York, 29 June to 1 July 2004.

WRIGHT, N.G., 2001. Conveyance implications for 2-D and 3-D modelling. In: *Scoping Study for Reducing Uncertainty in River Flood Conveyance*. R & D Technical Report to Defra/Environment Agency, HR Wallingford, UK.

WRIGHT, N.G., 2005. Introduction to numerical methods for fluid flow. In Bates, P.D., Lane, S.N., Ferguson, R.I. (editors), *Computational Fluid Dynamics: Applications in Environmental Hydraulics.* Wiley, Chichester.

YU, D. AND LANE, S.N., 2005. Urban fluvial flood modelling using a two dimensional diffusion-wave treatment, part 2: development of a sub-grid-scale treatment. *Journal of Hydrological Processes*, 20 (7), 1567-1583.

ZHANG, K., CHEN S.-C., WHITMAN D., SHYU M.-L., YAN J., AND ZHANG C., 2003. A progressive morphological filter for removing nonground measurements from airborne LIDAR data. *IEEE Transactions on Geoscience and Remote Sensing*, 41 (4), 872-882.

Appendix A - Questionnaire

Desktop Review of 2D Hydraulic Modelling Packages

Heriot Watt University, the University of Bristol, Cardiff University and UNESCO-IHE, Delft have been commissioned by the Environment Agency to undertake a desktop review of the uses of **2D hydraulic modelling packages for flood risk management studies**.

As part of this review we require to gather information on 2D flood modelling software that is currently being used by consultants and Environment Agency teams engaged in flood risk management.

The questionnaire below is the first stage in information gathering to assist with this process and we would be grateful if you could complete and return it to m.livingstone@hw.ac.uk by 28th November 2008.

Name ______________________________________

Job title_____________________________________

Email address________________________________

Organisation _________________________________

1. Indicate which of the following **2D modelling software packages** your organisation uses.

Software	**Used Y/N**
BreZo	
DIVAST	
DIVAST TVD	
FloodFlow	
Flowroute	
Grid-2-Grid	
HEMAT	
Hydro AS-Z2	
InfoWorks 2D RS/CS	
ISIS 2D	
JFLOW	
JFLOW GPU	
LISFLOOD-FP	
Mike-21	
RFSM	
RIC-Nays	
SOBEK	
TELEMAC	
TRENT	
TUFLOW	
Other	
Other	

2. Indicate which of the following applications your organisation applies 2D modelling packages to.

Use	Y/N
Urban drainage assessment	
Catchment flood management plans	
Strategic flood risk management	
Flooding from multiple sources	
Flood defence design	
Urban drainage design	
Contingency planning	
Real-time forecasting	
Flood warning	
Other	
Other	

3. We are interested in understanding the **staff time** necessary to set up and run 2D relative to 1D flood models. For each task given below please indicate if it requires more or less time for 2D modelling relative to 1D modelling. We realise that the modelling needs of each project are different and only rough estimates can be provided.

Activity	Relative to 1D modelling this task requires more/less time.
Data collection	
Model set up	
Resolving data issues	
Model calibration	
Model validation	
Setting up production runs	
Computer time for production runs	
Reporting	
Staff training	
Resolving software issues	
Other	
Other	

4. List up to 5 reasons why you would choose a 2D modelling approach for a flood management project rather than 1D.

i.____

ii.____

iii.____

iv.____

v.____

5. Which hardware platforms do you currently run 2D models on?

____

____

____

6. If you develop and maintain your own software please summarise below any development plans you have for the next 3 years.

____

____

____

7. For those packages that your organisation uses please provide ratings on a scale of 1 (poor) to 5 (excellent) for the following headings.

Criteria	**Software Name**		**Software Name**		**Software Name**	
	Rating	**Comment**	**Rating**	**Comment**	**Rating**	**Comment**
User Manual & Technical Reference						
Technical Support (including training)						
Data Compatibility with New Software Releases						
Flexibility of Data Input						
Model Setup						
Adding Structures						
Run Time						
Stability						
Presentation of flood depth and velocity predictions						
Visualisation Tools						
File Management						
Sensitivity Testing						
Uncertainty Analysis						

Appendix B – Circulation List

Balmforth	David	MWH
Benn	Jeremy	JBA
Budd	Sarah	Haskoning
Butler	Justin	Ambiental
Chen	Yipping	Atkins
Crowder	Richard	Halcrow
Djordjevic	Slobodan	University of Exeter
Ferguson	Scott	Capita Symonds
Fortune	David	HR
Gamble	Richard	Motts
Gouldby	Ben	HR
Godsland	Henni	Halcrow
Jenkin	Paul	PBA
Lamb	Rob	JBA
Long	Richard	Independent Consultant
Lohmann	Dag	RMS
Magenis	Paste	Royal Haskoning
Merrick	Andrew	EA
Morgans	Jonathan	Atkins
Muggeridge	Nathan	Mouchel
Myers	Peter	Faber Maunsell
Ray	John	EA
Pieris	Tilak	EA
Roberts	Mark	Civil Eng Solutions
Roberts	Matt	Capita Symonds
Samuels	Paul	HR
Sayers	Paul	HR
Spencer	Peter	EA
Terret	Nick	EA
Whitlow	Chris	Whitlow Young
Wicks	Jon	Halcrow
Widgery	Nigel	Jacobs
Wilson	Leanne	EA

Would you like to find out more about us, or about your environment?

Then call us on

08708 506 506* (Mon-Fri 8-6)

email

enquiries@environment-agency.gov.uk

or visit our website

www.environment-agency.gov.uk

incident hotline 0800 80 70 60 (24hrs)
floodline 0845 988 1188

* Approximate call costs: 8p plus 6p per minute (standard landline).
Please note charges will vary across telephone providers

Environment first: This publication is printed on recycled paper.