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Integrating 1D and 2D hydrodynamic models for flood simulation

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**The one-dimensional (1D) hydrodynamic model ISIS has been extensively used for designing river engineering and irrigation schemes and mapping flood risks. This paper presents the integration of a two-dimensional (2D) model with ISIS to enhance its capability for simulating floodplain flows. The 2D model is based on the DIVAST model, a research model widely used for predicting flows and water quality indicators in estuarine and coastal waters. One of the main advantages of using DIVAST is that the model has a very robust subroutine for simulating flooding and drying processes. In this study DIVAST is dynamically linked to the ISIS model and the linked model is used to predict overland flood flows. In order to increase the flexibility of the DIVAST model for dealing with complex flow situations while minimising the computational time, several modelling options were considered. These options include the so-called hydrodynamic approach, gravity wave approach and flood wave approach.
A series of numerical tests were undertaken to assess the accuracy and efficacy of these approaches for simulating flows over initially dried land and dam-break flows. The model was then used to predict the flood flow in an urban area for an assumed extreme flood flow condition.**

1. INTRODUCTION

Growing population and economic activities near rivers have caused an increased flood risk to many urban regions. More reliable and integrated computer models are needed to help identify and assess appropriate flood risk management measures. Currently, one-dimensional (1D) hydrodynamic models have been widely used in modelling flood flows. These types of models are computationally efficient for dealing with large and complex river/channel systems and various hydraulic structures. However, when modelling floodplain flows where the 'one-dimensional' assumption is in question, then the accuracy and appropriateness of a 1D model decreases. Quasi two-dimensional (2D) models have been developed for this situation, in which the floodplain is discretised into a network of fictitious river branches and spills linked with main river channels. Although this approach has been successfully used for many flood studies, it is generally time-consuming in setting up the initial model and the accuracy of predictions varies with the way in which the floodplain is discretised.

Depth-integrated 2D hydrodynamic models based on a regular grid have been used for many years for predicting free surface flows, but they are generally computationally more expensive and less flexible when dealing with channel networks and hydraulic structures. The increasing availability of digital topographic data in recent years provides this type of model with scope for wider application. For flood modelling, 2D models based on the mass balance equation and with the raster grid have been developed and increasingly used.[1] Such models discretise the floodplain according to a regular grid with each floodplain pixel in the grid treated as an individual storage cell. The inter-cell fluxes are treated using uniform flow formulae.

Coupled 1D and 2D models have been developed in recent years and successfully applied to large and complex river systems.[2,3] However, there are still a number of issues with the application of 2D modelling, including a huge difference in the computational resource requirements between the 1D and 2D models. For example, in modelling flood inundation in an urban area, it was found that the computational time required for a 2D model can be 1000 times higher than that required for a 1D model.[4] The main objective of this study is to enhance the capability of the ISIS modelling system by integrating a revised version of the DIVAST 2D model. Three options are available for the form of the governing equations of the 2D model: the fully hydrodynamic approach, gravity wave approach and flood wave approach. Two sets of tests were undertaken to compare the different versions of 2D models for two flood flow conditions. The first one was the propagation of flood waves along idealised open channels, which is to study the model accuracy for predicting travelling speed of wave front for different bed slopes. The second test was the dam break flow, with the aim being to compare the predictions made by the implicit ADI (alternating direction implicit) model and those made by the explicit method. Details will then be given of the application of integrated 1D and 2D model for predicting flood flows in the Greenwich area in London, where a breach of the embankment along the River Thames was assumed to take place.

2. INTEGRATING OF 1D AND 2D MODELS

2.1. ISIS model

ISIS Flow is a well-known 1D hydrodynamic model (developed jointly by Halcrow and HR Wallingford) that includes a number of ways to model floodplain flow, including extended cross-sections (which may include regions of zero conveyance), interlinked quasi-2D lattice of floodcells (RESERVOIR units) and parallel virtual rivers. The main features of ISIS Flow include

(*a*) full hydrodynamic simulation, based on four-point implicit finite-difference scheme
(*b*) looped and branched networks
(*c*) floodplain modelling
(*d*) wide range of hydraulic structures
(*e*) real-time control of moving structures.

2.2. DIVAST model

The DIVAST (depth-integrated velocities and solute transport) model is based on the solution of the depth-integrated Navier–Stokes equations and includes the effects of: local and advective accelerations, the earth's rotation, free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model. The differential equations are written in their pure differential form, thereby allowing momentum conservation in the finite-difference sense. Particular emphasis has been focused in the development of the model on the treatment of the advective accelerations, a surface wind stress and the complex hydrodynamic phenomenon of flooding and drying.

The 2D hydrodynamic equations are generally based on the depth-integrated three-dimensional Reynolds equations for incompressible and unsteady turbulent flows, with the effects of the earth's rotation, bottom friction and wind shear being included to give[5]

$$\frac{\partial \zeta}{\partial t}+\frac{\partial \boldsymbol{q}_x}{\partial x}+\frac{\partial \boldsymbol{q}_y}{\partial y}=0 \quad (1)$$

$$\underbrace{\frac{\partial \boldsymbol{q}_x}{\partial t}}_{1}+\underbrace{\beta\frac{\partial \boldsymbol{U}\boldsymbol{q}_x}{\partial x}+\beta\frac{\partial \boldsymbol{V}\boldsymbol{q}_x}{\partial y}}_{2}=\underbrace{f\boldsymbol{q}_y}_{3}-\underbrace{\boldsymbol{g}H\frac{\partial \zeta}{\partial x}}_{4}+\underbrace{\frac{\boldsymbol{\tau}_{xw}}{\rho}}_{5}-\underbrace{\frac{\boldsymbol{\tau}_{xb}}{\rho}}_{6}+\underbrace{\bar{\boldsymbol{\varepsilon}}H\left[\frac{\partial^2 \boldsymbol{U}}{\partial x^2}+\frac{\partial^2 \boldsymbol{U}}{\partial y^2}\right]}_{7} \quad (2)$$

$$\frac{\partial \boldsymbol{q}_y}{\partial t}+\beta\frac{\partial \boldsymbol{U}\boldsymbol{q}_y}{\partial x}+\beta\frac{\partial \boldsymbol{V}\boldsymbol{q}_y}{\partial y}=-f\boldsymbol{q}_x-\boldsymbol{g}H\frac{\partial \zeta}{\partial y}+\frac{\boldsymbol{\tau}_{yw}}{\rho}-\frac{\boldsymbol{\tau}_{yb}}{\rho}+\bar{\boldsymbol{\varepsilon}}H\left[\frac{\partial^2 \boldsymbol{V}}{\partial x^2}+\frac{\partial^2 \boldsymbol{V}}{\partial y^2}\right] \quad (3)$$

where ζ is the water elevation above (or below) datum; $\boldsymbol{U}, \boldsymbol{V}$ are the depth-averaged velocity components in the x, y directions; $\boldsymbol{q}_x = \boldsymbol{U}H$, $\boldsymbol{q}_y = \boldsymbol{V}H$ are the unit width discharge components (or depth-integrated velocities) in the x, y directions; h is the water depth below datum; H is the total water column depth $(= h + \zeta)$; β is the momentum correction factor; f is the Coriolis parameter; $\boldsymbol{g}$ is the gravitational acceleration; $\boldsymbol{\tau}_{xw}$, $\boldsymbol{\tau}_{yw}$ are the surface wind shear stress components in the x, y directions; $\boldsymbol{\tau}_{xb}$, $\boldsymbol{\tau}_{yb}$ are the bed shear stress components in the x, y directions; and $\bar{\boldsymbol{\varepsilon}}$ is the depth-averaged eddy viscosity. The numbered terms in equation (2) refer to the local acceleration (term 1), advective acceleration (2), body force (3), pressure gradient (4), wind stress (5), bed stress (6), and turbulent shear stresses (7). In the following tests, the body force and wind stress terms were assumed to be small and were neglected.

Three versions of the model were used in this study.[6]

(*a*) The hydrodynamic approach—in this approach a full set of equations are used.
(*b*) The gravity wave approach—in this approach the advective acceleration terms are ignored.
(*c*) The flood wave approach—if the friction term has the dominant influence, then only terms (4) and (6) in the momentum equation are essential for predicting the flood wave.

The governing differential equations are solved using the finite-difference technique and using a scheme based on the ADI formulation. The advective accelerations are written in a time-centred form for stability, with these terms and the turbulent diffusion terms being centred by iteration. While the model has no stability constraints, there is a Courant number restriction for accuracy in the hydrodynamic module. The finite-difference equations are formulated on a space-staggered grid scheme, with the water surface elevations and x-direction velocity components being solved initially for during the first half time step by using the method of Gauss elimination and back substitution.

2.3. Model integration

The 1D ISIS and 2D DIVAST models are linked to simulate flood flows, and particularly, overbank flows. At normal flow conditions, only the 1D model is used to predict the flow velocity and water level within the main river network. If large areas are inundated owing to a breach of a section of river embankment it is likely that the flows would no longer be 1D. In such a case the 2D DIVAST model is used to predict the flow velocity and inundation levels in the flooded area. The ISIS and DIVAST model is linked by a weir equation, in which the volume of flow from the 1D domain to the 2D domain is determined by the water level difference.

The main benefit of the linked model is that the advantages offered by both the 1D and 2D models can be fully utilised to give better predictions of flood flow. For example the capability of ISIS in dealing with structures and the capability of DIVAST in dealing with rapid flooding and drying processes are both critical to the accuracy of flood prediction. The user-friendly interface developed for ISIS can still be used for the linked model.

3. 2D MODEL TESTS

The main objective of the following tests was to study the performance of 2D finite-difference approximations based on the ADI method for simulating flood flows. Two numerical model tests were undertaken. The first test was to study the propagation of flood waves over a long distance and the second test was to study the behaviour of flood waves at the initial stage of a dam break event.

3.1. Flood wave propagation in an idealised open channel

The 2D model presented was first applied to predict the propagation of a flood wave along an idealised open channel.

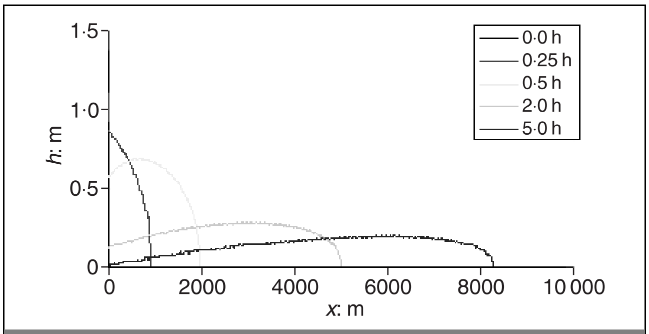

Fig. 1. Predicted water depths for full dynamic model—bed slope of 0·0001

The length of the channel was set to 10 000 m, and the width was assumed to be 100 m. Two channel bed slopes were tested, namely $S = 0{\cdot}001$ and $S = 0{\cdot}0001$, and the channel was initially assumed to be dry for both of these two cases. A sinusoidal hydrograph was used to represent the flood wave after the breaching of a dam, giving[7]

$$\boldsymbol{q} = \boldsymbol{q}_{\mathrm{p}} \sin\left(\frac{\pi}{T} t\right) \quad 0 \leqslant t \leqslant T \tag{4}$$

in which $\boldsymbol{q}_{\mathrm{P}}$ is the unit-width peak discharge and T is the duration of flooding. In the following tests $\boldsymbol{q}_{\mathrm{P}}$ was set to 10 m^3/s and T was set to 0·5 h. Model-predicted water depths at 0·25, 0·5, 2 and 5 h after the dam break are illustrated in Figs 1–3.

It can be seen from Figs 1 and 2 that for a mild bed slope the water depths (and surface levels) predicted both with and without the inclusion of the advective terms are very similar. The propagation speeds also agree closely. The number of grid cells used in this model was 1000 in the x direction and 10 in the y direction. The computational time required was about 30 min for the full dynamic model and 20 min when the advective terms were neglected. However, when only friction and the bed slope were considered in the momentum equation (see Fig. 3), then the speed of the flood wave became very small and the water depth increased dramatically at the upstream end of the channel. This seems to be unrealistic.

When the bed slope was increased to 0·001, the water depths for both the full hydrodynamic model and the model without the advective terms were still close, see Figs 4 and 5. However, signs of numerical oscillations were observed in the predicted water levels at an early stage of the flooding process, that is $t = 0{\cdot}25$ and 0·5 h. These oscillations disappeared when the gradient of the flood wave front was reduced. At this increased bed slope the

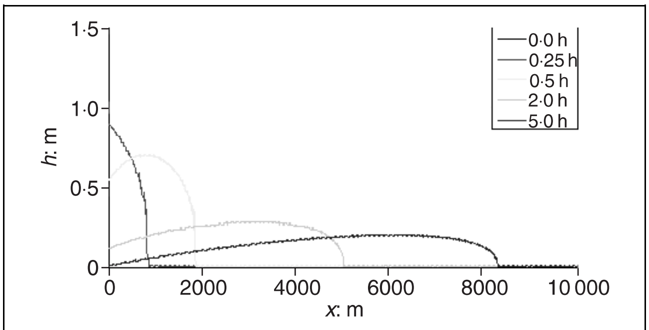

Fig. 2. Predicted water depths without advection—bed slope of 0·0001

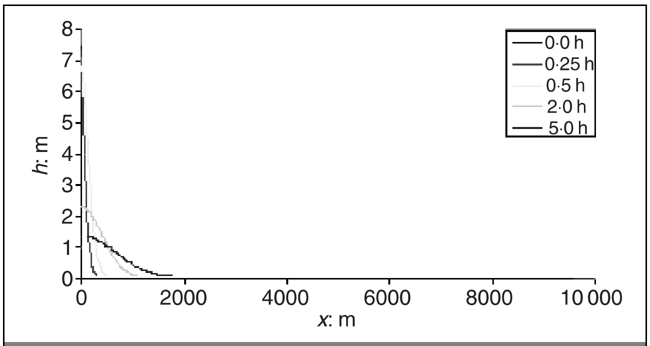

Fig. 3. Predicted water depths using flood wave approach, bed slope = 0·0001

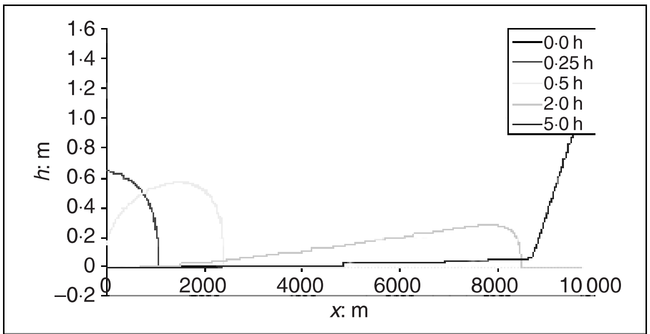

Fig. 4. Predicted water depths, fully dynamic model, bed slope = 0·001

flood wave model prediction was again unrealistic (results were similar to Fig. 3).

3.2. Dam-break flow

The first test undertaken was to study the performance of the numerical model for predicting the propagation of flood waves owing to the breach (or break) of a dam. Two cases were investigated: one with an initially dry bed downstream of the dam, and the other with an initially wet bed downstream of the dam. The model domain was 200 × 200 m, with the bed level being set to zero. A bed roughness height of 0·005 m was assumed for both cases. Although a number of numerical modelling studies of this test case have been published in the literature, no analytical solutions could be found for the 2D dam-break problem. Therefore in this study water levels predicted using an existing numerical model based on an explicit finite-volume method were used to verify the DIVAST model. The finite-volume model has been shown to be very accurate in predicting free surface flows with sharp water level gradients.[8]

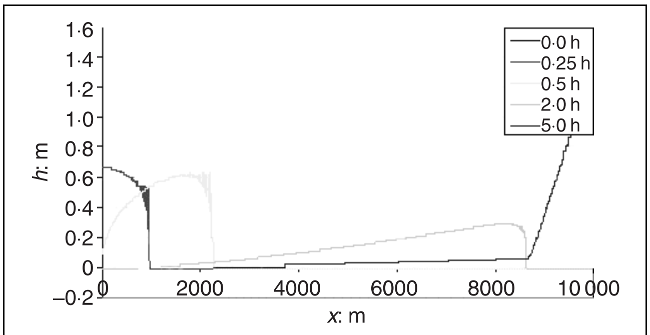

Fig. 5. Predicted water depths, no advection, bed slope = 0·001

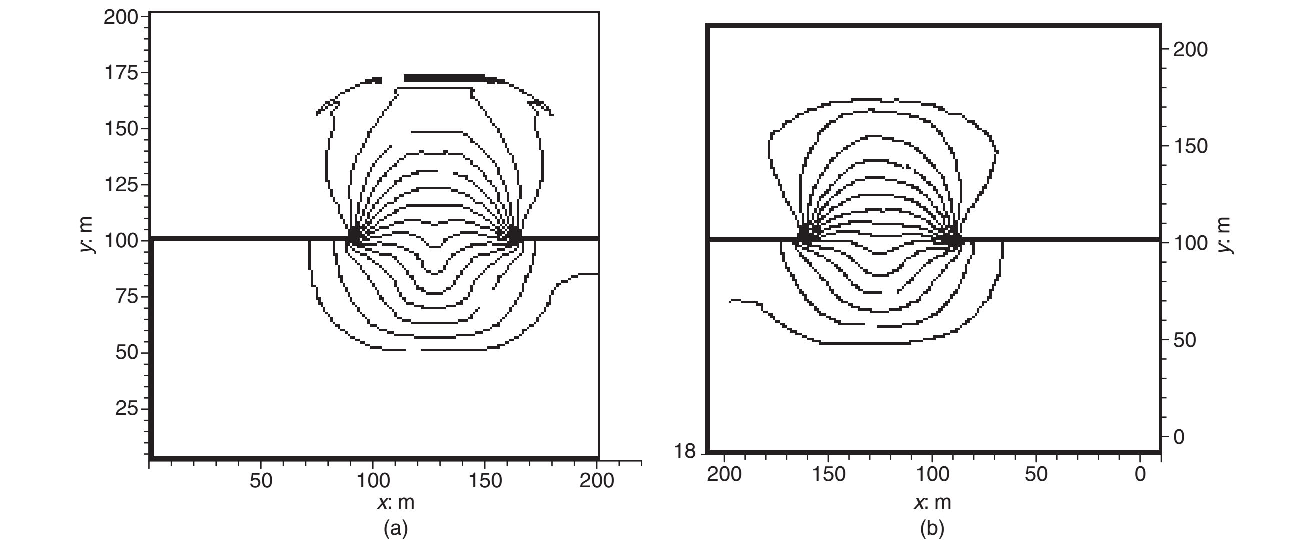

Fig. 6. Comparison of predicted water surface levels 6 s after dam break for a dry bed: (a) full hydrodynamic model; (b) finite-volume model

The solution is based on a second-order total variation diminishing (TVD) scheme and the model deploys an unstructured triangular grid.

In case 1 the initial water level was set to 10 m upstream of the dam and zero downstream, and the breach was set to be 75 m wide. Fig. 6 shows a comparison of the predicted water levels 6 s after the dam breach. The contours shown in Fig. 6(a) were predicted using the DIVAST model, with the contours shown in Fig. 6(b) being predicted using the explicit finite-volume numerical model. It can be seen that the water level predictions using these two methods are very similar, with the finite-volume model appearing to give smoother predictions at the wave front. The model-predicted water surface distributions were also shown to be comparable to those obtained by Caleffi *et al.* [9] using a TVD numerical scheme with a regular grid. Fig. 7 illustrates a 3D view of the water surface profile as predicted using the ADI scheme. It can be seen that at the flood wave front the water surface slope is relatively large. A more detailed investigation is currently being undertaken to obtain a better understanding of this phenomenon.

Figure 8 shows the water level distributions predicted using the gravity wave approach—that is, the advection term was set to zero. There is a significant discrepancy between the predictions made by the model both with and without the advective term, see also Fig. 6. When the advective terms were neglected, then the propagation speed of the wave front was reduced. Using the flood wave approach, the predicted wave speed was significantly smaller than that using the gravity approach.

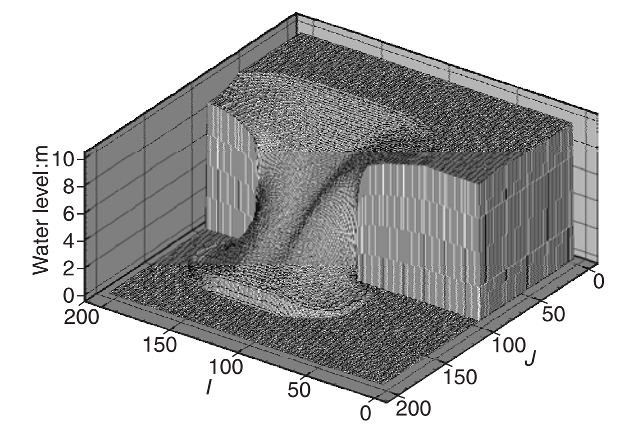

Fig. 7. Three-dimensional view of water surface predicted by hydrodynamic model (*I*, grid number in *x* direction; *J*, grid number in *y* direction)

For case 2 the initial water level was still set to 10 m upstream of the dam, but it was set to 5 m downstream. The width of the breach was again set to 75 m. The predicted water surface profile using the dynamic model is very similar to that predicted using the finite-volume model, see Figs 9(a) and (b). However, it is interesting to note that for this initially wet bed test case, the water level predictions made without the inclusion of the advective terms were closer to those predicted using the full dynamic model than for the dry bed test case, see Fig. 10.

4. MODEL APPLICATION TO THE RIVER THAMES

It is estimated that between Teddington Weir and Dartford Creek approximately 116 km^2 of hinterland is at risk of tidal flooding during an event exceeding the nominal 1-in-1000-year standard of protection provided by the existing flood defence system.[4]

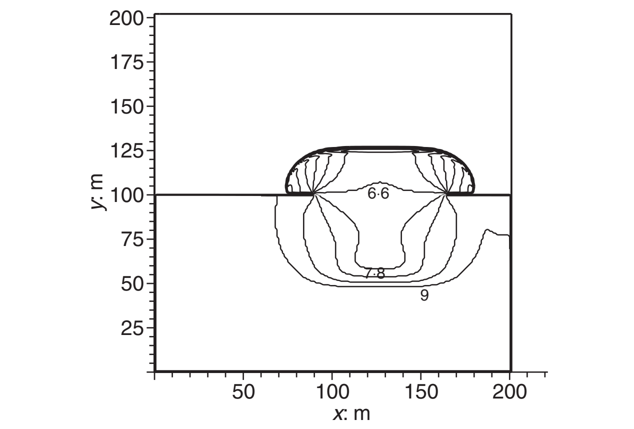

Fig. 8. Water surface contours predicted using gravity wave approach—dry bed

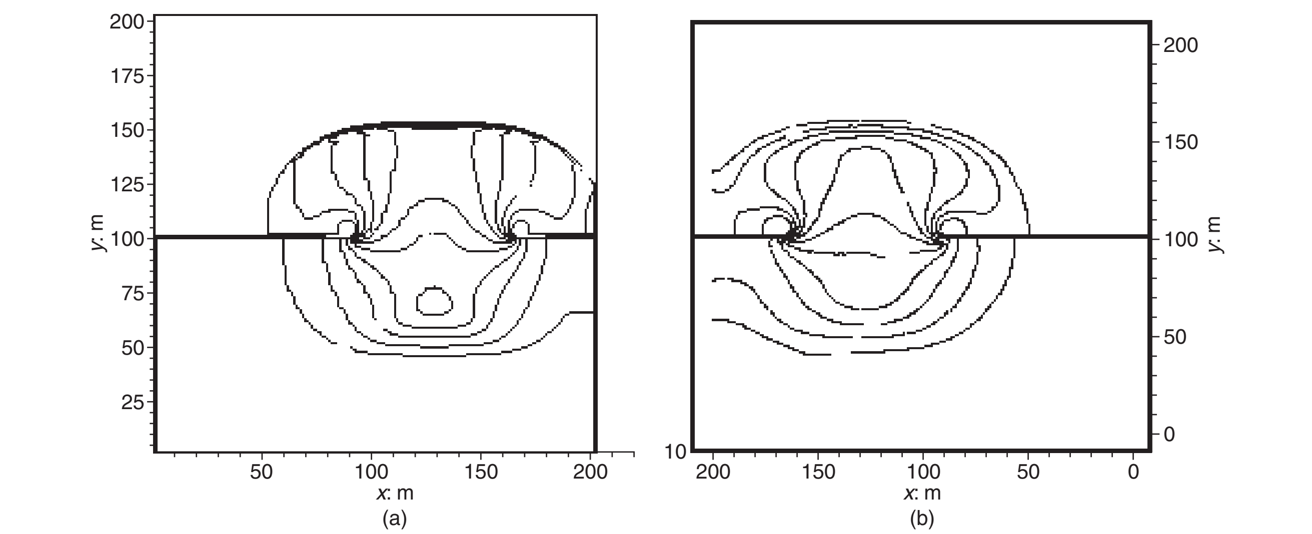

Fig. 9. Comparison of predicted water surface level 6 s after dam break for a wet bed: (a) full hydrodynamic model; (b) finite-volume model

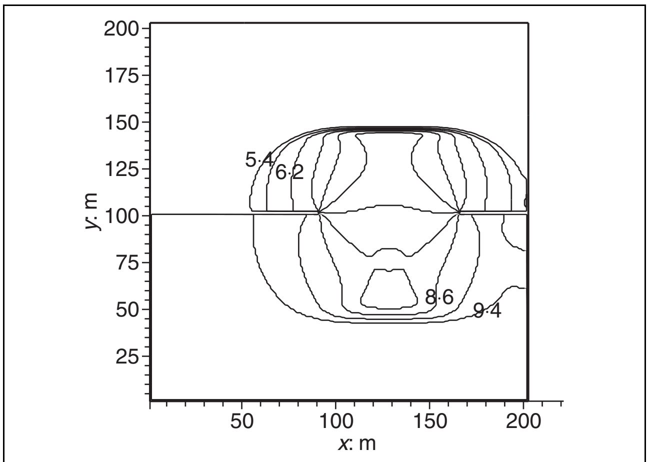

Fig. 10. Water surface contours predicted using gravity wave approach—wet bed

The probability of such an overtopping event occurring is predicted to increase in the future owing to a combination of sea level rise and geological settlement of south-east England. A side-effect of the success that the Environment Agency (the Agency) and its predecessor organisations have had in managing tidal flooding in London (through tidal defence walls, embankments and barriers, etc.) is that the public do not appreciate the residual risk. Also, the Agency has realised that it needs to improve its ability to plan for and manage a tidal flood event. A key element of this is the realisation that it needs to have a modelling tool to predict the area that will be affected following a breach or overtopping of the defences. With such information the Agency will be able to give emergency response teams and the public reliable information regarding the extent, timing and nature of the propagation of floodwaters.

The first stage in the development of this tool involved an investigation of the most appropriate modelling approaches. The Agency appointed Halcrow and HR Wallingford to test various solution techniques on a single representative embayment and make recommendations on the most suitable modelling solution. The Greenwich embayment was selected as the testing area (the floodplain in the Thames region is divided into 23 'embayments', each considered to be hydraulically discrete). Fig. 11 shows the embayments within the Thames region and the outer estuary.

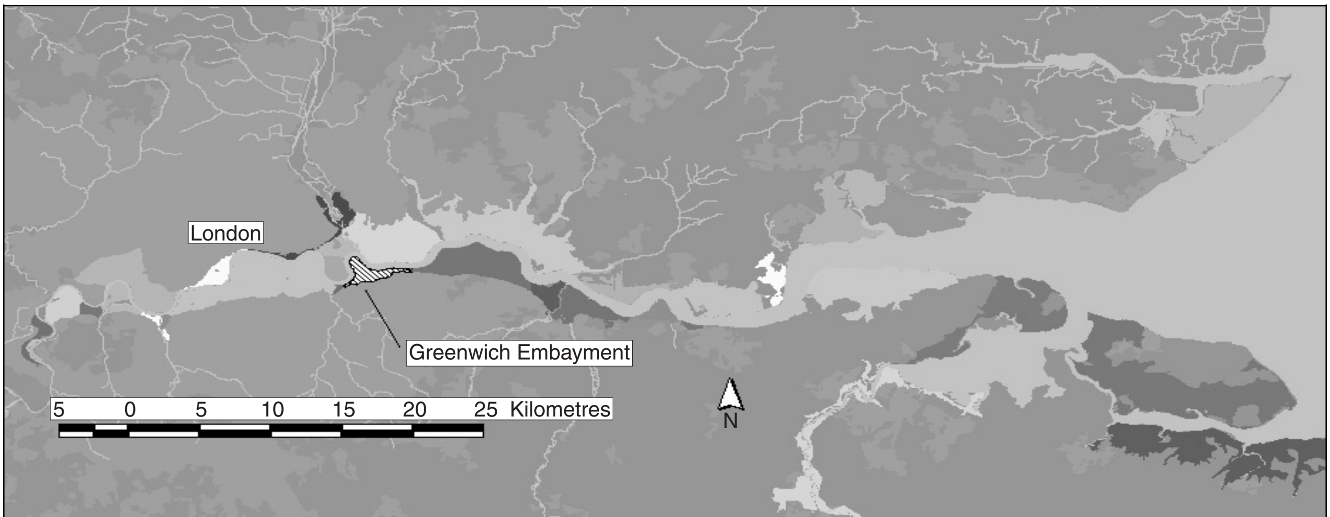

Fig. 11. Tidal Thames embayments (Greenwich embayment used for testing highlighted)

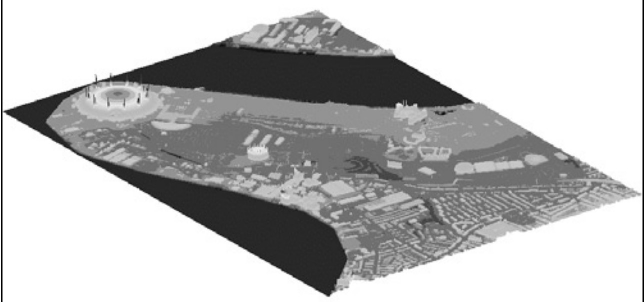

Fig. 12. 2D model domain (note Millennium Dome at end of peninsula)

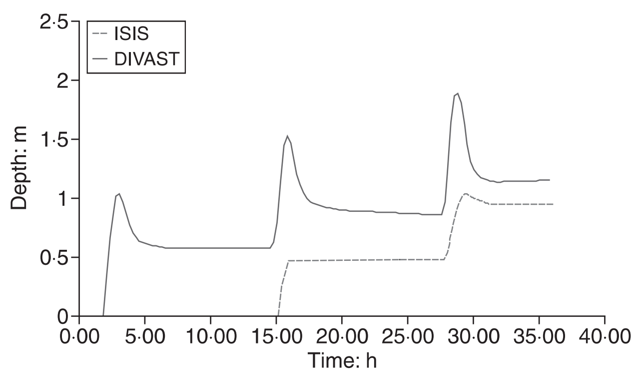

Fig. 14. Comparison of simulated flood depth time series at a point on floodplain

The linked ISIS and DIVAST model was applied to predict the flood wave propagation for a hypothetical extreme tide condition. The ISIS model was set to cover the whole tidal Thames from the tidal/fluvial boundary to the mouth of the estuary with the DIVAST model set up to cover the Greenwich embayment only. Fig. 12 shows the 2D model domain as linked to the ISIS model. The model bathymetry was generated using a geographic information system (GIS) system, based on 1 m grid LiDAR data. Both 10 m and 5 m grid size models were set up and analysed accordingly.

Extreme tidal and surge levels were assumed at the 1D model seaward boundary, and it was assumed that an embankment failure would occur at a preselected site. From these predictions the floodplain wave propagation paths can be clearly identified. Fig. 13 compares the final flood extent and flood depths generated by the linked model with those generated using a pseudo-2D 'flood cell' model (created using the standard ISIS software). The flood extents shown in the figure are both similar and this suggests that, for this scenario, the benefits of the full 2D approach are not significant. However, careful inspection of the flood extents shows that the pseudo-2D 'flood cell' approach results in many implausible isolated areas of flooding (that is, with no flood route to connect them with the breach site).

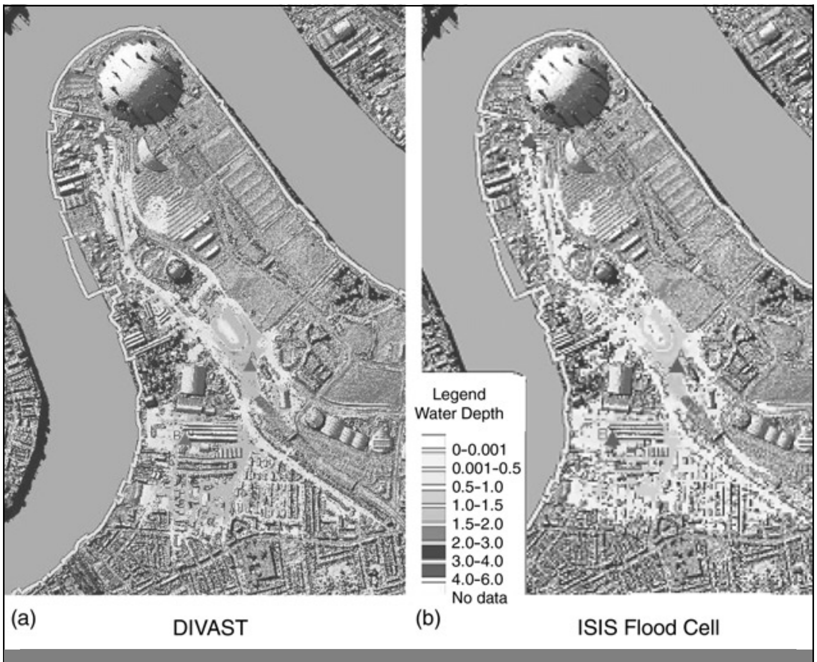

Fig. 13. Comparison of: (a) ISIS–DIVAST; and (b) ISIS flood cell

In addition, Fig. 14 shows important differences in flood depths and time of arrival of flood water between the two methods. Comparison of the linked model results with results from applying three further inundation modelling systems suggests that the linked model results are significantly more accurate than the pseudo-2D 'flood cell' approach and are close to the most reasonable results from the other applied modelling systems.

5. CONCLUSIONS

Details have been given of the development and testing of a linked 1D and 2D model for predicting flood inundation levels in complex river basins. The model has been tested for idealised test cases, followed by application to the Thames Estuary and the urbanised region of Greenwich. The new model has generally performed well in comparison with other similar models.

Following the model developments reported in this paper, there are a number of issues which require further investigation and these can be summarised as follows.

(*a*) The typical grid size for the 1D model is between 50 and 1000 m, and the typical grid size for the 2D model is between 5×5 m^2 and 20×20 m^2. The 2D model therefore requires a much longer computational time than the 1D model.

(*b*) Implicit 2D hydrodynamic models are generally based on the ADI method and can be used to predict flood waves with sharp surface gradients. The predictions are reasonably close to those predicted using an explicit shock-capturing numerical model.

(*c*) In modelling flood flows, neglecting the advection terms will not have a significant impact on the model predictions. However, neglecting both the advective and local acceleration terms will cause a significant slowdown in the flood wave speed.

(*d*) Further investigation is being undertaken to gain a better understanding of the implication of simplifying the 2D hydrodynamic equations on the model performance.

6. ACKNOWLEDGEMENTS

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