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The importance of spatial resolution in hydraulic models for floodplain environments

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Abstract

For many numerical modelling applications the problem of specifying an optimum mesh resolution remains unbounded and for mesh construction objective a priori rules do not exist. By contrast, the problem of specifying model parameter surfaces is largely bounded within known physical error distributions. In this paper we thus investigate the impact of varying mesh resolution on a typical non-linear finite numerical solver. Specifically, a two-dimensional finite element code which solves the Shallow Water equations was used to simulate unsteady flows in a meandering compound channel. A range of different mesh resolutions and parameter surfaces were simulated to determine relative dominance and, unlike previous studies, the effect on both bulk flow and distributed outputs were analysed. The results showed a wide variation in performance for mesh discretizations which fulfilled traditional length scale-based construction. Mesh resolution effects were at least as important as a typical calibration parameter and model response was shown to be highly complex. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Hydraulic modelling; Finite element; Floodplains; Spatial resolution

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1. Introduction

As a result of extensive research into numerical methods (the solution of non-linear partial differential equations derived from the laws of physics) there are now many readily available codes for simulating the behaviour of environmental systems. These schemes originated largely in the mathematics and engineering fields but have been rapidly taken up by earth scientists and can now be found in a wide range of fields from hydrology (Abbott et al., 1986) and hydraulics (Falconer and Chen, 1996;Falconer and Owens, 1990; King and Norton, 1978) to geomorphology (Lane et al., 1994; Miller, 1994) and groundwater flow (Ge and Garven, 1994; Gvirtman et al., 1997.). For example, hydraulics models have been constructed which are capable of being applied to rivers in the scale of 1–60 km (e.g. Gee et al., 1990; Baird et al., 1992; Feldhaus et al., 1992; Bates et al., 1992, 1995, 1996) whilst maintaining a high spatial and temporal resolution.

In the development of such models, there has been a trend among many modellers to increase the spatial resolution (the number of cells representing the spatial area of interest) in the expectation of improved insights into temporal and spatial processes. However, the spatial resolution at which a model is applied affects the solution of the equations and thus the simulation results. The relationship between model space/time resolution and simulation outputs is therefore

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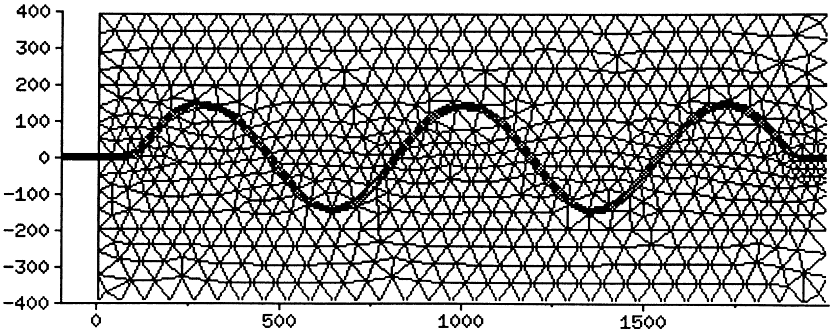
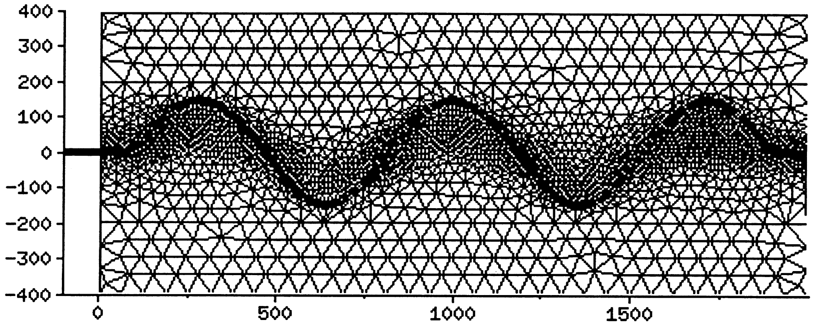
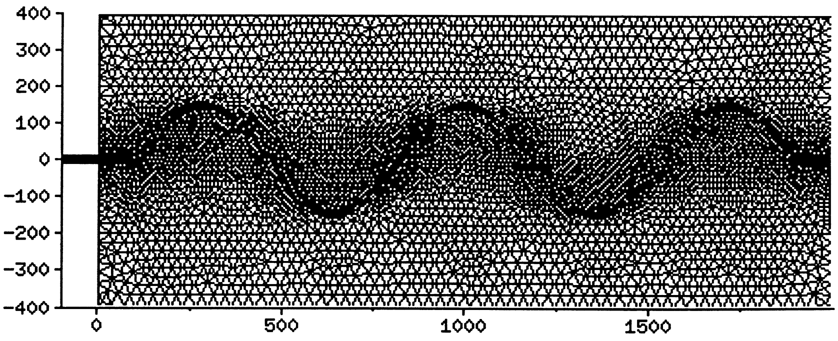


A). MESH 1: THE LOWEST RESOLUTION MESH.



B). MESH 4: THE MEDIAN RESOLUTION MESH.



C). MESH 7: THE HIGHEST RESOLUTION MESH.

Fig. 1. The hypothetical domain used in the analysis. The examples given are the lowest resolution mesh (mesh 1), the median resolution mesh (mesh 4) and the highest resolution mesh (mesh 7). Dimensions of domains are given in metres.

central to all modelling projects, but is often overlooked. Further, in the current applications of hydraulic and hydrological Computational Fluid Dynamics codes, mesh resolution is the only unbounded parameter value, where specific boundaries and error bands have not hitherto been considered. This is demonstrated in Fig. 1, which shows three finite element discretizations for simulating free surface flows in a hypothetical river/floodplain system. There are no a priori objective rules for mesh construction, so even using the best available knowledge of process length scales in compound channel flows (the typical mesh generation criteria in fluid dynamics applications), one cannot define which of these meshes is optimum. Each discretization could thus plausibly provide a satisfactory solution to the defined problem (as of course could many others not illustrated here). This is in contrast to calibration parameters, such as surface roughness, which are effectively bounded by known physically realistic ranges and error bands (e.g. Chow, 1959). In the past modellers have tended to look for the minimum mesh resolution at which numerical convergence could be achieved (e.g. Dietrich et al., 1990; Lardner and Song, 1992; Westerink et al., 1994) or used mesh construction criteria based on appreciation of the length scales within the flow (e.g. Gray and Lynch, 1977; Le Provost and Vincent, 1986; Luettich et al., 1992; Bates and Anderson, 1993) rather than rigorously examining mesh resolution impacts. Those studies on the effects of model spatial resolution that have been undertaken in hydrology and hydraulics (e.g. Bathurst, 1986; Farajalla and Vieux, 1995; Bruneau et al., 1995; Bates et al., 1996) demonstrate the sensitivity of model response to changing resolution but only consider bulk flow outputs from such schemes rather than the fully distributed results. While we may assume that the highest resolution provides the best result, neither this, nor the possibility that yet higher nodal densities would give a ‘further improvement’, is ever typically tested.

2. Spatial resolution impacts on model results

Owing to the heterogeneity of natural systems, there is a tendency to assume that an increase in the number of elements (increased spatial resolution) will improve the realism of the model’s predictive ability, as acknowledged by Farajalla and Vieux (1995). The definition of spatial resolution being applied in this article is the size of the grid cell (element) within the domain, and this will always be referenced to as an actual field scale (m^2). An increase in spatial resolution will result in an increase in the number of elements, thus decreasing the average element size. The hypothesis that a model’s predictive ability increases as the spatial and temporal resolution increases, stems from three avenues of thought:

1. expected improvements in solution stability as the grid spacing tends towards the true continuum level;
2. the ability of high resolution models to facilitate complex, and thereby more realistic parameterization of the code (cf. Beven, 1989);
3. a closer correspondence between field measurement model scales (cf. Bathurst and Wicks, 1991).

To date these arguments have not undergone explicit testing. This is the central aim of this paper where we present a comprehensive analysis of the effect of spatial resolution on a typical non-linear numerical scheme. The code selected for investigation, TELEMAC-2D, is a two-dimensional finite element hydraulic model which solves the depth averaged Shallow Water Equations and invokes the Boussinesq assumption to represent turbulent flows. This non-linear equation system is typical of many partial differential equations employed in environmental numerical modelling and has the advantage that the parameterization consists of only two variables (boundary friction and turbulent viscosity) and is therefore relatively simple and well bounded. Moreover, the use of computationally efficient and stable numerical algorithms in the code allows a wide range of mesh discretizations to be constructed for a given problem thus enabling a full investigation of spatial resolution effects. This model was applied to a typical hydraulic problem, the simulation of free surface flow in a compound meandering river channel, and the impact of changing mesh resolution analysed in terms of the ability of the scheme to simulate bulk flow characteristics, inundation extent and distributed hydraulics. The relative dominance of mesh resolution and typical calibration parameters was also examined.

Although no single study can perhaps fully

Table 1
A quantitative summary of the meshes applied in order to identify a suitable working resolution

	Mesh						
	1	2	3	4	5	6	7
Nodes	888	1199	1982	2858	3746	4652	6064
% in Ch.	36.89	35.45	40.26	38.80	33.45	36.86	31.53
Elements	1669	2284	3824	5578	7310	9128	11 890
Max.	2607.51	2551.36	1987.42	2528.80	1136.02	1593.97	676.51
Min.	37.04	20.83	11.11	7.41	6.17	4.63	3.97
Avg.	71.54	58.73	43.33	32.24	30.48	24.88	24.11
Std. dev.	18.59	23.34	21.92	23.24	16.71	18.38	12.37

illustrate a general problem, this initial investigation, using a model fully representative of its class, should be able to provide a considerable insight that can be used to define further, more comprehensive, research programmes. For example, this investigation should be able to determine whether increasing spatial resolution provides model results consistent with the controlling equations and process representation; whether guidelines for the appropriate level of spatial resolution can be provided for specific conditions, and finally whether new model inter-comparison methods are required to facilitate a full evaluation of the impact of spatial resolution.

3. Methodology

The hydraulic model applied in this study is the TELEMAC-2D modelling system. TELEMAC-2D solves second-order partial differential equations for depth averaged free surface flow derived from the full three-dimensional Navier Stokes equations as follows:

$$\frac{\partial h}{\partial t} + \mathbf{u}\cdot\mathrm{grad}(h) + h\,\mathrm{div}(\mathbf{u}) = q, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\mathrm{grad}(u) + g\frac{\partial h}{\partial x} - \mathrm{div}(v\cdot\mathrm{grad}(u)) = S_x - g\frac{\partial Zf}{\partial x}, \tag{2}$$

$$\frac{\partial v}{\partial t} + \mathbf{u}\cdot\mathrm{grad}(v) + g\frac{\partial h}{\partial y} - \mathrm{div}(v\cdot\mathrm{grad}(v)) = S_y - g\frac{\partial Zf}{\partial y}, \tag{3}$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\mathrm{grad}(T) - \mathrm{div}(V_\mathrm{T}\cdot\mathrm{grad}(T)) = S_\mathrm{T}, \tag{4}$$

where h is the depth of the water (m), u, v are the velocity components (m s^{-1}), T the non-buoyant tracer (—), g is the acceleration owing to gravity (m s^{-2}), V, V_T are momentum and tracer diffusion coefficients (m^2 s^{-1}), Zf is the bed elevation (m), t is the time (s), x, y are the horizontal space co-ordinates (m), q is the introduction or removal of fluid (m s^{-1}) and S the source term (m s^{-2}).

The model thus calculates water depth and velocity in the x and y directions at each computational node. A complete mathematical description of the modelling system is presented by Hervoeut and Van Haren (1996) while modifications implemented for the application of the modelling system to a river floodplain, and the effect of different solver techniques are discussed by Bates et al., (1995).

The analysis was performed on a purely hypothetical example, although both the domain considered and the input hydrographs were scaled to real events that have been considered in past analyses. Real examples were not considered for several reasons: (i) A simple, computationally efficient domain was needed to enable a large number of simulations to be completed. (ii) Boundary conditions and topography needed to be controlled so only the effect of mesh resolution was considered. (iii) Comparison against field data was not believed to be beneficial as we do not wish to analyse the model's predictive ability for a particular reach and the data required for such a study is unlikely to exist.

The dimensions of the domain were 2000 m × 800 m with a 20 m wide, 2 m deep sinuous channel

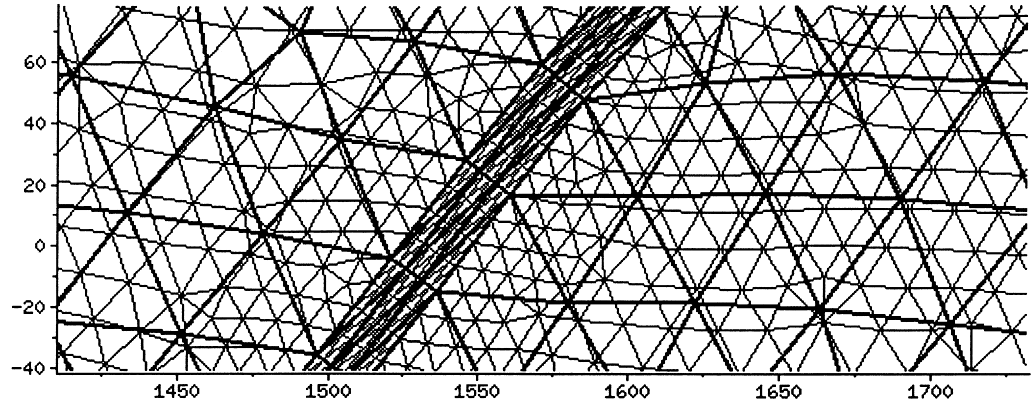


Fig. 2. The difference in spatial resolution between mesh 1 and mesh 7 for an area representing a near channel region of the domain.

flowing down the middle, see Fig. 1. From this template seven separate meshes were constructed, ranging from 1169 to 11 890 elements (average element size 71.54–24.11 m^2), using the I-DEAS mesh generating package. A statistical summary of the meshes is presented in Table 1 while the actual difference in spatial resolution can be seen in Figs. 1 and 2.

Simple topography was prescribed for the domain, as it is the question of resolution that is of interest here and not the effect of topography. The cross-section of the domain was divided into three sections: above and below an absolute *y* value of 200 m, a gradient of 0.01 was specified; between $+200$ m and -200 m a gradient of 0.001. A longitudinal downstream gradient of 0.005 was imposed.

The dimensions of the channel also altered as the resolution increased, because of the means employed to define the topography. As the number of nodes varied across the channel, from 4 to 7, the cross-sectional area of the channel varies. Therefore, prior to any difference that may be generated in the solution of the equations, the actual channel volume is different. However, no scaling corrections were made as one of the first effects of spatial resolution is the filtering of information. Further, if different resolution meshes were applied to natural reach input hydrographs and stage data, these would not be scaled for the representation of the channel. Manning friction coefficients were prescribed of 0.025 for the channel and 0.06 for the floodplain.

The boundary conditions prescribed were an imposed flow rate at the upstream end of the reach while at the downstream boundary all variables were allowed to vary freely. A synthetic downstream boundary condition was considered an unnecessary constraint on model behaviour as the results obtained would primarily reflect the boundary conditions assumed. Further it was felt that this would have led to additional complications in the interpretation of results. Test simulations showed that any enhancement of water surface slopes only occurred within an extremely localised region, less than 50 m from the downstream boundary, and that the upstream water levels were relatively insensitive to this simplifying assumption.

As we are here concerned with overbank flow, simulations commenced at bank-full discharge. Initial conditions therefore consisted of steady state flow with a near bank-full water depth of 1.75 m within the channel, while on the floodplain no water was prescribed. The simulations were then run for 20 000 s allowing all perturbations caused by the start-up procedure to propagate out of the domain, until a true steady state exists. Identical numerical techniques were implemented for all seven meshes. Although TELEMAC-2D is an implicit code and therefore stability may be maintained for higher Courant numbers, the results reported in this article always involve a Courant number less than 1 ($Cr_{max} = 0.7$). This guarantees that it is the effect of resolution which is being analysed and not the quality of the simulations.

Three separate events were applied to the domain.

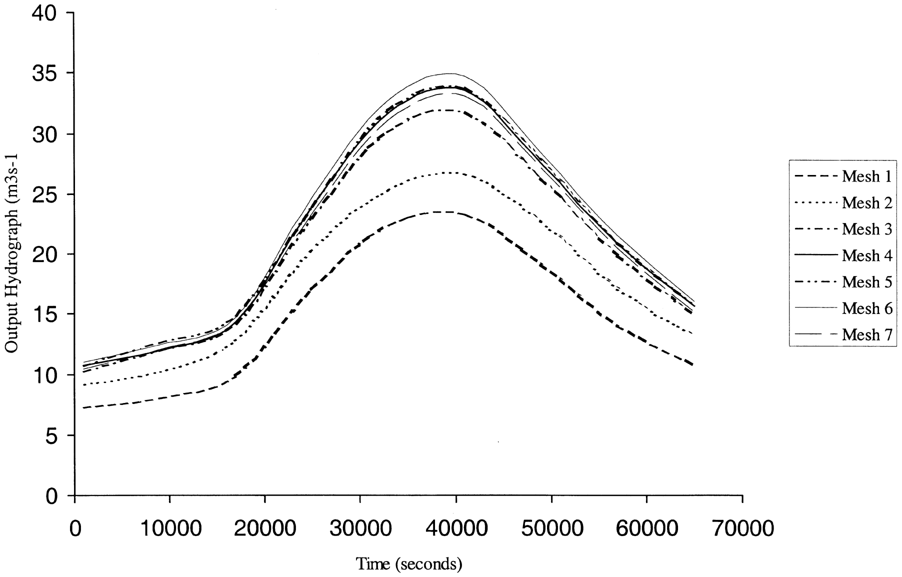


Fig. 3. The output hydrographs for event 2.

The magnitudes of the events were calculated from the dimensions of the channel and floodplain. The research design was based on simulations of (i) a high magnitude low frequency event where the whole domain flooded with appreciable water standing on the floodplain; (ii) an intermediate event where up to 50% of the domain flooded and; (iii) a low magnitude high frequency event where overbank flow occurred, although large areas of the domain were not inundated.

The model results were analysed in four different contexts enabling further insight into the hydraulic processes operating within a floodplain, in order to examine the strengths of the arguments commonly cited as advantages of increasing spatial resolution.

- *Output hydrograph (total flow):* This type of model output is typically used to validate model predictive ability in field applications as this is usually the only data available.
- *Inundation extent:* One of the growing advantages of the application of high resolution two-dimensional hydraulic models is the prediction of inundation extent for flood protection schemes, insurance surveys and similar applications. It is therefore essential that the flood water level can be accurately simulated for risk assessment.
- *Relative sensitivity of spatial resolution versus calibration:* The effect of spatial resolution and a field representative calibration coefficient (the friction coefficient) are considered in relation to a measure of model predictive ability, to identify which has more influence on the model. Currently, model sensitivity to friction has been relatively well explored; however, the same cannot be said with regard to mesh resolution. In particular, we wish to determine whether the calibration for an event is stationary between different mesh resolutions or whether some feedback occurs.
- *In-domain results:* These consist of the actual u, v and h values calculated by TELEMAC-2D at specific x, y co-ordinates during the simulation. This analysis examines the effect of a change in the spatial resolution on the governing equations. Primarily, attention was directed towards the nodes located on the channel banks, as it was believed that this was one of the most sensitive locations in the domain when considering floodplain modelling, owing to the momentum exchange mechanism operating between the main channel and floodplain flows.

Table 2
The effect of resolution on the peak output discharge ($m^3 s^{-1}$)

Event	Peak output discharge ($m^3 s^{-1}$) for mesh						
	1	2	3	4	5	6	7
Event 1	37.94	42.87	50.35	53.85	54.04	55.66	52.93
Event 2	23.47	26.85	31.90	33.93	34.08	35.09	33.40
Event 3	14.70	17.67	20.28	21.13	21.20	21.75	20.76

4. Results

The results are discussed in the order listed before followed by a synopsis of the general trends observed from the analysis.

4.1. Output hydrograph

When bulk flow characteristics, such as the peak discharge, the volume of the outflow hydrograph and the mean flow were analysed, a standard pattern was identified. This is illustrated in Fig. 3, which shows the results from event 2. As the spatial resolution increases, the bulk flow characteristics increase from mesh 1 to 6, although they decrease for mesh 7. There is an increase in the peak discharge from 23.60 to 35.09 $m^3 s^{-1}$ (+48%) from mesh 1 to 6, then a decreases by 5.1% from mesh 6 to mesh 7. A similar pattern of similar proportion is identified if other bulk flow variables are analysed. If the results are analysed from mesh 4 to mesh 7 there is minimal variation in peak discharge, with peak discharges increasing from 33.93 to 35.09 $m^3 s^{-1}$, then decreasing to 33.40 $m^3 s^{-1}$ for mesh 7. This indicates, as previously suggested, that there is an optimum mesh resolution beyond which results may not significantly vary. Similar trends may be identified in the bulk flow characteristics for event 1 and 3, see Table 2.

As the spatial resolution increases, the element size becomes smaller and from mesh 1 to mesh 6 there is an increase in the magnitude of the hydrograph. However, there is no difference in time to peak. For mesh 7 there is a consistent decrease in peak discharge.

4.2. Inundation extent

It is necessary to understand the effect of mesh resolution on inundation extent predictions so that accurate risk assessments may be made. In this analysis inundation extent is expressed as a percentage of the domain inundated (event 2 used as example). In Table 3 the percent of the domain inundated to 25, 10 and 5 cm is shown, while in Fig. 4 the inundation to 25 cm is shown.

If the results in Fig. 4 are studied a consistent trend can be identified. As the resolution increases, the extent of inundation decreases. This is shown most dramatically for the area inundated to 25 cm. However the same trend may be identified in Table 3 for inundation depths of 10 and 5 cm, especially at the beginning and the end of the simulation. This is a direct consequence of the effect of channel size; the lower the mesh resolution, the wider the channel. This is similar to the problem discussed earlier with the loss of information resulting from mesh filtering and may not be a direct effect of the effect of resolution on the solution of the equation but is caused by the filtering of topography by the mesh.

4.3. Relative sensitivity of spatial resolution and calibration

This section is directed towards assessing the transferability of parameter values between meshes representing the same reach, but of different resolutions. Calibration of models can often be a computationally demanding procedure, and this operation may be

Table 3
The effect of resolution on the percentage of the domain inundated

Inundation depth. (cm)	Percentage of domain inundated for mesh						
	1	2	3	4	5	6	7
25	21.11	18.46	15.58	12.89	12.42	11.44	11.08
10	73.45	73.25	73.40	75.67	74.01	76.07	74.71
5	96.97	97.17	97.03	97.84	96.82	96.82	96.10

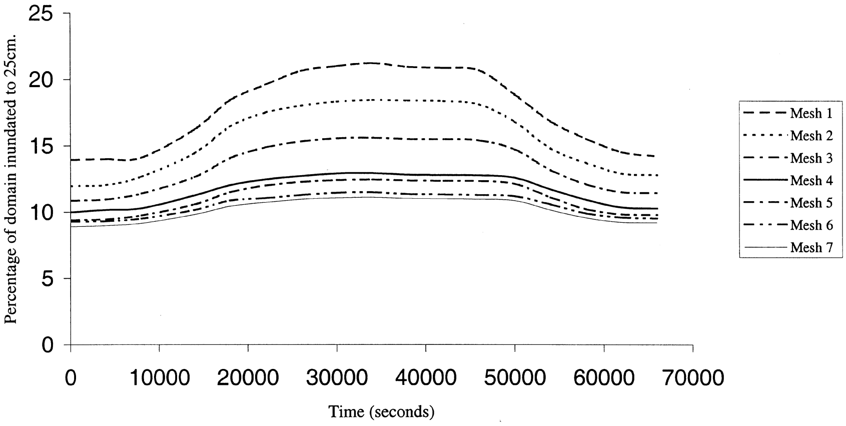


Fig. 4. The effect of resolution on inundation extent to 25 cm for event 2.

made more efficient if models can be calibrated on a low resolution, computationally efficient model, and then parameter values transferred to a higher resolution model. For this investigation, event 2, the intermediate event where up to 50% of the domain was flooded, was used as the input hydrograph. The simulation of this event using mesh 4 from the aforementioned analysis was designated as the control and further simulations conducted using a range of floodplain friction values ($n = 0.111$, 0.083 and 0.056, respectively). The channel friction coefficient ($n = 0.025$) was retained for each simulation as previous work (Hardy, 1997) has demonstrated that floodplain friction has a far greater effect on model results compared with channel friction. If the relationship between the spatial resolution, the friction calibration coefficient and the model efficiency is studied, Fig. 5, a definite pattern emerges. The graph may be

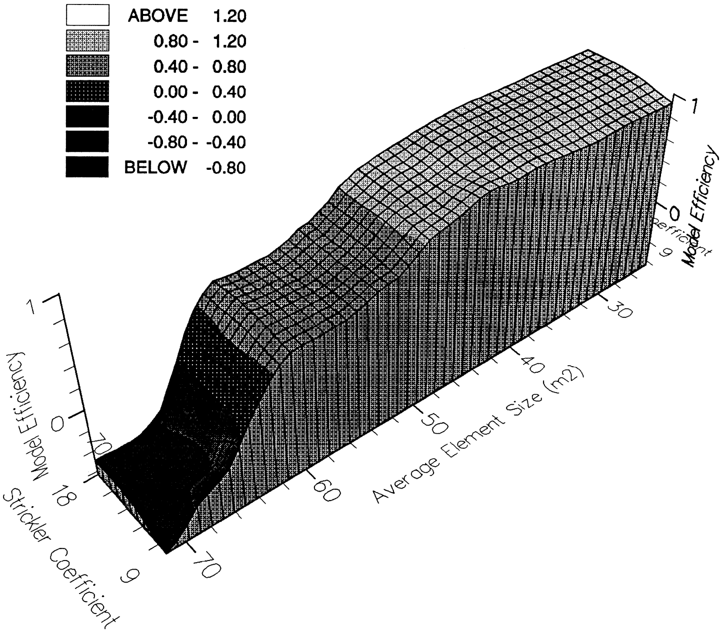
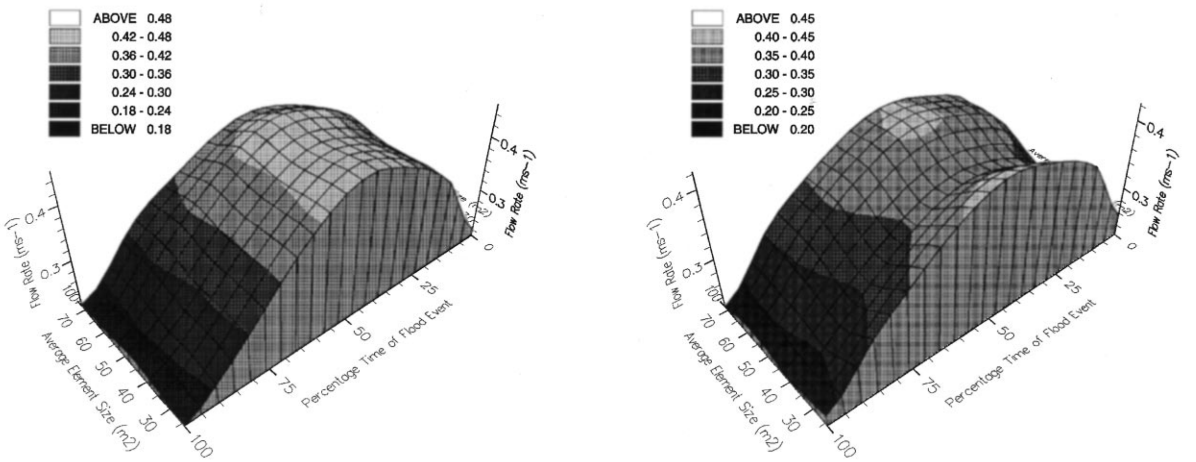


Fig. 5. The relationship between friction, spatial resolution and model efficiency.

Table 4
The co-ordinates of the points used for the in-domain analysis of the scalar flow rate and water depth

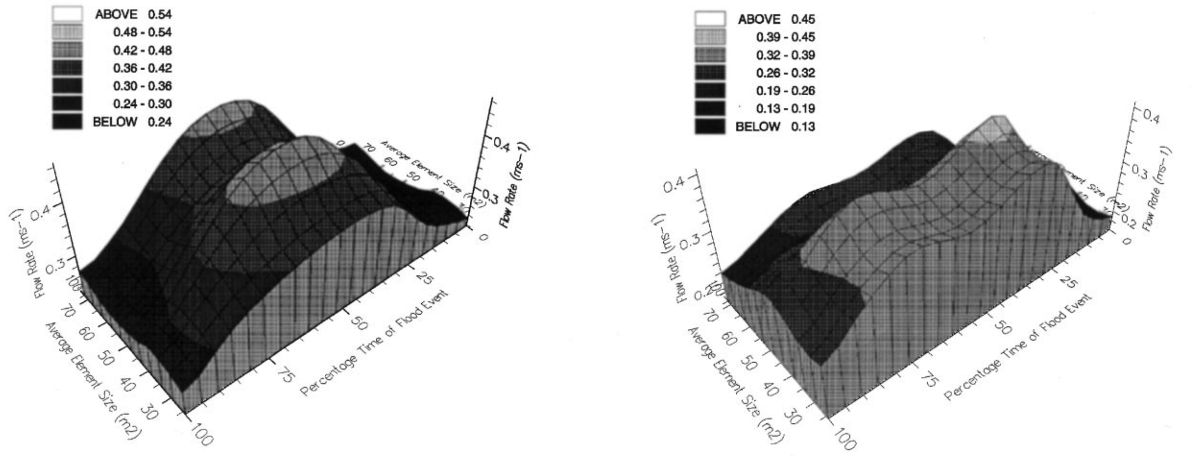
CO-RD.	Points used for in-domain domain analysis							
	1	2	3	4	5	6	7	8
X	551.19	548.32	760.54	778.91	998.24	1003.56	1856.35	1842.32
Y	− 110.25	− 129.52	− 50.35	− 108.56	150.23	130.48	50.45	− 5.86

divided into three distinct sections by spatial resolution boundaries. In the first region where element sizes are greater than 53 m^2 the model efficiency (Nash and Sutcliffe, 1970) is less than 0.5 showing a low predictive ability. In the second most critical region between element areas 53 and 43 m^2, there is a dramatic increase in model efficiency, from 0.5 to 0.9. Increasing the spatial resolution below 43 m^2



a). The velocity at point 2 for event 2.

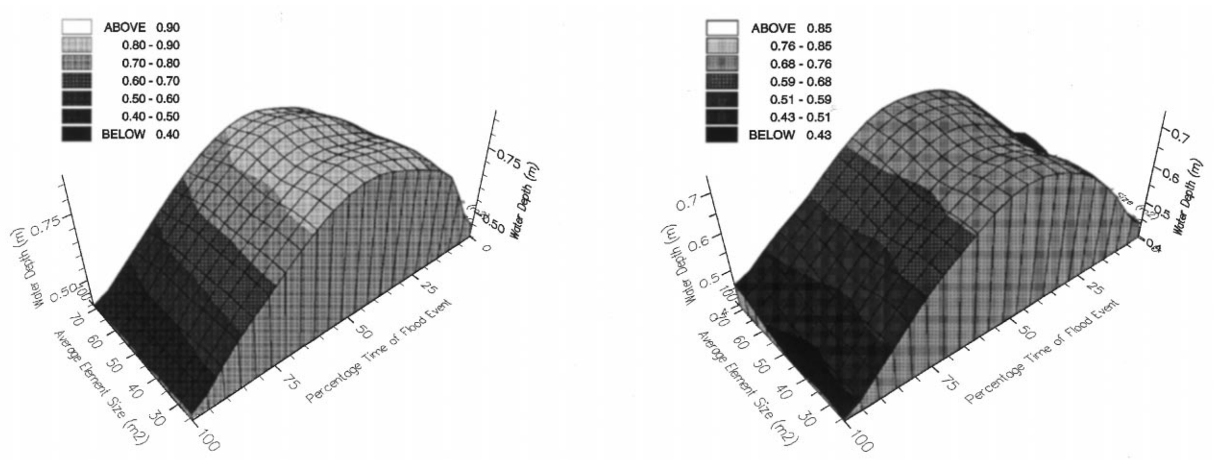
b). The velocity at point 4 for event 2.



c). The velocity at point 6 for event 2.

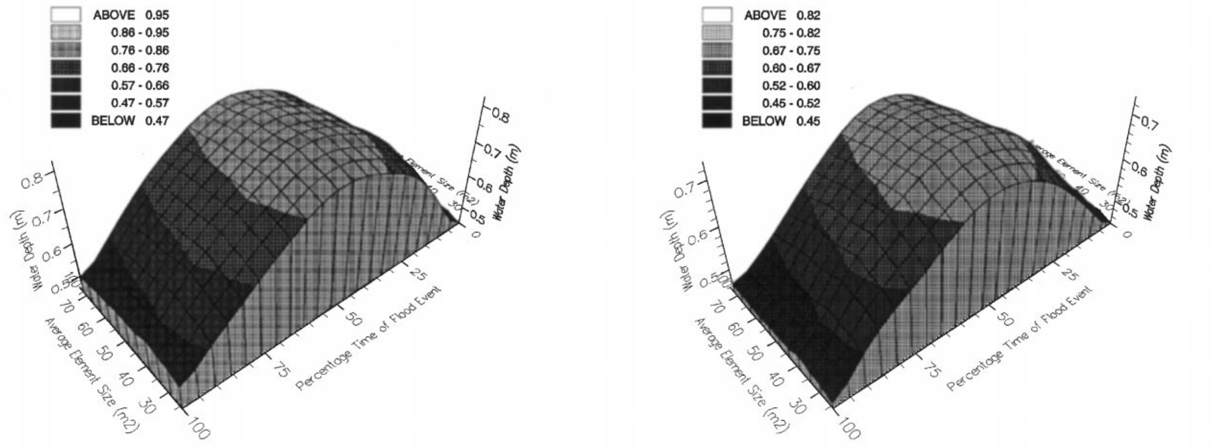
d). The velocity at point 8 for event 2.

Fig. 6. The effect of spatial resolution on the internal velocity predictions.



a). The water depth at point 2 for event 2.

b). The water depth at point 4 for event 2.



c). The water depth at point 6 for event 2.

d). The water depth at point 8 for event 2.

Fig. 7. The effect of spatial resolution on the internal water depth predictions.

appears to have little, if any, effect on improving the model's efficiency. If the effect of the friction coefficient is studied, there appears to be little impact on the model efficiency with no definite pattern emerging. The graph suggests that the spatial resolution has a greater effect on the model's predictive ability than does the typical calibration parameter.

4.4. In-domain results

Eight nodal points were identified within the domain at which individual hydraulic results (*h*, *u* and *v*) were analysed. Owing to the manner in which these meshes were constructed, in the I-DEAS mesh generation package, only in-channel and nodal points on banks had identical *x*, *y* co-ordinates for all seven meshes, thus directly affecting the choice of points. This was, however, felt to be a necessary requirement for rigorous inter-comparison of mesh resolution effects. The location of the points is demonstrated in Table 4. The results presented here are from the simulations of events 2 by analysis of scalar flow rate (resolving *u* and *v*) and water depth. Whilst possible auto-correlation effects between mesh resolutions makes the interpretation of these results rather complex, analysis of results showed an embedded pattern of systematic behaviour which could be used to formulate a first-order analysis.

4.4.1. Scalar flow rate at identified internal points

These results are shown in Fig. 6(a)–(d). The most identifiable pattern in all the graphs is the hydrograph direction, with the velocity increasing to the peak then decreasing variation with changing spatial resolution is of more interest. The differences in the calculated velocity can be quite dramatic and are demonstrated in Fig. 6(b) (the result from point 4). Primarily, there is an increase in the velocity as the element decreases in size and later the velocity levels-off. However, below a spatial resolution of 54 m^2 there is a dramatic decrease in the velocity rate prior to a rapid increase for the highest resolution mesh. The scalar flow rate ranges from 0.367 to 0.424 $m\,s^{-1}$, a difference of 15.53%. This pattern was also identified for the same location in event 3 with a 14.84% variation in the scalar flow rate at the peak flow.

Similar patterns may be identified for the other points although there is no consistency in the trends from mesh to mesh. Trends are, however identifiable from event to event, suggesting that it is somewhat dependent on the geographical location of the nodal point within the domain. This may be because of a number of factors including the complex feedback processes operating in the domain as well as the effect of spatial discretization on the governing equations.

4.4.2. Water depth at identified internal points

The results are shown in Fig. 7(a)–(d). These indicate very similar patterns and interestingly, not an inverse pattern, to those identified in the velocity rate through the hydrograph direction. If the node is located in an 'active' region of the mesh, such as the outer section of a meander bend where water tends to move out of bank, the difference in the simulated variables will be greater than in an 'inactive' area, such as the outer floodplain, where the effect of mesh resolution may not have such a great effect.

The results from this analysis have not produced clearly identifiable trends, in contrast to the analysis of the bulk flow. However, it has been demonstrated that the spatial resolution has a dramatic effect on internal hydraulic predictions. The geographical location within the domain is also an important factor, although it is not yet possible to identify a location and characterise the trend. For example, by having a nodal point on the apex of the meander bend, water depth will increase with spatial resolution, although the solution will be a reflection of calculations made at surrounding nodes and thus imply spatial feedback. It is therefore not possible to dissect these results much further, though the analysis enables a cautionary note to be made that the choice of element size is extremely important and will directly affect the internal hydraulic predictions.

5. Discussion

The results obtained in this paper have indicated the importance of spatial resolution to the predictions obtained from numerical simulations. This is an important result as in a classical sense all the meshes used in this analysis fulfil the traditional criteria of flow length physics typically used to condition the choice of mesh resolution. Yet within this range of physically acceptable solution significant variation in model results was noted. The results have also indicated that:

- Spatial resolution directly affects bulk flow characteristics. For the meshes studied, as the element size decreases, bulk flow increases up to a point of the penultimate mesh. The bulk flow characteristics for the highest resolution mesh, however, decrease.
- Spatial resolution directly affects inundation extent although it may be an effect of the loss of topographic information.
- Spatial resolution has a greater effect than the typical calibration parameter, friction, in altering the hydraulic simulations. This indicates that initial model set-up needs to be carefully considered and the transfer of parameter values should not occur.
- The spatial resolution has a dramatic effect on the internal results. Identification of systematic trends is not feasible owing to the complex nature of the system; however, the effect of the spatial resolution should always be considered.

Understanding the effects of mesh resolution in the development of a high resolution space/time model is clearly vital. Moreover, one of the advantages of the finite element technique is that the concentration of elements in a specific area can be increased if this region is believed to be sensitive. This needs to be reconsidered, as the same is true if an adaptive meshing technique is applied, where the topographic gradient determines the concentration of elements. If an area has a high concentration of elements (whether it is a subjective decision by the mesh user or has been created by the mesh generation procedure), then the simulated hydraulics (h, u and v) may be different in that area from what they would be if an equally weighted element size mesh had been created. This is demonstrated in the 15% variation of the scalar flow rate for a variation in mesh resolution. Although most hypotheses assume that the higher the spatial resolution the closer the simulated hydraulics are to the true solution, for field simulations there is currently no means of telling how close to the true solution the mesh actually is. It therefore appears that a complex feedback process operates within the modelling system driven by the spatial resolution of the mesh and has not previously been identified when applying distributed models to natural environments.

Against this background the three central questions we raised in relation to evidence of consistency with process equations, mesh resolution guidelines and new inter-comparison methods are thus perhaps ambitious. Their centrality in terms of model inference has, however, been demonstrated by the results from this investigation, particularly given their prominence in a relatively small sample of the whole model parameter space.

We can, however, recommend that any future modelling projects, whether for this or other environmental problems, should construct at least four meshes of different spatial resolutions to ascertain the envelope of response to spatial resolution. This would enable the construction of boundaries for the mesh development, prior to more complex calibration processes. The transfer of such information, in the construction of a numerical algorithm relating spatial resolution to reach size in a more general sense, is not possible according to this initial study. However, further studies of this nature may provide an improved insight enabling a clearer definition of mesh/spatial boundaries to be achieved.

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