The Institution of Engineers, Australia
Conference on Hydraulics in Civil Engineering
Hobart 28 –30 November 2001

Improving the Performance of a Two-dimensional Hydraulic Model for Floodplain Applications

A.D. McCowan
B.E.(Hons), Dip H.E.(Delft), PhD, F.I.E.Aust
Principal, Water Technology, Melbourne
E.B. Rasmussen
M. Eng. Sci.
DHI Water & Environment
P. Berg
M. Eng. Sci. PhD
DHI Water & Environment

Abstract: This paper describes some of the recent developments that have been made to MIKE 21, as part of the new MIKE Flood modelling system. These developments have been aimed at increasing the robustness of the flooding and drying routines, and at extending MIKE 21's capability to include modelling of high Froude Number flows. Through these improvements, it has been possible to carry out realistic simulations of flood wave propagation over an initially dry bed, and of a range of high Froude Number flow conditions, including super-critical flows, broad-crested weir flows, hydraulic jumps and even dam-break flows. The emphasis in making these changes has been on ensuring that the high accuracy and computational efficiency of the MIKE 21 numerical solution procedure has been maintained.

Keywords: Two-dimensional, Floodplain Modelling, Flooding, Drying, Super-critical Flow, MIKE 21

1 INTRODUCTION

Over the last decade, there has been an increasing use of fully two-dimensional hydraulic models for the investigation of flood flows, particularly through urban areas. (See for example Bishop et al, 1995, Collins et al, 1999, or McCowan and Daly, 2000). Until relatively recently (Stelling et al, 1998), most of the models that have been used for two-dimensional floodplain simulations have had their origins in estuarine and coastal flow modelling. As such, many of these models have not necessarily been well suited to this new flood-modelling role. This is because most coastal and estuarine models are not designed to consider the high Froude Number (and even super-critical) flows that can occur under flooding conditions, and cannot properly describe flooding of initially dry land down a sloping floodplain.

DHI Water and Environment's MIKE 21 two-dimensional modelling system has been one of the leading models used in full two-dimensional flood analysis throughout Australia. Over the years there have been a number of improvements to MIKE 21 to enhance its ability to model floodplain flows. These have included on-going improvements to the flooding and drying routines, and the incorporation of routines for describing hydraulic structures. Until recently, however, the general release version of MIKE 21 has not had the capability to model super-critical flows.

This paper describes some of the recent developments that have been made to MIKE 21, as part of the new MIKE Flood modelling system. These developments have been aimed at increasing the robustness of the flooding and drying routines, and at extending MIKE 21's capability to include modelling of high Froude Number and super-critical flows. The emphasis in making these changes has been on ensuring that the high accuracy of the numerical solution procedure used by MIKE 21 is maintained.

A number of examples have been used to illustrate the effectiveness of the new developments. These include simulations of:

- A range of typical floodplain flow scenarios.
- Sub-critical to super-critical flow transition and subsequent hydraulic jump formation.
- Dam-break flows over an initially dry floodplain.

2 BACKGROUND

MIKE 21 is based on the numerical solution of the depth-averaged equations describing the conservation of mass and momentum in two horizontal dimensions. In a simplified form, these equations can be expressed as:

Mass: $$\frac{\partial s}{\partial t} + \frac{\partial(ud)}{\partial x} + \frac{\partial(vd)}{\partial y} = 0$$

x-Momentum $$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial s}{\partial x} + \frac{gu\sqrt{u^2+v^2}}{C^2 d} + E\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) = 0$$

y-Momentum $$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y} + u\frac{\partial v}{\partial x} + g\frac{\partial s}{\partial y} + \frac{gv\sqrt{u^2+v^2}}{C^2 d} + E\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) = 0$$

Where: s is the free surface elevation, u and v are the depth averaged velocities in the x and y directions, d is the water depth, C is a Chezy bed-friction coefficient, and E is an eddy viscosity coefficient.

These equations are solved using finite difference approximations, and an alternating direction implicit (ADI) scheme. The basic properties of this type of scheme have been discussed at length by Abbott et al (1981). These include unconditional stability, in the linear sense. This means that there is no stability limit on the time step, which must then be determined by accuracy requirements.

Since the introduction of the first System 21, the forerunner of MIKE 21 (Abbott et al 1973), the main emphasis on model development has always been on maintaining a high level of accuracy in the numerical solution. This has been achieved through time and space centring of all the main terms in the equations, and taking particular care with the numerical description of the non-linear convective momentum terms (Abbott and Rasmussen, 1977). In this way it has been possible to maintain second-order accuracy, without the characteristic "zig-zagging" or "wiggles" associated with most second-order convection schemes (Leonard, 1976).

With the inclusion of a "Smagorinsky-type" eddy viscosity formulation (after Smagorinsky, 1963), it was then possible to obtain realistic simulations of flow separations and eddy formation associated with rapid expansions and wakes behind structures.

The formation of an eddy at a rapid expansion, such as may occur downstream of a bridge abutment, is shown in Figure 1. For this example, the water depth was initially uniform at 1.0m, and the upstream inflow velocity was set to 1.0m/s. The model grid size was 5.0m, and the time step 1.0s.

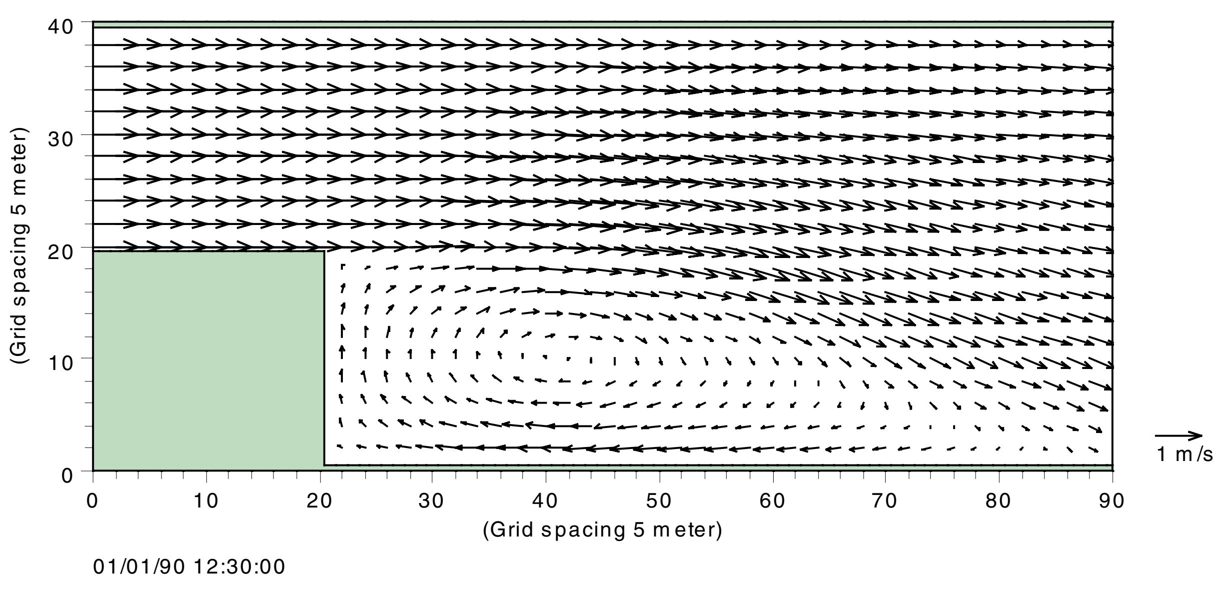

Figure 1 - Example of Eddy Formation Downstream of a Rapid Expansion

The application of two-dimensional models, such as MIKE 21, to simulating the hydrodynamics of estuaries, bays and coastal seas has been well proven through almost three-decades of practical experience. Although the basic modelling principles remain the same, experience has shown that there are a number of areas that may require additional attention before coastal two-dimensional models can be successfully applied to floodplain studies. These include:

- Flooding and drying algorithms to simulate realistic flooding of initially dry land down sloping floodplains, and provide correct reproduction of flood wave propagation.
- Modelling of steep gradients, and even locally super-critical flows.
- The incorporation of hydraulic structures such as, weirs, culverts and bridges.

Work carried out to improve the performance of MIKE 21 with respect to the first two of these points is described below. The incorporation of hydraulic structures has been carried out by coupling MIKE 21 with the structures routines from the MIKE 11. This and other developments that have been made as part of the new MIKE Flood modelling system are reported elsewhere.

3 FLOODING AND DRYING

3.1 Coastal Applications

In most coastal applications, the flood and dry algorithms need only cope with the periodic flooding and drying of relatively small areas of almost horizontal inter-tidal flats. In these applications, the main issues are in determining when to flood (or dry) a particular grid point, and how to cope with numerical transients that may be generated when grid points are added or subtracted from the computation. The former of these can be a particular problem with models based on the numerical scheme of Leendertse (1967). This is because the grid points defining the water surface elevations are offset from the grid points containing the bed surface elevations. This can create problems with determining when a grid point should be flooded or dried. As the Leendertse scheme forms the basis of many estuarine/coastal models, much of the published work on flooding and drying (see for example Falconer and Chen, 1981, or Stelling et al, 1986) has been concentrated on improving the flooding and drying characteristics of Leendertse-type models.

In MIKE 21 the grid points containing the water surface and topographic information are coincident. This makes identification of grid points to be flooded or dried relatively straight-forward. In its original coastal form, the main features of the flooding and drying scheme were as follows:

- Flooding of an initially dry grid point would be carried out when the water surface elevation in any of the adjacent grid points was above the bed level of the grid point being considered plus a small flooding threshold depth. Once a grid point was flooded, further checks would be carried out to see whether the next dry grid point also met the flooding criterion and, if so, the next, and so on. This allowed for sequential flooding of multiple grid points within a single time step.
- Drying of a water point would be carried out when the water depth in that particular grid point fell below a small drying threshold depth.
- If a particular grid point met both the flooding and drying criteria, then the flooding criterion prevailed. That is, grid points would be kept "wet" wherever possible.
- Numerical transients, that could be generated as grid points were brought into (or removed from) the computation, were controlled by bed-friction. This was done by weighting the water depth used in computing the friction associated with flows, into or out of shallow grid points, heavily toward the depth in the shallower grid point.

This approach was found to perform adequately in most coastal applications. It was also very efficient as computation is only carried out in the grid points that are actually flooded at any particular time.

3.2 Extension to Floodplain Modelling

Experience gained in early two-dimensional flood models showed that there could be a number of problems associated with applying the above approach to floodplain studies. These early problems included:

- Numerical flood induced mass errors: Although MIKE 21 ensures conservation of mass during repeated flooding and drying cycles, an initially dry grid point was assumed to have a user specified initial depth (typically 0.2 or 0.3m in coastal models) when it was flooded for the first time. Potential errors from this source could be minimised by setting the initial flooding depth to a small number, such as 0.01 or 0.02m.
- Sticking grid points: With high velocity floodplain flows MIKE 21 would occasionally compute an extremely small, or even negative, water depth. When this occurred the water depth would be reset to a small number (default = 0.0002m) to enable the computation to continue. In some instances the shallow weighting of the friction term would result in the friction becoming so high as to preclude significant flow into or out of such a grid point, irrespective of the water level in adjacent grid points. Allowing the user to increase the reset value (typically to 0.01m) helped significantly, but some sticking problems persisted.
- Retarded propagation of flood wave fronts: When modelling steeply rising floods, it was found that the shallow water weighting of the friction term could result in the front of a flood wave propagating more slowly than it should. Increasing the default reset value (discussed above) improved the situation, but some problems persisted, particularly with very steeply rising hydrographs, such as can occur in dam-break simulations.

3.3 Approaches Considered

A number of approaches were considered for overcoming the remaining problems described above. These included the introduction of "slots" in all floodable grid points to enable the computation to continue over initially dry but floodable land. This approach had been used successfully in earlier experiments at DHI. The use of slots would overcome the sticking problems and could be implemented in such a way as to provide the correct propagation speed of a flood wave front. However, there can be problems with slots when modelling flows in steep terrain, and the use of slots would be expected to increase the computational time significantly.

An alternative approach has been put forward by Stelling et al (1998). They presented a new numerical scheme that has been aimed specifically at describing two-dimensional flows in floodplain applications. The Stelling scheme imposes a condition that water depths remain positive, allowing the computation to proceed even when the water depth is zero (i.e., the grid point is effectively dry). The scheme appears to work well, but includes significant numerical dissipation through (amongst other things) up-winding of the convective terms in the momentum equation. With computation continuing on effectively dry grid points, it could also be expected to increase the computational time significantly. As such, the overall approach was not considered appropriate for general introduction to MIKE 21.

3.4 Modifications to the MIKE 21 Flood and Dry Scheme

The Stelling et al (1998) scheme also included up-winding of the water depth used in the computation of the friction term. This approach appeared to have particular promise for overcoming the remaining problems associated with the existing MIKE 21 flood and dry scheme. This is because up-winding of the water depth used in the friction term would result in the friction for flow from a deep grid point to a shallow grid point being calculated on the basis of the water depth in the deep grid point. Conversely, the friction for flow from a shallow grid point to a deep grid point would be calculated on the basis of the water depth in the shallow grid point. This would make it relatively easier for water to flow into a shallow grid point, and more difficult for it to flow out. Intuitively, this was considered to be a more physically realistic approach.

Accordingly, up-winding of the water depth used in the friction term was introduced into MIKE 21. After extensive testing, it was found that with this approach, it was possible to:

- Use very small initial flooding depths (<0.001m), thereby eliminating the mass balance problems associated with the initial flooding cycle.
- Eliminate sticking points, as the friction for flows into initially dry, or very shallow grid points, is determined by the water depth in the upstream grid point.
- Improve the flood wave propagation characteristics, through the elimination of the shallow water weighting of the friction term for inflow to shallow grid points. As a result, the dynamics of the flood wave now determine the main propagation characteristics of a flood wave.

A numerical example has been used to illustrate the effectiveness of the revised flood and dry scheme. The example involved water spilling out over a wide, initially dry horizontal bed, and then down slopes with gradients of 1:100 and 1:50. The grid size was 5.0m and the time step was 1.0s. The discharge at the upstream boundary was held constant at 1.0m^2/s per metre width of floodplain. The water surface elevation at the downstream boundary was set to a constant level of 0.0m. The bed roughness was equivalent to a Manning's *n* of 0.03 over the floodplain.

The results obtained using the original MIKE 21 flood and dry scheme are presented in Figure 2. This shows profiles of water depths at 30-second intervals after the water first began to spill out over the floodplain. Artificial build-up of the water surface behind the wave front is clearly evident, particularly on the steeper 1:50 slope. Here the height of the wave front has become more than twice the equilibrium depth for uniform flow in this region.

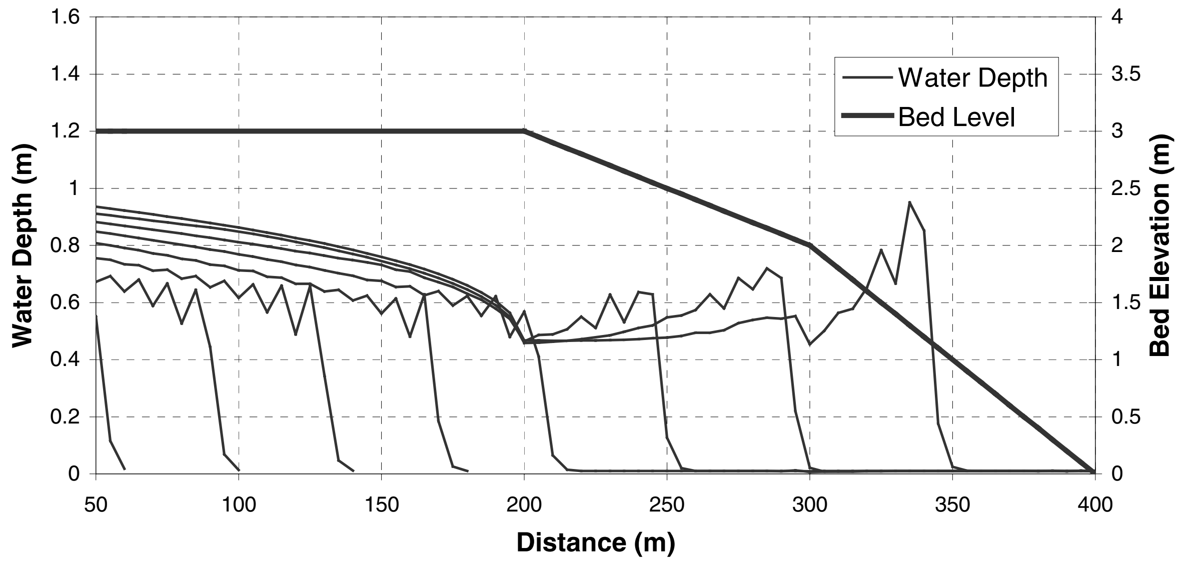

Figure 2 - Water Depth Profiles Computed Using the Original MIKE 21 Flood and Dry Scheme

The corresponding results for the revised flood and dry scheme are presented in Figure 3. This shows the flood wave propagating more smoothly out over the floodplain. The front propagates approximately 20% faster than with the original scheme, and there is no artificial build up of water behind the front.

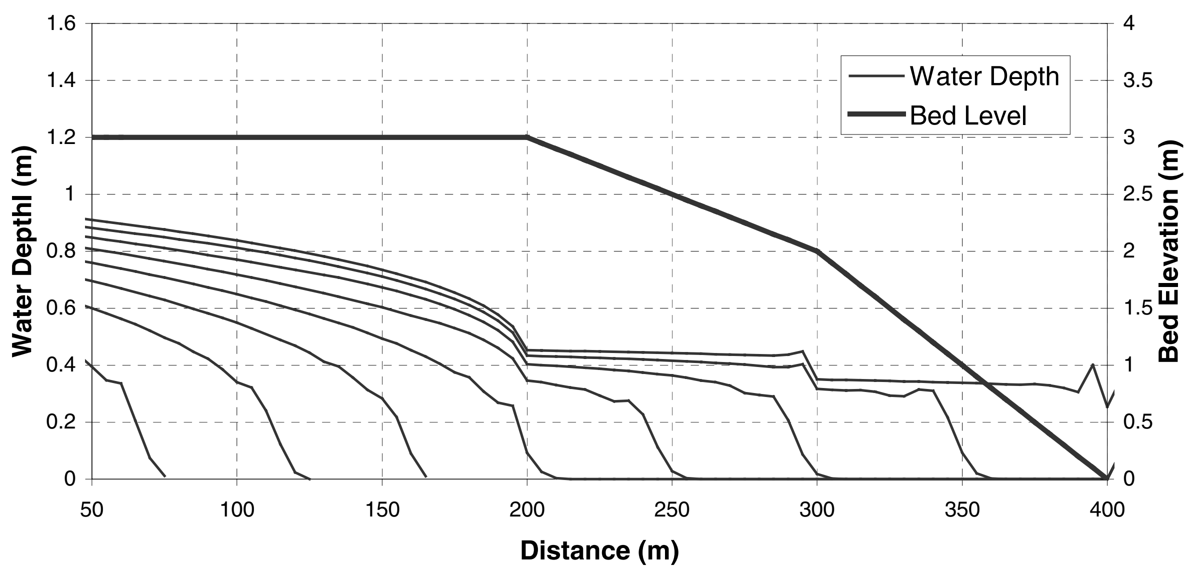

Figure 3 - Water Depth Profiles Computed Using the Revised Flood and Dry Scheme

Down the steeper 1:50 slope, the flow goes super-critical in both cases. Once the wave front hits the downstream boundary condition, the solution procedure becomes ill-conditioned, and large amplitude oscillations build-up over the super-critical region, as shown in Figure 4. For the original MIKE 21 scheme, the effects of build up behind a "sticking" grid point are clearly evident at a distance of about 350m downstream.

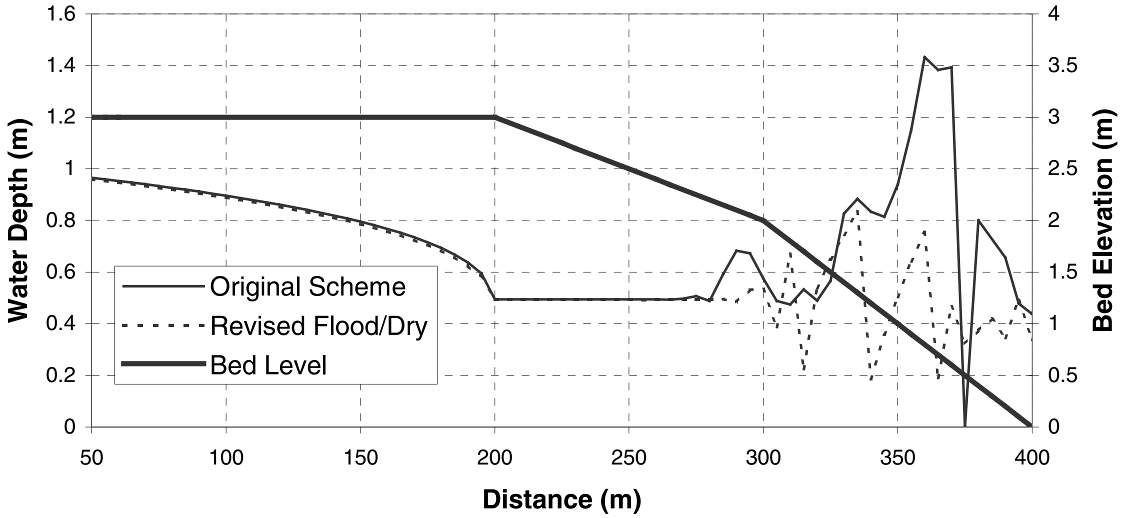

Figure 4 - Build up of Large Amplitude Oscillations over the Region of Super-Critical Flow

The revised flood and dry scheme was found to work well in most applications. In some cases, however, numerical transients during flooding or drying would cause locally super-critical flows, which in turn would result in unrealistic oscillations and even instability. As such, it was found that the revised scheme could only be used reliably in conjunction with the modifications for high Froude Number flows, discussed below.

4 HIGH FROUDE NUMBER FLOWS

In most floodplain applications, high velocity and even super-critical flows can occur frequently. However, the structure of most two-dimensional coastal models, including MIKE 21, is restricted to modelling sub-critical flows, where the Froude Number *Fr* is less than one. That is, where:

$$Fr = u \big/ \sqrt{gd} < 1.0$$

Further, in areas of high velocity gradients, it has been found that time and space-centred (non-dissipative) approximations to the convective momentum terms, as used in MIKE 21, can lead to unrealistic oscillations and even local instabilities in the numerical solutions (Leonard, 1976).

4.1 Selective Numerical Dissipation

In MIKE 21, the selective introduction of numerical dissipation has been used to improve the robustness of the numerical solution in areas of high velocity gradients, and to provide the capability to simulate locally super-critical flows. The rationale behind this approach is that the numerical dissipation introduced at high Froude Numbers can be considered to be roughly analogous to the physical dissipation generated by hydraulic jumps, and/or increased levels of turbulence in high velocity flows.

Two approaches to introducing the numerical dissipation were considered. These were:

- Selective application of a numerical filter.
- Selective up-winding of the convective momentum terms.

With both these approaches, the numerical dissipation was introduced selectively through a weighting factor α, which is applied to the finite difference terms providing the numerical dissipation, and where:

$$\alpha = 0.0 \qquad Fr \le 0.25$$

$$\alpha = 1.3333.(Fr - 0.25) \qquad 0.25 < Fr < 1.0$$

$$\alpha = 1.0 \qquad Fr \ge 1.0$$

This brings the effects of numerical dissipation in gradually as the Froude Number increases from 0.25 to 1.0.

The weighting factor α for each grid point is calculated every time step, immediately prior to the calculation of the momentum equation coefficients. This ensures that numerical dissipation is only introduced at grid points where high Froude Number flow is occurring, and that the normal high accuracy solution of MIKE 21 is obtained throughout the rest of the model domain.

4.2 Numerical Filtering

With this approach, a numerical filter was applied to the velocity variables at the old time step in the numerical approximation to the $\partial u/\partial t$ and $\partial v/\partial t$ terms in the x and y momentum equations. For computation from time step nΔt to time step (n+1)Δt, the $\partial u/\partial t$ term in the x momentum equation, centred on the jth grid point, can be approximated as follows:

$$\frac{\partial u}{\partial t} \approx \frac{\Delta u}{\Delta t} \approx \frac{(u^{n+1} - u^{n})_j}{\Delta t}$$

Introducing the "dissipative interface" of Abbott (1979), as a filter on the velocity variable at the old nΔt time step, this term can be approximated by:

$$\frac{\partial u}{\partial t} \approx \frac{\Delta u}{\Delta t} \approx \frac{u_j^{n+1} - \left[\beta.u_{j-1} + (1-2\beta)u_j + \beta.u_{j+1}\right]^n}{\Delta t}, \qquad \text{where } \beta = \alpha/2$$

Using a Taylor's series expansion, this expression can be rearranged to form:

$$\frac{u_j^{n+1} - \left[\beta.u_{j-1} + (1-2\beta)u_j + \beta.u_{j+1}\right]^n}{\Delta t} \approx \frac{\partial u}{\partial t}_j - \beta.\frac{\Delta x^2}{\Delta t}.\frac{\partial^2 u}{\partial x^2} + O\left[\Delta x^4\right]$$

That is, the filter introduces a numerical dissipation term of the same form as the main eddy viscosity term in the x-momentum equation, but with an effective eddy viscosity coefficient of $\alpha.\Delta x^2/2\,\Delta t$. For a typical floodplain application, where the grid size may be typically 10m and the time step 1s, the effective numerical eddy viscosity coefficients may be an order of magnitude or more greater than physically realistic values. The numerical dissipation introduced in this way, is frequency dependent, and has its greatest effect on high frequency oscillations of the type shown in Figure 4, above.

It is noted that, when α = 1, the numerical approximation to the time derivative reduces to the form attributed to Lax (1954), and that the "Lax scheme" has often been used for modelling hydraulic jumps and super-critical flows (Abbott, 1979).

When introduced into the MIKE 21 solution procedure, a filter, similar to that described above, damped out the tendency for unrealistic oscillations to occur in regions of steep velocity gradients, and allowed the computation to continue through regions of super-critical flow. It was found, however, that the smoothing effect of the filter was most noticeable on the velocity variables, and that some oscillations in water levels persisted in super-critical flow regions. As such, this approach has not been introduced into the production form of MIKE 21. (It is noted that a similar filter could not be used on the $\partial s/\partial t$ time derivative term in the mass equation. This was because mass conservation could not be assured when using variable α factors in the vicinity of steep water surface gradients.)

4.3 Up-Winding of the Convective Momentum Terms

With this approach, the centring of the numerical approximation to the convective momentum terms is selectively "up-winded" in the direction from which the flow is coming.

In a form centred on the jth grid point in the x-direction, the $u\partial u/\partial x$ term in the x-momentum equation can be approximated as:

$$u\frac{\partial u}{\partial x}_j \approx \frac{u}{2\Delta x}\left(u_{j+1}-u_{j-1}\right)$$

For flow in the positive x-direction, the selectively up-winded approximation to this term can be expressed as:

$$u\frac{\partial u}{\partial x}_j \approx (1-\alpha)\frac{u}{2\Delta x}\left(u_{j+1}-u_{j-1}\right)+\alpha\frac{u}{\Delta x}(u_j-u_{j-1})$$

Using a Taylor's series expansion, this expression can be rearranged to form:

$$(1-\alpha)\frac{u}{2\Delta x}\left(u_{j+1}-u_{j-1}\right)+\alpha\frac{u}{\Delta x}(u_j-u_{j-1}) \approx u\frac{\partial u}{\partial x}_j - \alpha\frac{u\Delta x}{2}\frac{\partial^2 u}{\partial x^2}+O\left[\Delta x^2\right]$$

As for the filter considered above, it can be seen that up-winding the convective momentum terms also introduces a numerical dissipation term of the same form as the main eddy viscosity term. As before, the effective numerical eddy viscosity coefficients may be an order of magnitude or more greater than physically realistic values. Similarly, the numerical dissipation is frequency dependent, and has its greatest effect on high frequency oscillations.

In numerical testing, it was found that selective up-winding of the convective momentum terms also damped out the tendency for unrealistic oscillations to occur in regions of steep velocity gradients, and also allowed the computation to continue through regions of super-critical flow. With the up-winding approach, however, it was found that the implementation could be adjusted such that the numerical dissipation smoothed out oscillations in both the water level and the velocity variables. As such, selective up-winding of the main convective momentum terms has been introduced into the production version of MIKE 21.

5 TEST EXAMPLES

The revised MIKE 21 has now been tested over a wide range of test examples and practical floodplain applications. The results from a selection of test examples are presented below.

5.1 Variable Steepness Floodplain

The numerical example from Section 3.4, that was used to illustrate the effectiveness of the revised flood and dry scheme, was repeated with the up-winding of the convective momentum terms in place. Results corresponding to those given in Figure 4 are presented in Figure 5. These show that, in the horizontal and 1:100 slope sections of the floodplain, the results for the fully revised MIKE 21 scheme are comparable to those obtained when only the flood and dry procedure was modified. In the steeper 1:50 slope section it is clear that the up-winding of the convective momentum terms allows stable computation to continue throughout this region of super-critical flow. It is noted that the flow velocity in this region is approximately 2.5m/s giving a Froude Number, Fr $\approx$ 1.25.

5.2 Overtopping of a Levee Bank

The exercise in Section 5.1 was modified by introducing a 2.0m high levee bank approximately two-thirds of the way along the horizontal part of the floodplain. The results presented in Figure 6 show a build up of water behind the levee bank to a level of about 0.7m above the crest level of the levee. This is consistent with the level computed by standard broad-crested weir formulae. The flow becomes super-critical on the downstream face of the levee bank (with Froude Numbers of Fr > 2.5), and there is a drowned hydraulic jump at the base of the levee. Further downstream, the results are virtually identical to those presented in the previous example.

It is noted that for the results presented below, two grid points were used to resolve the width of the levee bank crest. If only one grid point is used to resolve the levee bank then the surface level of the water behind the levee may be 30% lower than that predicted by a broad-crested weir formula. In this situation, the broad-crested weir formulation built in to MIKE 21 should be used. Further work is continuing to enable realistic computation of flows over single grid point wide levee banks.

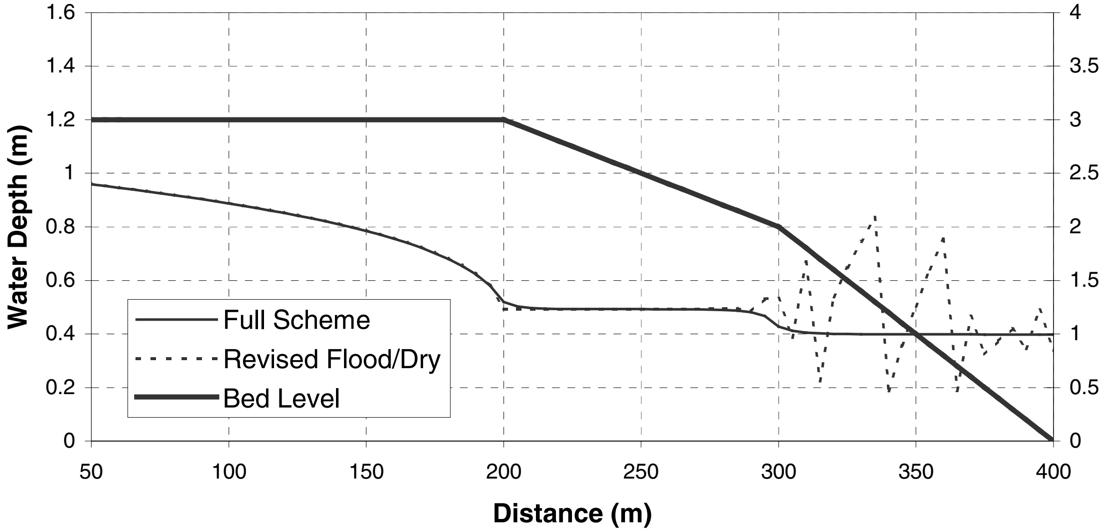

Figure 5 - The Effect of Up-winding the Convective Momentum Terms on Floodplain Flows

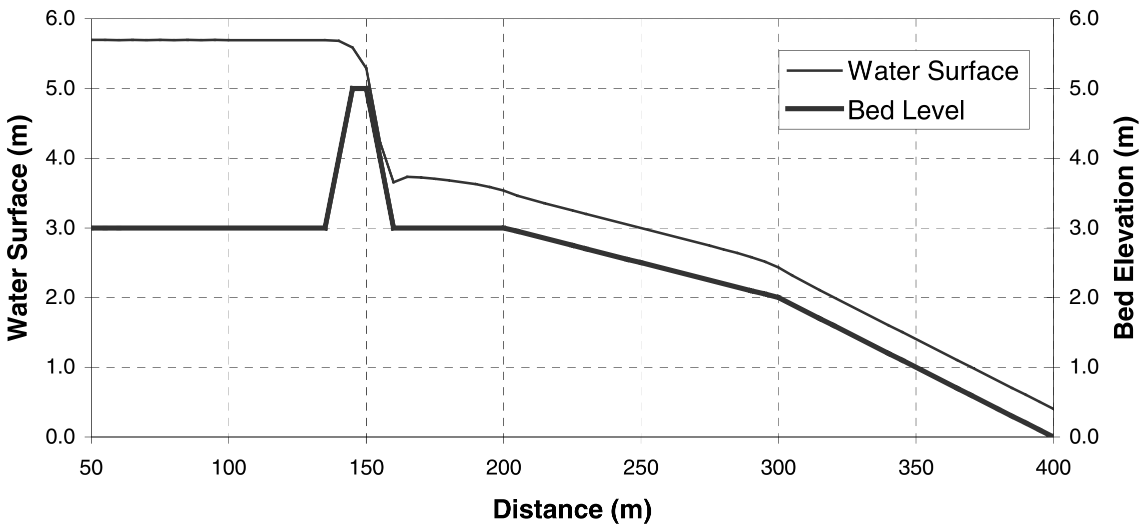

Figure 6 - Over-topping of a Levee Bank Using the Revised MIKE 21 Scheme

5.3 Hydraulic Jump Simulation

The hydraulic jump example is that of Stelling et al (1998). It consisted of a 500m long channel having an initial bed level of 0.0m. The central 100m of the channel bed was raised to an elevation of 5.0m, with sinusoidal approaches as shown in Figure 7. A uniform discharge of $20m^2/s$ per metre width of channel was applied to the upstream boundary, and the downstream tailwater level was set constant at 7.0m. The model had a grid size of 2.5m and a time step of 0.1s. The bed roughness was equivalent to a Manning's *n* of 0.03.

The results in Figure 7 show initially sub-critical flow accelerating and becoming super-critical near the downstream end of the sill. Super-critical flow continues to accelerate down the back face of the sill (with Froude Numbers $Fr > 2$) before becoming drowned in an hydraulic jump resulting from the imposed downstream boundary condition. The results appear to be consistent with those obtained by Stelling et al (1998).

5.4 Dam-Break Simulation

The dam-break example was also taken from the work of Stelling et al (1998). It consisted of a 64 x 114m basin having a horizontal bed level of 0.0m. The basin was divided in two as shown in Figure 8. The left half contained water with an initial surface level of 5.0m, and the right half was initially dry. A vertical wall

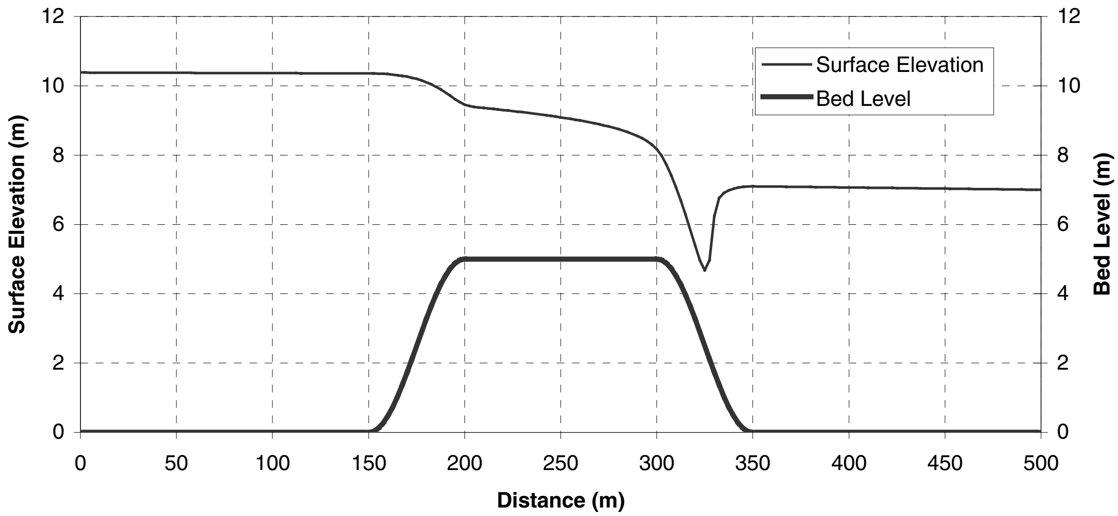

Figure 7 - Results of the Hydraulic Jump Test Case

separating the two halves had a 10m wide gap in the centre. The model had a grid size of 1.0m and a time step of 0.1s. As before, the bed roughness was equivalent to a Manning's *n* of 0.03.

Typical results are presented in Figure 8. This shows velocity vectors and water surface level contours at 0.2m intervals, 10 seconds after the simulation start. Velocity vectors at only every second grid point are shown. Areas remaining dry (i.e., that are not yet included in the computation) are shaded light grey. After an initial jet effect through the breach in the dam wall, the results show the flood wave spreading out almost radially across the initially dry floodplain. Qualitatively, the results show similar characteristics to those presented by Stelling et al (1998). (There is insufficient information to allow a more detailed comparison.) Further, although the velocities are generally high (and sometimes extremely high) and the flow is super-critical near the front of the wave, the computation remains smooth, and there is no evidence of any local instability. Further work is continuing on extending MIKE 21's dam-break modelling capability.

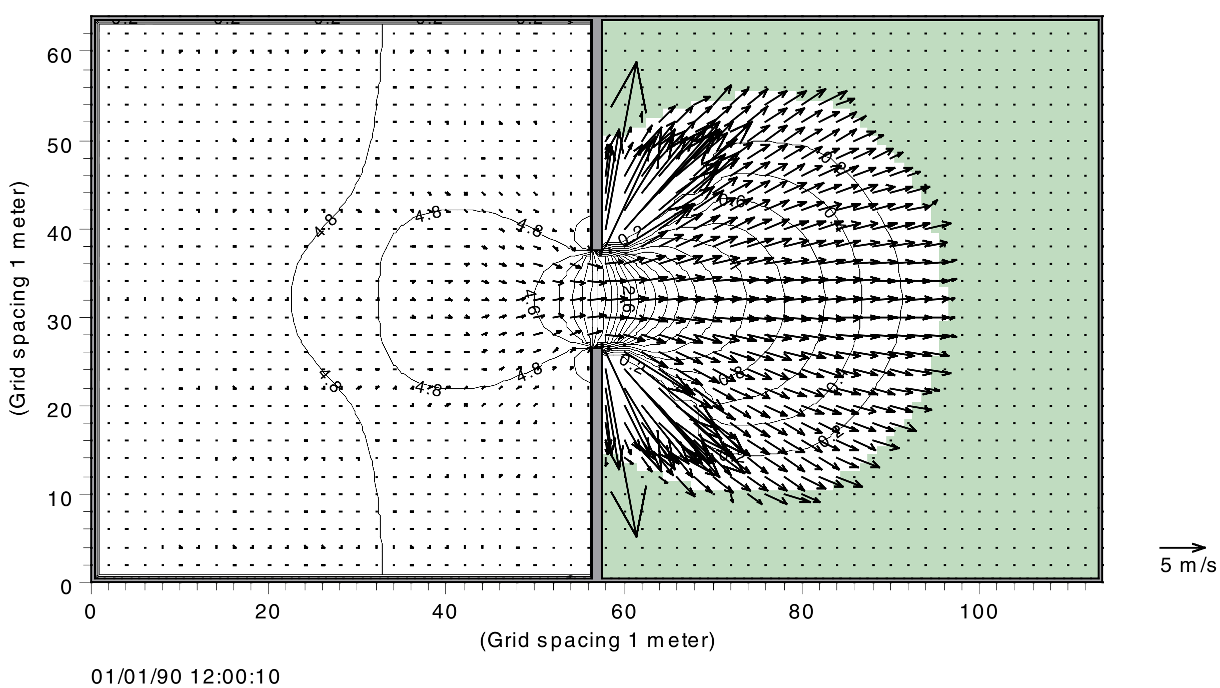

Figure 8 - Dam-Break Test Case Results – 10s after start

6 CONCLUSIONS

The work described in this paper has resulted in significant improvements being made to the floodplain modelling capability of the MIKE 21 two-dimensional modelling system.

Through up-winding of the water depths used in the bed-friction term it has been possible to improve the robustness of the flooding and drying routine and, thereby:

- Eliminate any potential for mass balance errors through the use of very small water depths (< 0.001m) in the initial flooding cycle.
- Eliminate "sticking" problems associated with flows into very shallow grid points.
- Provide a realistic description of the propagation of a flood wave front over an initially dry bed.

This has been achieved while retaining the computational efficiency of the original flood and dry routine (which avoids the need for unnecessary computation over what are effectively dry, but floodable, areas).

The selective introduction of numerical dissipation has been used to extend the capability of MIKE 21 to include the modelling of high Froude Number flows. This has been achieved by selective up-winding of the convective momentum terms. Through this approach, it has been possible to extend MIKE 21's capabilities to include modelling of super-critical flows, broad-crested weir flows, hydraulic jumps and even dam-break flows. The use of a time and space varying Froude Number dependent switch ensures that the numerical dissipation is only included in areas where it is needed. This ensures that the high accuracy of MIKE 21's normal solution procedure is maintained throughout the rest of the model domain.

7 REFERENCES

Abbott, M.B., (1979). *Computational Hydraulics, Elements of the Theory of Free Surface Flows,* Pitman, London.

Abbott, M.B. and Rasmussen, C.H. (1977). On the Numerical Modelling of Rapid Contractions and Expansions in Models that are Two-dimensional in Plan, *Proc. 17th Congress IAHR,* Baden-Baden.

Abbott, M.B., Damsgaard, A. and Rodenhuis, G.S. (1973). System 21, Jupiter, A Design System for Two-Dimensional Nearly Horizontal Flows, *Journal of Hydraulic Research*, Vol. 1.

Abbott, M.B., McCowan, A.D. and Warren, I.R. (1981). Numerical Modelling of Free-Surface Flows that are Two-Dimensional in Plan, in *Transport Models for Inland and Coastal Waters*, H.B. Fischer editor, Academic Press, New York.

Bishop, W.A., McCowan, A.D., Sutherland, R.J. and Watkinson, R.J. (1995). Application of Two-Dimensional Numerical Models to Urban Flood Studies, *2nd Int'l Symp. on Stormwater Management,* Melbourne.

Collins, N.I., Callaghan, D.P. and McCowan, A.D. (1999). Zero Flooding Impact Assessment – The Need for Full Two-Dimensional Analysis, *8th Int'l Conf. on Urban Storm Drainage*, Sydney.

Falconer, R.A. and Chen, Y. (1981). An Improved Representation of Flooding and Drying and Wind Stress Effects in a 2D Tidal Numerical Model, *Proc. Instn of Civil Engrs*, Part 2.

Lax, P.D. (1954). Weak Solutions of Non-linear Hyperbolic Equations and Their Numerical Approximations, *Comm. Pure and Applied Mathematics,* No 7.

Leendertse, J.J. (1967). Aspects of a Computational Model for Long Water Wave Propagation, Memorandum RH-5299-PR, Rand Corporation, Santa Monica.

Leonard, B.P. (1976). A Survey of Finite Differences of Opinion on Numerical Muddling of the Incomprehensible Defective Confusion Equation, *Proc. A.S.M.E. Winter Annual Meeting,* Pub. No. AMD-34.

McCowan, A.D. and Daly, M.X. (2000). Modelling of Floodplain Flows – Case Study Examples, *Hydrology and Hydraulics for Floodplain Managers, Workshop 3 Flood Level Estimation*, Monash University.

Smagorinsky, J. (1963). General Circulation Experiments with the Primitive Equations, *Monthly Weather Review* NWB, No. 93.

Stelling, G.S., Kernkamp, H.W.J. and Laguzzi, M.M. (1998). Delft Flooding System (FLS): A Powerful Tool for Inundation Assessment Based Upon a Positive Flow Simulation.

Stelling, G.S., Wiersma, A. and Willemse, J. (1986). Practical Aspects of Accurate Tidal Computations*, ASCE, Jour of Hyd Engg*, No. 9.