Three dimensional modeling of flow over a natural dune field in a large river with time evolving topography

R.J. Hardy & S.N. Lane
Department of Geography, University of Durham, Durham. DH1 3LE, UK.

D.R. Parsons
School of Earth and Environment, University of Leeds, Leeds. LS2 9JT, UK.

J.L. Best
Department of Geology, University of Illinois at Urbana-Champaign, Urbana, Illinois. USA.

O. Orfeo
Centro de Ecologica Aplicada del Littoral (CECOAL), Corrientes 3400, Argentina.

R. Kostschuk
Department of Geography, University of Guelph, Ontario, Canada

ABSTRACT: Our ability to numerically predict the interaction between complex topography and three dimensional flow using Computational Fluid Dynamics (CFD) in large rivers has yet to be fully developed. This is the result of three limiting factors, our inability; *i*) to design numerically stable meshes for complex topographies at these spatial resolutions; *ii*) to allow the topography to evolve though time; and; *iii*) to collect high resolution data appropriate for the boundary conditions of the numerical scheme. This poster deals with the numerical simulation of flow over a ≈ 1 km section for a natural dune field located in the Rio Paraná, NE Argentina over a period of days. The numerical methodology is based upon the development and application of a new five term mass flux scaling algorithm that modifies the mass conservation equation through a numerical porosity approach within a regular Cartesian discritization. The advantage of this approach is; *i*) complex topography can be incorporated into the model maintaining a regular Cartesian discritization and; *ii*) the topography can evolve, through either erosion or deposition, without the need for re-meshing in a numerically stable framework. Bathymetric measurements were made in the field using a multibeam echo sounder (MBES) which provided an unparalleled topographic dataset to provide boundary conditions to test this new numerical modelling approach. Measurements of flow were made using an acoustic Doppler current profiler and are used both as inlet boundary conditions and validation data. The results demonstrate the importance of topographic forcing on determining flow structures in large rivers.

1 INTRODUCTION

Dunes are one of the most common depositional bed forms in river channels, forming in a range of sediment sizes from silt and sand through to gravel (Dinehart, 1992; Best, 1996; Carling, 1999; Kleinhans, 2001, 2002; Carling *et al.*, 2005). Their presence significantly influences both the nature of the mean and turbulent flow and consequently exerts a strong control of the entrainment, transport and deposition of sediment (Parsons *et al.*, 2005, Best, 2005). In recent years progress has been made in our knowledge of dune dynamics due to the significant advances in our ability to monitor flow and dune morphology both in the laboratory and field (Best, 2005). However, our ability to predict the interaction between complex topography and three dimensional flow using Computational Fluid Dynamics (CFD) in large rivers has yet to be fully developed. This is not the case in meso- or micro- applications, where the application of CFD has allowed an insight into processes understanding that would otherwise not be possible with either the application of a depth-averaged (two-dimensional) models (Lane *et al.*, 2004) and in some cases an extensive field based survey (Roy *et al.*, 1996).

One of the most problematic factors in applying CFD to understand geomorphological process is the incorporation of complex topographies within the spatial discretisation. In the majority of applications, and at all spatial scales, the representation of natural topography requires the application of boundary fitted co-ordinates (BFC's). This involves mesh deformation in Cartesian space and then parameterization of smaller scale topography through a roughness parameterization. If this approach is used two problems may emerge. First, mesh deformation may change the magnitude of numerical diffusion in the model and lead to uncertainties as to whether observed changes in process representation are due to topographic effects or grid adjustment effects. Previous research into the performance of numerical code has emphasized that there is a need for careful investigation of numerical diffusion associated with grid specification, the accuracy of discretization (Manson and Wallis, 1997), convergence problems associated with fine grids in finite volume discretizations (Cornelius *et al.*, 1999) and the need to undertake grid independent calculations (Hardy *et al.*, 2002). However, provided attention is given to the way in which the numerical solution achieves convergence (Cornelius *et al.*, 1999), finite volume treatments using structured grids have particular appeal as they provide a fast and efficient numerical solution and can be numerically stable in channels of simple geometry. Secondly, uncertainty surrounds the validity of roughness parameterization in CFD scheme (Lane, 2005) where a roughness parameter is primarily used as an effective parameter to represent sub-grid topography.

This has led to the development of alternative methods for incorporating complex topographies within a CFD framework (e.g. Biron *et al.*, 2007). One such approach is a mass flux scaling approach where a percentage of the cell is blocked out depending on the amount of topography within a discretisation volume and subsequent modification to the drag term. This is based upon a porosity approach which has previously been developed within a regular Cartesian mesh and applied and validated for the inclusion of complex topography (Lane *et al.*, 2003; Lane *et al.*, 2004; Hardy *et al.*, 2005; Hardy *et al.*, 2006; Hardy *et al.*, 2007). This approach has several potential advantages; primarily, as previous demonstrated, complex topography can be included in a stable Cartesian discretization and; secondly, this topography potentially can change (through either erosion or deposition) within a stable numerical framework. This is explored in this paper by looking at the interaction between form and flow in large river channels over scales of approximately ≈ 1 km over a series of days. This is achieved by the development of a new five term mass flux scaling algorithm that modifies the mass conservation equation to include topography that is able to evolve through time. The methodology is applied and tested on a dune field located in the River Paraná, North East Argentina, where an extensive field data collection has been undertaken using Mulitibeam Echo Sounding (MBES) and acoustic Doppler current profiling (adCP) for boundary conditions and validation data. This provides an unparallel dataset for a large river to test this new numerical modeling approach.

2 NUMERICAL METHODOLOGY

The methodology assumes that the topographic data takes the same form as the Digital elevation model (DEM), such as; i) the density of topographic data is equal to the grid density; ii) the numerical grid was defined with vertices that are exactly collocated to the DEM so that the DEM elevations mapped directly onto grid cells. The coordinate system is orientated such that the *i*-axis is always in the downstream direction, the *j*-axis is always in the cross-stream direction and the *k*-axis is always vertical. This means that the predominant flow direction is parallel to one of the axes and avoids numerical problems associated with fluid flow at acute angles to grid cell faces. For all cells that are completed blocked the cell is completely blocked using a volume approach. For cells which interface between bed and water the area of each of the four effective cell faces is modified, this subsequently reduces the flux which can pass through each cell. This is illustrated through a schematic diagram (Figure 1) which has been simplified for diagrammatical purposes into a simple two-dimensional case. The same notation is being applied but for this simplification face areas have been replaced by edge lengths. For this ideal case it is assumed that the cell is square such that A_e and A_w are replaced by Δy and A_n and A_s are replaced by Δx. The bed topography cuts through the cell in question, reducing the flux through the *e* and *w* faces and completely blocking the *s* face. The *n* face is unaffected. Thus in the example presented in Figure 1, the two-dimensional finite volume equation becomes:

$$a_P\varphi_P + 0.3a_E\varphi_E + 0.6a_W\varphi_W + a_N\varphi_N + 0.0a_S\varphi_S = Q_P.$$

While the value of a_P is modified through the continuity condition:

$$a_P + 0.3a_E + 0.6a_W + a_N = 0,$$

since this equation is used to find the value of a_P.

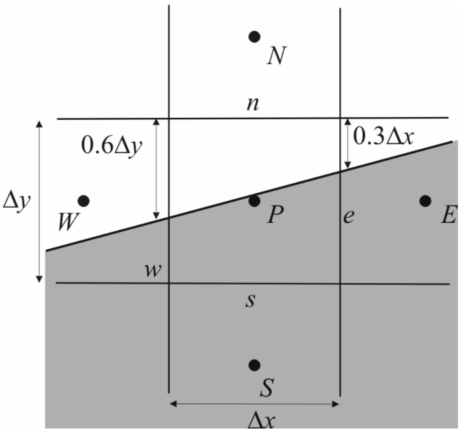

Figure 1: A two dimensional schematic diagram representation of the five term mass flux scaling algorithm.

The above mass flux scaling algorithms are incorporated into a CFD scheme. The numerical scheme solves the full three-dimensional Navier-Stokes equations discretised using a finite-volume method. The interpolation scheme used is hybrid-upwind, where upwind differences are used in high convection areas (Peclet number > 2) and central differences are used where diffusion dominates (Peclet number < 2). Although this scheme can suffer from numerical diffusion, it is very stable. The pressure and momentum equations are coupled by applying SIMPLEST, a variation on the SIMPLE algorithm of Patankar and Spalding (1972). The convergence can precede either smoothly or with damped oscillations to the final solution. To achieve relaxation either: (i) realistic maximum and minimum values may be imposed on the solution; or (ii) relaxation may be used to limit the amount of change allowed in any variable at a given iteration. Weak linear relaxation was used for the pressure correction, while weak false time step relaxation was used for the other variables. The convergence criterion was set such that the residuals of mass and momentum flux were reduced to 0.1% of the inlet flux.

3 FIELD SITE AND METHODOLOGY

The study area is a 0.25 km wide, 1.8 km long area of dunes in the Rio Paraná, just upstream of the confluence of the Rio Paraguay, NE Argentina. At the dune field, the Rio Paraná is 2.5 km wide and 5-12 meters deep and at the time of survey the discharge of the full river section was 11 000 m^3s^{-1}. Measurements of the 3D bathymetry and 3D flow have previously been discussed by Parsons *et al.*, (2005). The MBES provides information on the river bed morphology at a centimetric resolution and millimetric precision over scales from ripples superimposed on dunes to the entire river reach, and provides an unparalleled methodology by which to examine the form of alluvial roughness (Wilbers, 2004). Measurements were repeated daily over a period of 7 producing 7 DEMS. This topographic information was incorporated into the numerical discritisation using the mass flux algorithm discussed above. The computational domain was regular in the *x* and *y* directions, with a grid resolution of 2 m. In the *z* direction the grid resolution was increased 0.25 m. To allow inclusion of topography data using the porosity treatment, the maximum extent of the domain was set at 11 m. Thus, the computational grid was sized at 484×139×44 (2 960 144 grid cells).

4 RESULTS

The results demonstrated here are over a period of 24 hours where the topography is evolved on a 1 hour time step.

4.1 *Dune Dynamics*

The original topography (Figure 2) has previously been analyzed by Parsons *et al.*, (2005) who described classical low angle dunes with dune height ranging between 1.2 to 2.5 m high and wavelengths from 45 to 85 m The majority of forms are highly asymmetric, with leeside slope angles typically around 8.5 to 18º and stoss slope angles are much shallower, typically around 1.5º to 2.5º (Parsons *et al.,* 2005). There is a cross stream gradient with deeper flow located in the top right of the domain and its effect is observed in the orientation of the crest lines which appear normal to the gradient. The dunes also appear very stable. Figure 2b covers the same dune field 24 hours later, with the midline profile shown in Figure 2c. There is very little change in morphology between the two days. Interestingly the dune field has shifted faster where the three-dimensionality in crestline curvature is highest.

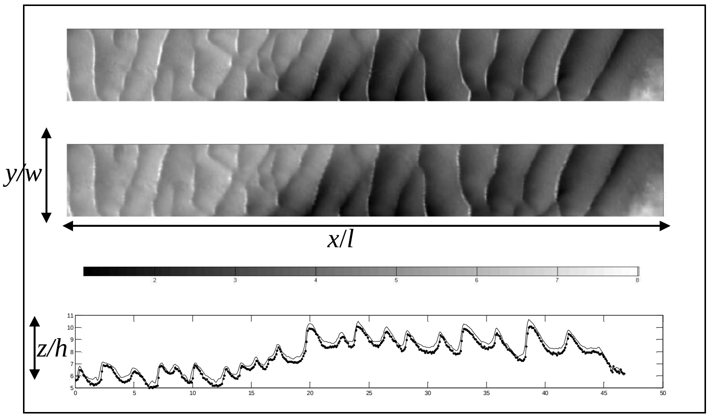

Figure 2: The digital elevation model represented through the porosity algorithm for two separate days (a,b). The change in the midline profile (c) shows the change in topography. Note *z/h* is increased by a multiple of 10.

4.2 *Flow structures*

The predicted flow structures are shown in Figure 3 and 4. Figure 3 shows a planametric view of the resolved components velocity (*u*-, *v*- & *w*-) 0.75 *z/h* above the bed where flow is from left to right. There are two distinct characteristics that can be observed. The first is the effect of the deepening flow in the top right hand of the domain where faster flow is predicted (> 0.4 $\mathrm{ms^{-1}}$). The second characteristic that can be observed is the low flow (< 0.1 $\mathrm{ms^{-1}}$) located in the lee of each of the dunes. Towards the deeper part of the domain flow the flow in the lee of the dunes is steered towards the deeper water. The influence of this topographic hollow can be seen to be dominant through the flow depth.

Classical flow separation can be observed in the *w*- component (Figure 4) due to the influence of the three dimensional morphology. This includes flow separation and reattachment with most of the generated flow structures influencing the whole flow depth. For both Figures demonstrating flow structure modification over the dunes it is difficult to determine any flow structure evolution due to the fact that the dune field over this 24 hour period is in equilibrium and there is very little morphological evolution. However, numerically this provides a methodology for the development of a time dependent CFD-sediment transport scheme.

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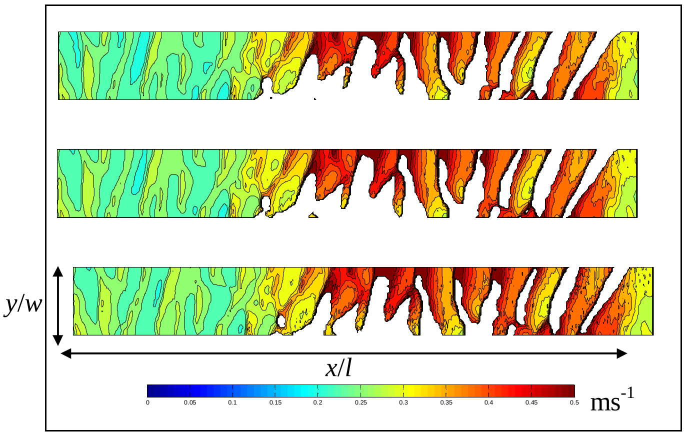

Fig 3: Velocity magnitude for 0.75 *z/h*. a) 1 hour; b). 12 hours, c) 24 hours.

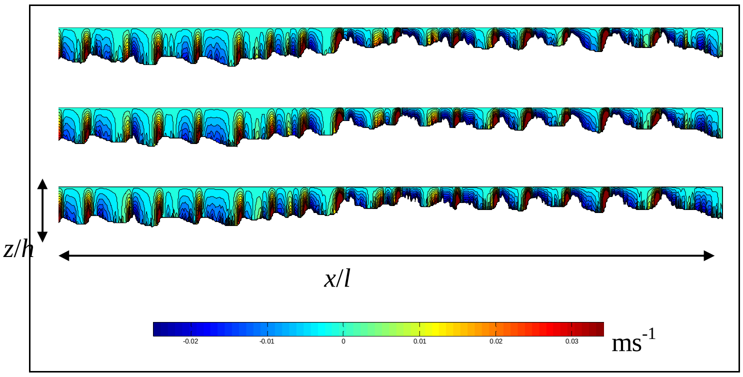

Fig 4: w-component of velocity for 0.5 *y/w*. a) 1 hour; b). 12 hours, c) 24 hours.

5 DISCUSSION

This paper has presented a new methodology for the inclusion of complex topography into a Cartesian mesh. The methodology now enables the prediction of flow structures with the application of a three dimensional Computational Fluid Dynamics scheme over scales of 1 km. The present limitation of this methodology is that it is dependent on the quality and resolution of the topographic boundary condition. If high resolution topography does not exist the methodology is not applicable. The results from qualitative validation are encouraging and full validation of the numerical scheme is presently been undertaken with comparison against the aDcp data collected at various transects throughout the domain. The results have demonstrated that the larger scale topography significantly influence the flow structure. Even though high resolution topographic form, such as dune height, wavelength, scour depth and crest line curvature the main are included the main flow structures are formed by the cross stream gradient located in the top right of the domain. Such enhanced topographic steering of the flow may have a significant influence on the distribution of shear stresses and sediment transport rates over the dune crests.

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