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Hydrodynamic Behaviour of a Two-Stage Channel with Horizontal and Inclined Floodplains: A Numerical Investigation

HYDRODYNAMIC BEHAVIOUR OF A TWO-STAGE CHANNEL WITH HORIZONTAL AND INCLINED FLOODPLAINS: A NUMERICAL INVESTIGATION

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ABSTRACT

This paper presents the hydrodynamic behaviour of the two-stage River Blackwater model with horizontal and inclined floodplains using two-dimensional (2D) and three-dimensional (3D) numerical models. The 2D model solves the shallow water depth-averaged continuity and Navier-Stokes equations with the depth-averaged form of the $k-\varepsilon$ turbulence model for free surface flow. The 3D model solves the three-dimensional Reynolds-averaged continuity and Navier-Stokes equations with the renormalization group (RNG) $k-\varepsilon$ turbulence model for steady-state flow. The performance of the models is assessed by comparing predicted results with the experimental data obtained from a 1:5 scale physical model of the River Blackwater, located at the UK Flood Channel Facility. The predicted model results are used to investigate the flow processes along the channel in both the horizontal and inclined floodplain cases.

Keywords: floodplain, numerical model, overbank flow, River Blackwater, two stage channel

1. INTRODUCTION

Predicting hydrodynamic behaviour and understanding flow processes in natural rivers is of great importance for addressing river engineering problems because engineering solutions are increasingly required to retain natural channel features and to maintain a balance between environmental and ecological issues. Two-stage channels are one approach to providing this balance where the overbank flow exhibits a complex three-dimensional structure resulting from the interaction between the floodplain flow and the main channel flow (Rameshwaran and Willetts 1996, Shiono and Muto, 1998 and Willetts and Rameshwaran, 1996). As a consequence of the construction of a major road bypass during 1993-94, a length of the River Blackwater near Farnborough in Hampshire, UK was reconstructed as a doubly meandering two-stage channel, which was designed to provide a more environmentally reliable basis for future river-channel restoration projects (Figure 1, Sellin *et al*., 2001). The main channel had a sinuosity of 1.18, whilst the flood channel (wider upper channel) had a lower sinuosity of 1.06. The designed channel longitudinal valley slope was 1×10^{-3}. The shape of the main channel cross-section was trapezoidal. The main channel bank slopes were 45° with a bank-full depth of 0.75m and a base width of 4.25m. The berms had an inclination of 1 in 30 normal to the main channel. The typical reach averaged cross-section used in reconstruction is shown in Figure 2. A recent field survey conducted in March 2007 for section A-A (Figure 1) and shown in Figure 3, shows that neither the main channel is trapezoidal nor does the floodplain berm have an inclination of 1 in 30 towards the main channel. In fact, it shows that the right-hand side berm of the floodplain is now inclined in the opposite direction. Therefore, it is important to predict and understand the hydrodynamic behaviour in such a river during floods in order to explain the topographical changes.

(a) Aerial view of the River Blackwater (b) River Blackwater two-stage channel

Figure 1 River Blackwater.

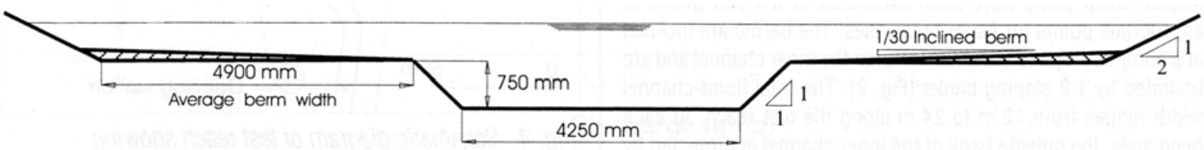


Figure 2 Typical averaged cross-section.

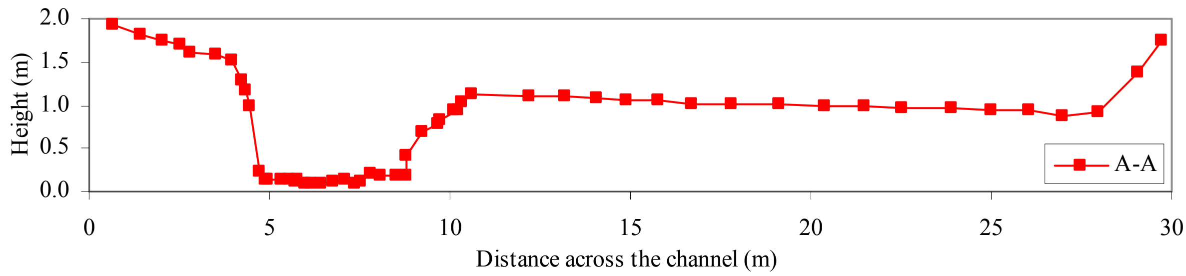
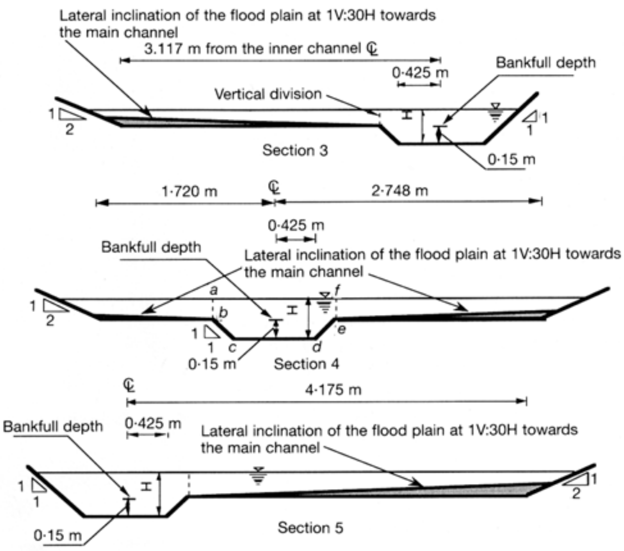


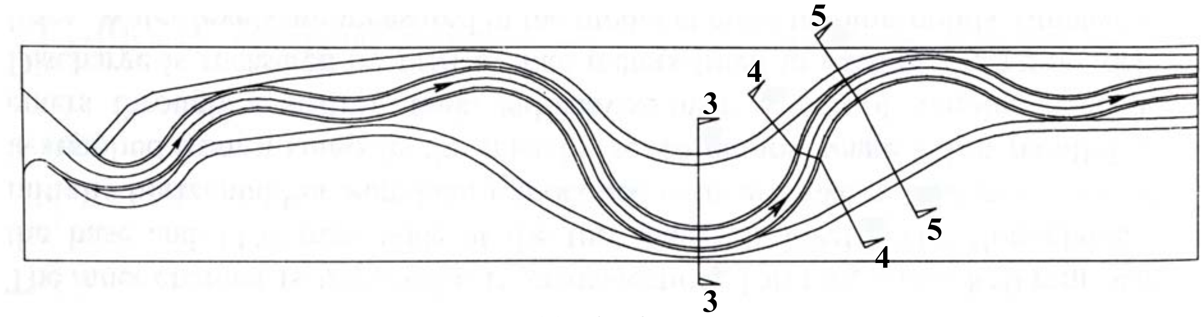
Figure 3 Surveyed cross-section A-A in March 2007.

In recent years, Computational Fluid Dynamic (CFD) models have increasingly been used for two-stage channel flow cases, in order to understand their hydrodynamic behaviour (e.g. Rameshwaran and Shiono, 2002, 2003; Rameshwaran and Naden, 2004a). The main aim of this paper is to predict and investigate the flow behaviour in the large-scale physical model of the River Blackwater using two-dimensional (2D) and three-dimensional (3D) models, in order to understand the flow phenomena occurring in natural situations. The UK Flood Channel Facility (UK-FCF) at HR Wallingford has provided a focus for research on the hydrodynamic behaviour of two-stage channels. Here, a 1:5 scale model of the River Blackwater was constructed, to investigate the effect of the floodplain roughness and inclination (Lambert and Sellin, 1996). The flow predictions were performed using the 2D model TELEMAC-2D and 3D model PHOENICS. The performance of the 2D and 3D models is assessed using experimental data obtained from the UK Flood Channel Facility. The flow processes along the two-stage channel in both the horizontal and inclined floodplain cases are investigated using model results. Further field and CFD modelling studies are currently underway to understand the hydrodynamic flow behaviour in the River Blackwater.

(a) 1:5 scale physical model



(b) Cross-sections looking from downstream



(c) Planform

Figure 4 The River Blackwater physical model.

2. PHYSICAL MODEL

The full description of the physical model study is given in Lambert and Sellin (1996) and only brief details are given here. The undistorted 1:5 scale model of the River Blackwater was constructed in the 56 m long and 10 m wide UK Flood Channel Facility flume, as shown in Figure 4a. The detail of the channel geometry and the location of the cross-sections (sections 3, 4 and 5) where flow field measurements were taken, are illustrated in Figures 4b and 4c. The channel surfaces were composed of smooth cement mortar. Experiments were carried out with different roughness conditions. The roughened main channel and floodplain surfaces were obtained by placing a layer of gravel on the smooth channel surfaces. The side walls (banks) were left smooth for all experimental runs. The floodplains were either horizontal or at an inclination of 1 in 30 (Figure 2).

Detailed measurements of horizontal velocity were made in cross-sections 3, 4, and 5 along the channel under steady state flow conditions. The flow angle was recorded by a vane connected to a rotary potentiometer. The horizontal velocity was measured using a miniature propeller meter, whilst flow rate was determined using calibrated orifice plates. The water surface elevations were measured using digital point gauges. The geometric configurations and flow conditions for the cases considered in this study are listed in Table 1.

Table 1 Geometric configurations and flow conditions.

Case	Main Channel	Floodplain	H_{MC} (m)	H_{FP} (m)	Q (m^3/s)
1	d_{50}=8mm	d_{50}=13mm	0.237	0.084	0.165
2	d_{50}=8mm	d_{50}=13mm	0.237	1 in 30 inclined FP	0.127

H: Water depth, Q: Discharge MC: Main channel, FP: Floodplain, d_{50}: 50th percentile of the bed particle sizes, Roughness layer thickness: - 13mm in main channel and 16mm on floodplain.

3. NUMERICAL MODELS AND BOUNDARY CONDITIONS

3.1 2D Model

The 2D flow predictions were performed by solving the depth-averaged continuity and Navier-Stokes equations with the depth-averaged form of the $k-\varepsilon$ turbulence model for free surface flow by using the finite-element model TELEMAC-2D. The full detail of the model equations is given in Rameshwaran and Shiono (2002, 2003). The SUPG advection scheme was used for continuity and momentum equations. The $k-\varepsilon$ turbulence equations were solved by the fractional step method. A detailed description of the solution procedure is provided by Hervouet and Van Haren (1996). The following boundary conditions are applied to the flow domain: (a) *At inlet*: constant flow rate Q, (b) *At outlet*: water elevation h, (c) *At floodplain banks*: $\partial u/\partial y = 0$ and $v = 0$ and (d) *On channel bed*: wall function equation with roughness height value k_s.

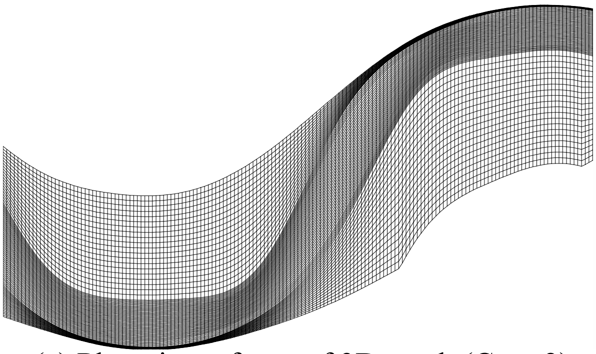
3.2 3D Model

The 3D flow calculations were performed by solving the three-dimensional Reynolds-averaged continuity and Navier-Stokes equations with the renormalization group (RNG) $k-\varepsilon$ turbulence model for steady-state flow. The model equations were solved numerically using the general-purpose finite-volume code PHOENICS, employing the non-staggered-grid approach. The approximation of the convection term was handled by the QUICK based non-linear higher order scheme SMART. The pressure-velocity coupling was achieved using the SIMPLEC algorithm. The discretised equations were solved with a Stone-based extension of a tri-diagonal solver. The detail of solution procedures has been described in Rameshwaran and Naden (2004a). The following boundary conditions were utilised: (a) *At inlet*: mean value of streamwise velocity, (b) *At Outlet*: atmospheric pressure on the free surface and fully developed flow condition elsewhere, (c) *At free surface*: fixed lid assumption with free surface correction (see Rameshwaran and Naden, 2004b) and (d) *On channel bed*: generalized form of the wall function equation with roughness height value k_s.

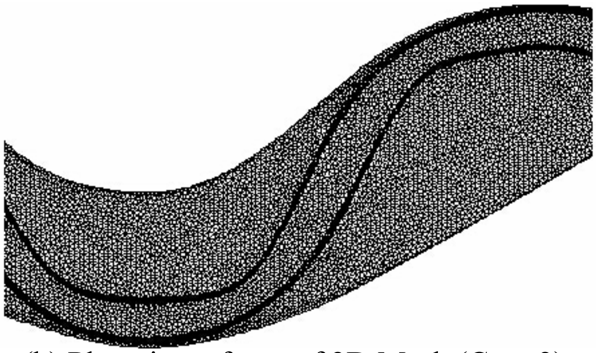
Table 2 Main characteristics of the 2D and 3D meshes.

Case (2D)	Elements	Nodes	Max. (m)	Min. (m)
1	33237	17146	0.230	0.005
2	33239	17147	0.230	0.005
Case (3D)	Cells	x- cells	y - cells	z - cells
1	800000	500	80	20
2	600000	500	80	15

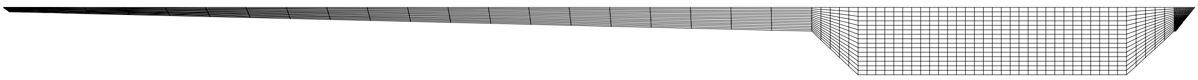
Max. & Min.: Maximum & Minimum Inter-node distances.



(a) Plan view of part of 3D mesh (Case 2)



(b) Plan view of part of 2D Mesh (Case 2)



(c) Section 3 cross-sectional view of 3D mesh (Case 2)

Figure 5. 2D and 3D meshes.

4. MESHES

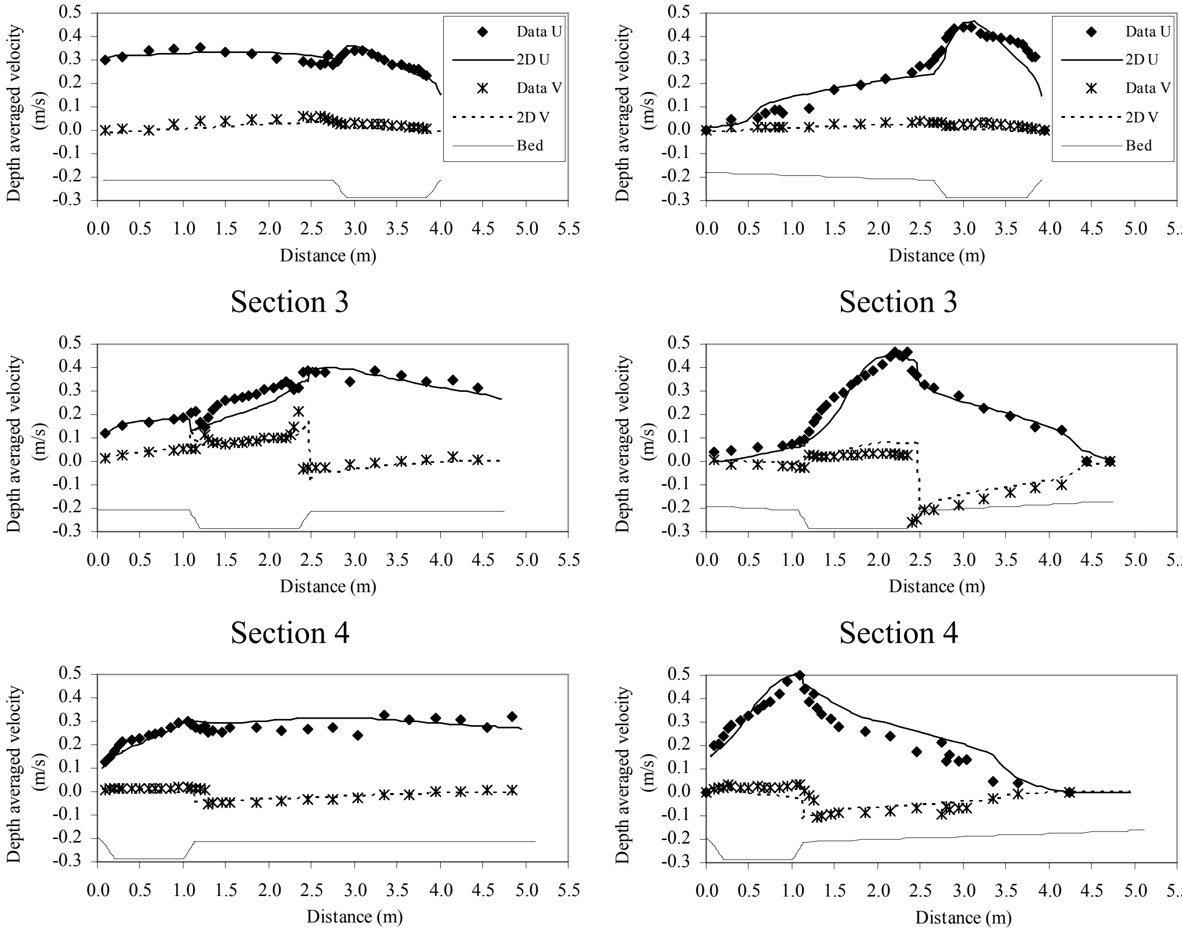
In the 2D model, an unstructured triangular finite element mesh was used for the whole physical model domain, including wet and dry areas. Unlike the 2D model mesh, the 3D finite volume mesh was constructed only for the wet area (i.e. flow area). Boundary Fitted Co-ordinates (BFCs) were used in the Cartesian frame to construct a 3D mesh. The first grid cells adjacent to the channel boundary were constructed within the fully turbulent region where the non-dimensional wall distance Y^+ value for each cell was within the range $30 < Y^+ < 300$. The effects of mesh resolution on numerical accuracy were explored, and are described in Rameshwaran and Naden (2004b). The 2D and 3D meshes are listed in Table 2 and shown in Figure 5.

5. SOLUTION SEQUENCE

Computation commences from quiescent initial conditions for the chosen mesh for both models. In subsequent runs, the convergence procedure is accelerated by adopting prior steady state solutions as initial conditions. In the 2D model, the relative increment time-stepping termination tolerance is set to the order of 10^{-4} for solution convergence to steady state. During the calculations, wet and dry (i.e. submerged and exposed) areas are detected and accounted for in the 2D model. In the 3D model, convergence is achieved when mass is balanced within 0.1% and, for each solved variable, the residual is reduced to 0.1% and the spot value has settled down to an almost constant value.

6. RESULTS AND DISCUSSION

Figure 6 shows the comparison between the measured and predicted depth-averaged streamwise and transverse velocities by the 2D model, for both horizontal and inclined floodplain cases for sections 3 to 5 (Figures 4b and 4c). It shows that the streamwise velocity is reasonably well predicted for all sections expect for the main channel section 4 for case 1, where the streamwise velocity is under-predicted and on the right side floodplain section 5 where the streamwise velocity is slightly over-predicted. The transverse velocity is reasonably well predicted for both cases 1 and 2. Figure 6 also shows that the 2D model performs well in capturing wet and dry areas, as reflected in the case 2 right side floodplain prediction for sections 4 and 5, where the predicted velocities are zeros. Overall, the prediction of velocities by the 2D model appears to be reasonable.

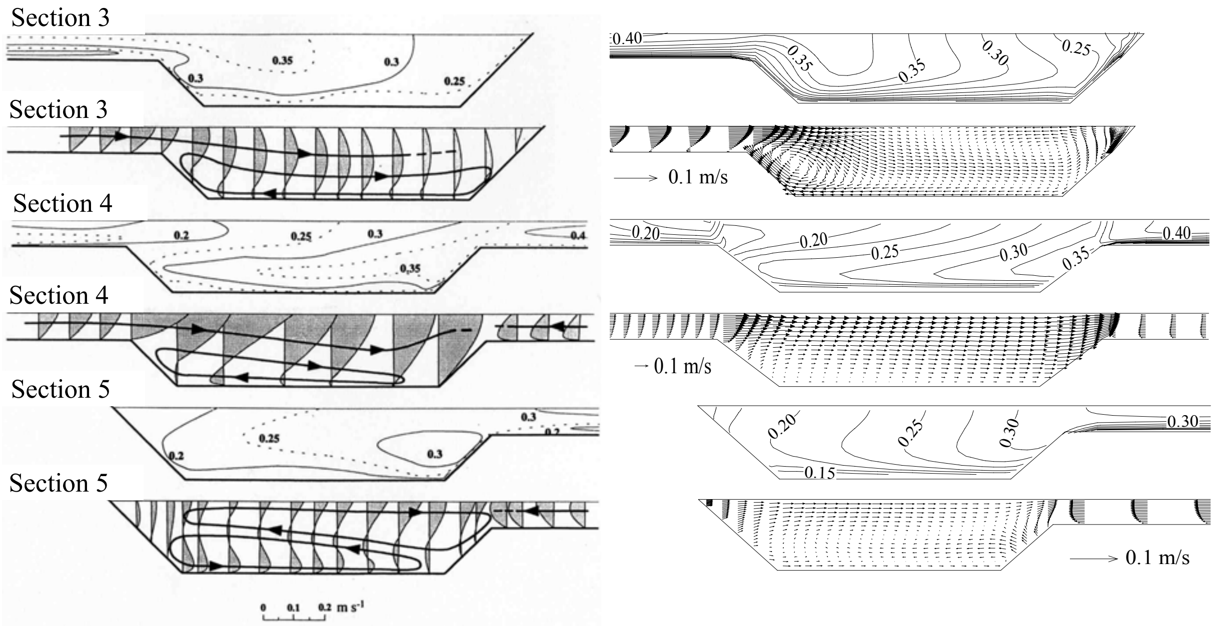


Section 5 | Section 5

(a) Case 1 (Horizontal floodplain) | (b) Case 2 (Inclined floodplain)

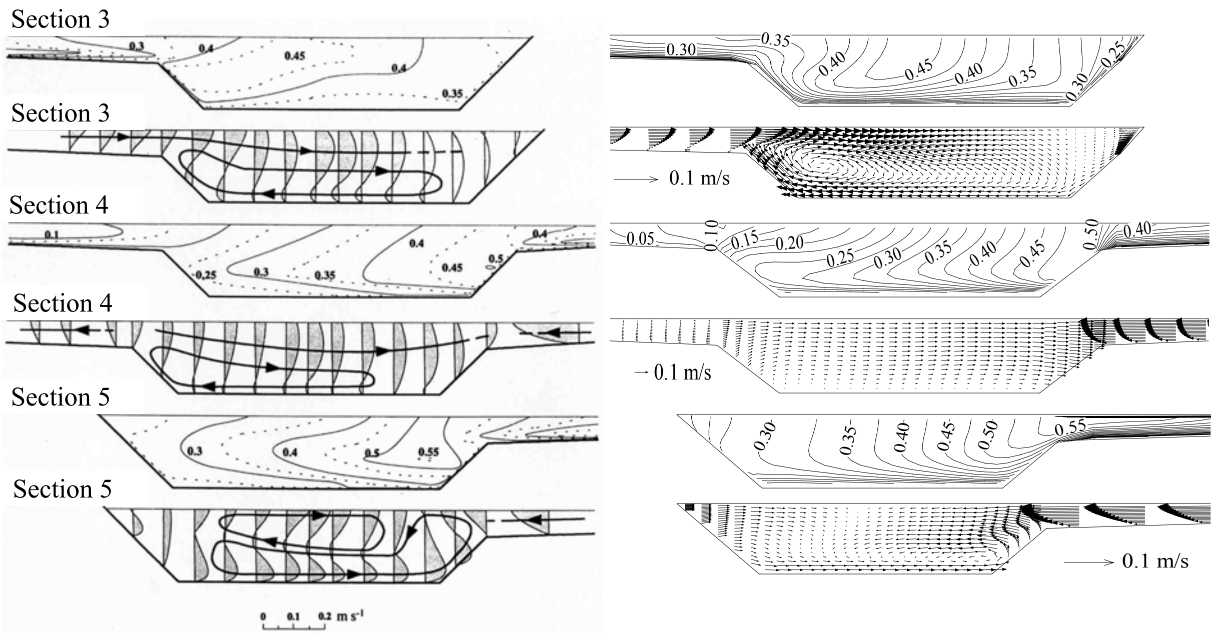
Figure 6 Comparison of depth averaged streamwise velocity U and transverse velocity V (Looking downstream left to right).

The plots of the measured (Naish and Sellin, 1996) and predicted streamwise velocity distributions and secondary flow fields for the 3D model are shown in Figures 7 and 8, for the horizontal floodplain case 1 and inclined floodplain case 2 respectively. They show that the 3D model reproduces the streamwise velocity magnitude, pattern and maximum velocity contour location reasonably well for both cases 1 and 2. Figures 7 and 8 also show that the secondary flow pattern constructed using the measured transverse velocity (Naish and Sellin, 1996) and the predicted secondary flow vectors agree well.



(a) Data (b) 3D model results

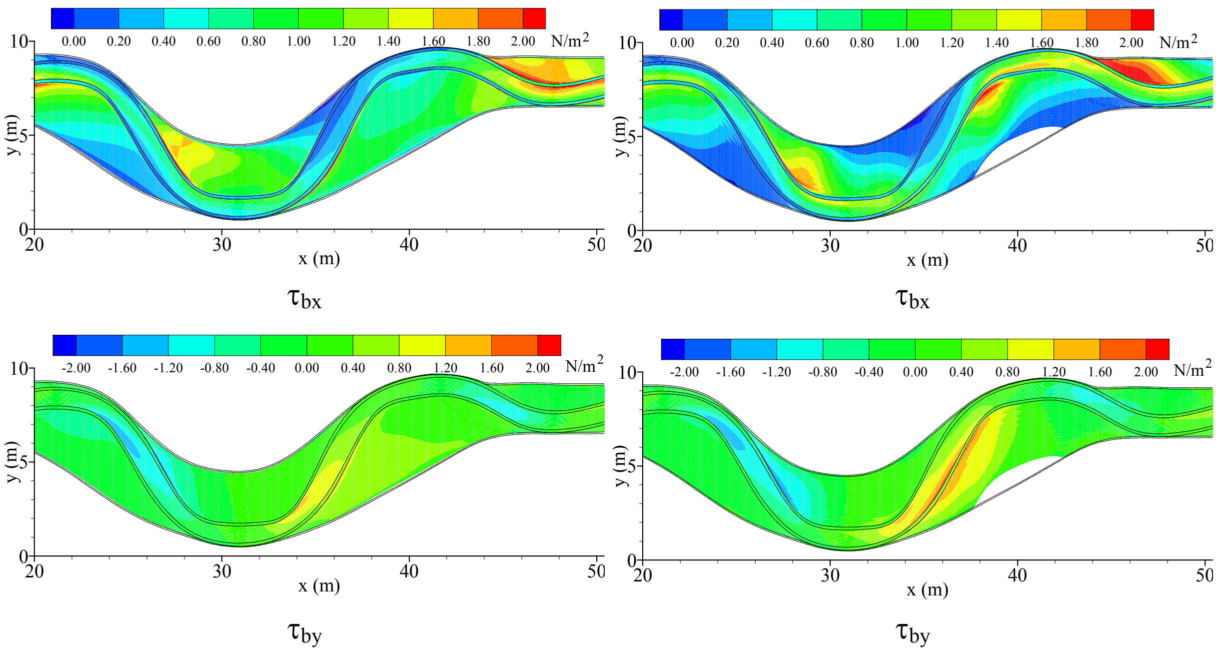
Figure 7 Comparison of streamwise velocity and secondary flow field for case 1 - Horizontal floodplain (Looking downstream left to right)



(a) Data (b) 3D model results

Figure 8 Comparison of streamwise velocity and secondary flow field for case 2 - Inclined floodplain (Looking downstream left to right)

With the same main channel flow depth of 0.237 m for both cases, Figures 6 to 8 show that in the inclined floodplain case 2, the main channel streamwise velocity has increased compared to the horizontal floodplain case 1; although the discharge is about 25% less than case 1 (Table 1). This demonstrates that the inclined floodplain channels more water through the main channel. Figures 7 and 8 also show that the magnitude of secondary vectors are slightly higher at apex section 3 and much higher at apex section 5, but smaller at cross-over section 4 in the inclined floodplain case 2 compared to the horizontal floodplain case 1. When comparing case 2 with case 1, flow entering the channel from floodplain is very similar at apex section 3, smaller at cross-over section 4 and larger at apex section 5. This demonstrates that flow entering from the floodplain controls the magnitude of secondary flow.

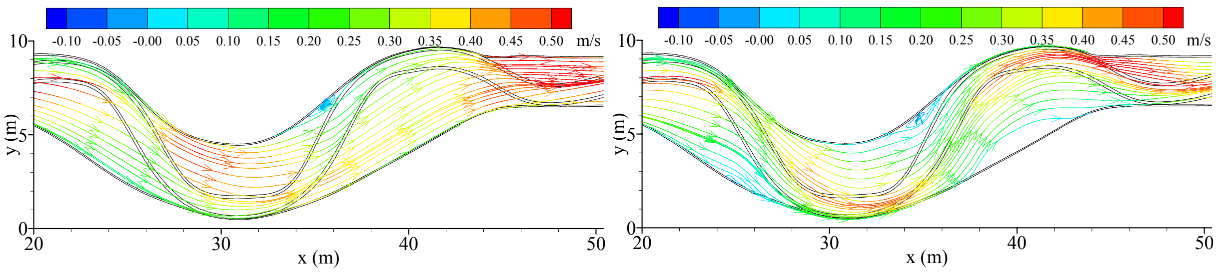


(a) Case 1 (Horizontal floodplain) (b) Case 2 (Inclined floodplain)

Figure 9 Comparison of bed shear stresses τ_{bx} and τ_{by}

Figure 9 shows the bed shear stresses τ_{bx} and τ_{by} predicted by the 3D model for cases 1 and 2, between 20 m and 50 m of the physical model area. The section A-A in Figure 3 is represented in the physical model at around 40 m. By comparing cases 1 and 2, (Figure 9) the floodplain inclination has generally increased the bed shear stress magnitudes in the main channel as a result of the higher velocity. The high values of τ_{bx} and τ_{by} for the main channel are located at the inner bend at apices and the right hand side of the cross-over, which correspond to the highest velocity regions, as shown in Figures 6 and 8. On the floodplain, the bed shear stress magnitudes are higher where the main channel flow enters onto the floodplain berms. These areas with higher bed shear stress in the main channel and on the floodplain berms will induce more erosion than in other areas. As flow depth and discharge go higher, this flow process becomes pronounced and eventually changes the main channel shape and flattens the floodplain berms.

Figure 10 shows the stream lines predicted by the 3D model at the water surface for cases 1 and 2. It shows that in the inclined floodplain case 2, the flow tends to follow berm contours along the floodplain wall. Here the maximum water surface velocity regions are located in the inner side of the main channel and at the downstream side of floodplain berms as expected. In the horizontal floodplain case, it can be seen that the floodplain flow enters the main channel and the main channel flow expels onto the floodplain more distinctly. There is a very interesting flow pattern (Figure 10a) at the cross-section around 40 m. Here the maximum velocity streamlines are situated in the right-hand floodplain bank region due to the expelling flow from the main channel from the previous bend. This behaviour is also reflected in the bed shear stress prediction for that cross-section (Figure 9a), where the maximum bed shear stress is located near the floodplain bank region. Again, the higher the bed shear stress, the greater the erosive capacity. This hydrodynamic flow behaviour may thus account for the changes to the main channel shape and floodplain bed in the River Blackwater since reconstruction in 1993-94 with the present main channel and floodplain form (Figure 3) in which the floodplain is inclined in the opposite direction compared to the initial construction. An alternative explanation may be that sediment has been deposited along the floodplain berm near main channel. Further work with a range of discharge conditions incorporating the effects of natural vegetation is needed to investigate this alternative explanation.



(a) Case 1 (Horizontal floodplain) (b) Case 2 (Inclined floodplain)

Figure 10 Comparison of flow patterns at water surface.

7. CONCLUSIONS

A study of the hydrodynamic behaviour of a two-stage channel, with horizontal and inclined floodplains and using both 2D and 3D models, was carried out. The 2D and 3D model performance was assessed by comparing with the 1:5 scale physical model data of the River Blackwater. The depth-averaged streamwise and transverse velocity distributions were reasonably well predicted by the 2D model, for both the horizontal and inclined floodplain cases. The 3D model also reproduced the streamwise velocity and the pattern of the secondary flow fairly well for both cases. The flow field results along the two-stage channel show complex hydrodynamic behaviour of the flow. One of the interesting flow behaviours is the faster apparent flow near the floodplain bank regions than other floodplain areas in the horizontal floodplain case, due to expelling flow from the main channel. This unusual hydrodynamic flow behaviour has modified the floodplain berms since reconstruction in 1993-94 to their present form. This study also shows that the 2D model can be used to assess flow behaviour on the horizontal plane reasonably well, although the vertical flow structure in the meandering channel cannot be assessed. The 3D model is therefore required to assess details of the vertical flow structure such as secondary flow behaviour.

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REFERENCES

Hervouet, J.M. and Van Haren, L. (1996) Recent advances in numerical methods for fluid flows. *Floodplain Processes*, Edited by M.G. Anderson, D.E. Walling and P.D. Bates, John Wiley & Sons Ltd, Chapter 6, pp. 183-214.

Lambert M.F. and Sellin R.H.J. (1996) Velocity distribution in a doubly meandering compound river channel. *Proceedings of ICE - Water and Maritime and Energy*, 118, pp. 10-20.

Naish, C. and Sellin, R.H.J. (1996) Flow structure in a large-scale model of a doubly meandering compound channel. Coherent Flow Structures in Open Channels, Edited by P.J. Ashworth, S.J. Bennett, J.L Best and S.J. McLelland, John Wiley & Sons Ltd, Chapter 30, pp. 631-654.

Rameshwaran, P., and Willetts, B.B. (1997) The mixing mechanism in turbulent two-stage meandering channel flows, *International Association for Hydraulic Research XXVII Congress*, 10–15 August 1997, San Francisco, CA, USA, A, pp.746–751.

Rameshwaran, P. and Naden, P.S. (2004a) Modelling of turbulent free-surface flow in two-stage meandering channels. *Proceedings of ICE - Water management*, 157(3), pp. 159-173.

Rameshwaran, P. and Naden, P.S. (2004b) Three-dimensional modelling of free-surface variation in a meandering channel. *Journal of Hydraulic Research*, 42(6), pp. 603-615.

Rameshwaran, P. and Shiono, K. (2002) Predictions of velocity and boundary shear stress in compound meandering channel. *River Flow 2002*, International Conference on Fluvial Hydraulics, September 4 - 6, Louvain-la-Neuve, Belgium, Edited by D. Bousmar & Y. Zech, Volume 1, pp. 223-231.

Rameshwaran, P. and Shiono, K. (2003) Computer modelling of two-stage meandering channel flows. *Proceedings of ICE - Water and Maritime Engineering*, 156, pp. 326-339

Sellin R. H. J., Wilson C. A. M. E. and Naish C. (2001) Model and prototype results for a sinuous two-stage river channel design, *Journal of Chartered Institution of Water and Environmental Management*, 13, pp. 207-216.

Shiono, K. and Muto, Y. (1998) Complex flow mechanisms in compound meandering channels with overbank flow. *Journal of Fluid Mechanics*., 376, pp. 221-261.

Willetts, B.B. and Rameshwaran, P. (1996) Meandering Over-Bank Flow Structures. *Coherent Flow Structures in Open Channels*, Edited by P.J. Ashworth, S.J. Bennett, J.L Best and S.J. McLelland, John Wiley & Sons Ltd, Chapter 29, pp. 609-629.