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TWO-DIMENSIONAL NUMERICAL SIMULATION OF FLOW DIVERSIONS

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ABSTRACT: This paper reports the results of the numerical simulation of open channel flow diversions using the two-dimensional (2D) hydrodynamic model River2D. In flow diversions a lateral branch channel splits from the main straight channel diverting part of the incoming water. Diversions are found in lateral intakes and river bifurcations. Two lab experiments were simulated: (1) A 30^o lateral channel that diverts 50% of the incoming flow and has a width-depth ratio of 2.8; and (2) a narrow 90^o lateral channel that diverts 81% of the flow and has a width-depth ratio of only 0.5. The first diversion has been recently simulated using the 3D model Delft3D; but it had limited success to accurately simulate the length of an eddy inside the branch channel because of limitations with the resolution of its structured mesh. River2D, which uses a flexible finite element mesh, was able to reproduce the water depths of the first diversion with a discrepancy of only 1%; as well as the length of the eddy. River2D was also able to reproduce the velocity profiles in the branch channel of the second narrow and deep diversion, which is at the limits of applicability for 2D shallow water models. Despite the flow being highly 3D for the presence of a helical flow and eddies, River2D performed reasonably well. The results suggested that River2D can be promising tool for designing the layout of lateral intakes or the study of alluvial river bifurcations.

1. INTRODUCTION

Open channel flow diversions, as considered in this paper, are those in which part of the flow in a main channel is diverted into a lateral branch channel. Flow diversions are found in many practical situations, such as irrigation canals splitting from a main channel, run-of-the river intakes and river bifurcations (Barkdoll 2004). Experimental studies of flow diversions date back several decades (Bulle 1926, Taylor 1944, Ramamurthy and Satish 1988, Neary and Odgaard 1993, Barkdoll et al. 1998), while numerical modeling is more recent (Shettar and Murthy 1993, Neary et al. 1999, Heer and Mosselman 2004). Numerical models are usually based on structured (regular) computational meshes (or grids) composed of quadrilateral elements. Such meshes may have problems to represent the geometry of acute diversions with sharp corners (Heer and Mosselman 2004). For those cases, a numerical model that uses unstructured meshes made of triangular elements, such as River2D, may be more appropriate.

1.1. River2D hydrodynamic model

River2D is a two-dimensional (2D) depth-averaged hydrodynamic model developed by the University of Alberta (available at www.River2D.ca). River2D applies the Finite Element Method to solve the 2D depth averaged St. Venant Equations. The computational mesh is unstructured (irregular) and composed of triangular elements that can easily accommodate complex planform geometries of almost any type. For every node (vertex of a triangular element) in the computational domain, River2D computes the values of water depth h and depth-averaged velocity components (u,v) in the two respective coordinate directions (x,y).

Depth-averaged transverse shear stresses are modeled with a Boussinesq type eddy viscosity formulation. For example (Steffler and Blackburn, 2002):

$$[1] \qquad \tau_{xy} = \nu_t \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$

Where ν_t is the eddy viscosity coefficient. The eddy viscosity is assumed as

$$[2] \qquad \nu_t = \varepsilon \frac{h\sqrt{g(u^2 + v^2)}}{C}$$

Where C is the Chezy friction factor, g is the gravitational acceleration and ε is a calibration coefficient that ranges between 0.2 and 1.0. River2D's default value is $\varepsilon = 0.5$ (Steffler and Blackburn 2002). However, for the present applications this coefficient was set to $\varepsilon = 0.2$.

1.2. Objective

The main objective of this paper is to test the applicability of River2D's unstructured Finite Element mesh to simulate flow through diversions for two challenging test cases: An acute 30^o diversion with sharp corners and a 90^o diversion with a very small width-depth ratio. The results showed River2D performed reasonable well for both cases. The implications for modeling river bifurcations and lateral intakes are briefly discussed at the end.

2. EXPERIMENTAL DATA AND NUMERICAL MODEL

2.1. Bulle's 30-degree diversion

Bulle (1926) carried out experiments on alluvial diversions with angles of 30, 60, 90, 120 and 150 degrees relative to the main channel. I selected the 30^o diversion for the present numerical simulation, which is the same experiment recently simulated by Heer and Mosselman (2004) using a 3D model. The width of both the diversion and main channels is 0.20 m. The discharge was 5 l/s and the bed slope 0.003. The downstream boundary condition was controlled with weirs to split the flow evenly through both the main and branch channels. Bulle performed experiments with a fixed bed without sediments or with a layer of sediments over the fixed bed. Bulle found that the flow separates in the upstream wall of the branch channel generating a vertical axis eddy (Fig. 2), where sediment deposited during the experiments with bedload transport. The structure of the flow was highly three-dimensional; most of the flow entering the diversion came from the near-bed layers of flow in the upstream main channel; which caused a disproportionate amount of sediment to enter the diversion during experiments with bedload transport. The size of the recirculation zone (eddy) was also 3D, being larger close to the bed and smaller closer to the water surface. Bulle found that the size of the eddy could be reduced by streamlining the upstream corner of the branch channel. He demonstrated this effect in an experiment where he replaced the sharp corner by a circular arc of 0.6 m radius (Fig. 5).

In the numerical model, 5.4 m of the main channel and 2.5 m of the branch channel were simulated. The mesh was made of triangular elements of different size. Larger elements of about 4 cm were used away from the entrance to the branch channel, while elements of 1 cm or smaller were used in the area around the diversion to better capture the geometry (Fig. 1). The total number of elements was 6066 with 3336 nodes. The roughness height was set to k_s = 1 mm (equivalent to a Manning's n = 0.0122), which was considered reasonable for a laboratory flume. An additional mesh with a rounded upstream corner was also made to simulate the reduction of the eddy.

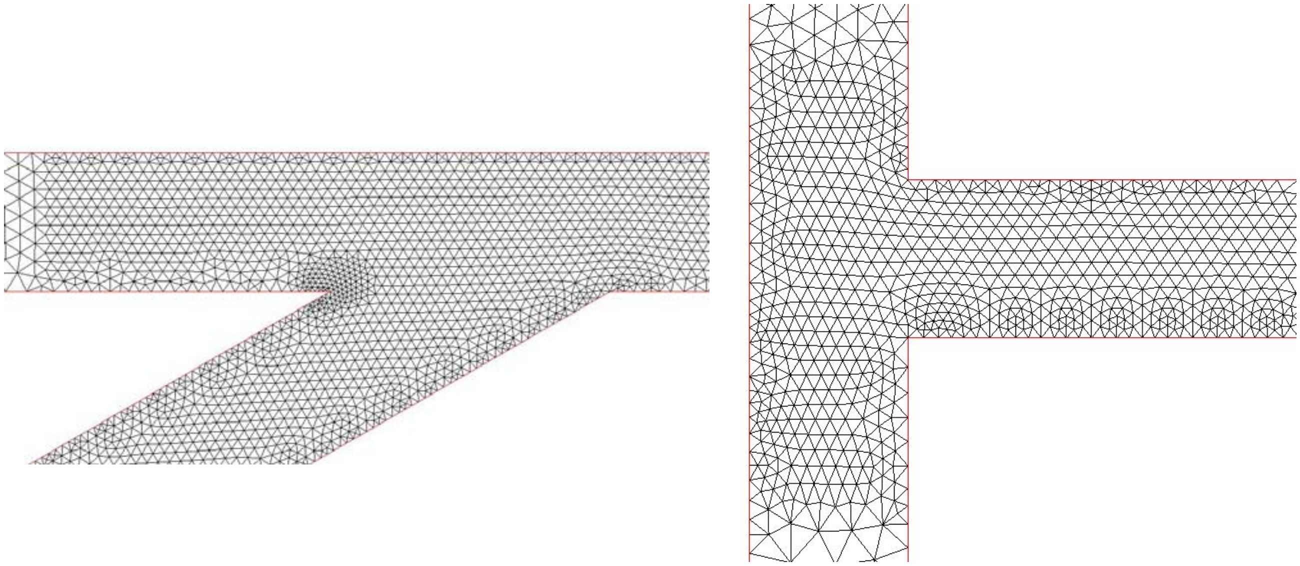

Figure 1. Details of the Finite Element mesh around the entrance to the branch channel for Bulle's 30^o diversion (left plot) and Barkdoll et al.'s 90^o diversion (right plot).

2.2. Barkdoll et al.'s 90-degree diversion.

Barkdoll et al. (1998) performed experiments in a 90^o diversion made of fibreglass coated plywood. The main and branch channels were both 15.2 cm wide and 30 cm deep. The total inflow rate was 11 l/s, of which 81% was diverted towards the branch channel (Fig. 6). The branch channel had a length equal to 12 times the channel width. Measurements of velocity profiles close to the water surface were taken with an electromagnetic velocity meter at several cross sections along the main and branch channels.

Barkdoll et al. (1998) did not report the value of the bed slope or the roughness; therefore flat bed and roughness height k_s = 1 mm (Manning's n = 0.0128) were assumed in the numerical model. The total number of elements was 3377 with 2093 nodes; most of the nodes were located around the diversion entrance (Fig. 1).

3. RESULTS

Figures 2 through 5 show the results of the numerical simulation of Bulle's 30^o diversion. River2D correctly reproduced the extension of the recirculation zone in the branch channel (Fig. 2); although it did not predicted the small eddy in the right wall of the main channel. The water depth along the main and branch channels were predicted with an average 1% error (0.5 mm); the model slightly underpredicted the water depths along the branch channel (Fig. 3). Fig. 4 shows the contours of measured velocities at 2 mm from the bed, as well as the depth-averaged velocities computed by River2D. Although the velocity plots in Fig. 4 are not strictly comparable (depth-averaged velocities and bed velocities differ in both magnitude and direction), similarities between the contour lines are evident. A velocity dip close to the downstream corner of the diversion, a strip of high velocity close to the right wall of the branch channel and the recirculation zone in the opposite wall are correctly predicted by River2D.

Bulle demonstrated that the eddy in the branch channel reduces from about 1.0 m to 0.7 m when the upstream corner is rounded by an arc of 0.6 m radius. River2D predicted exactly the same reduction in the length of the eddy (Fig. 2 and 5).

Figure 6 shows the comparison between the measured and computed velocity profiles along the branch channel of Barkdoll et al. (1998) experiment. The computed velocities were normalized by dividing them by Uo = 0.32 m/s in order to make the profiles at the centerline of the most downstream section (y* = 12) coincide. Although the measured profiles represent surface velocities, while River2D computes depth-averaged velocities, the similarity between the two profiles is rather good. River2D clearly shows the recirculation area (U/Uo < 0) along the left wall between sections y* = 2 and y* = 4. However, the measured profiles show a notorious decrease of the velocity close to the right wall, that it is not predicted by the model. This is likely an effect of the wall friction that is ignored by River2D.

The computational time required to achieve a steady state solution using a Pentium IV-3 GHz was about 30 seconds for the 30^{o} diversion and about 15 seconds for the 90^{o} diversion.

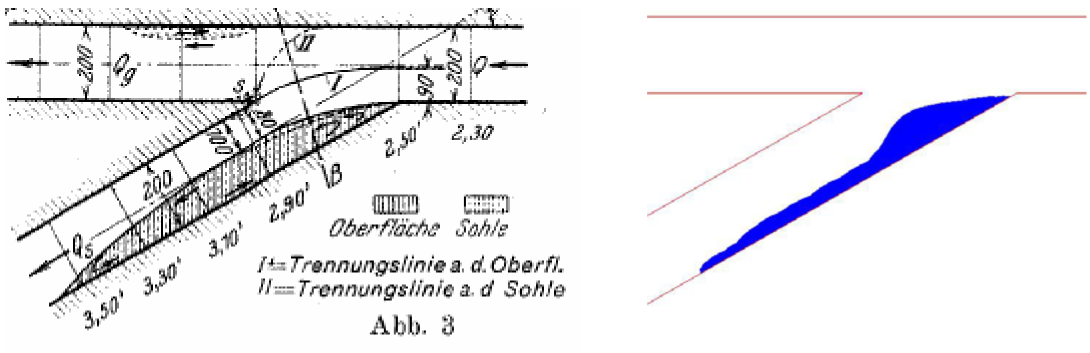

Figure 2. Extension of the recirculation zone in the diversion channel measured by Bulle (left plot) and predicted by River2D (right plot).

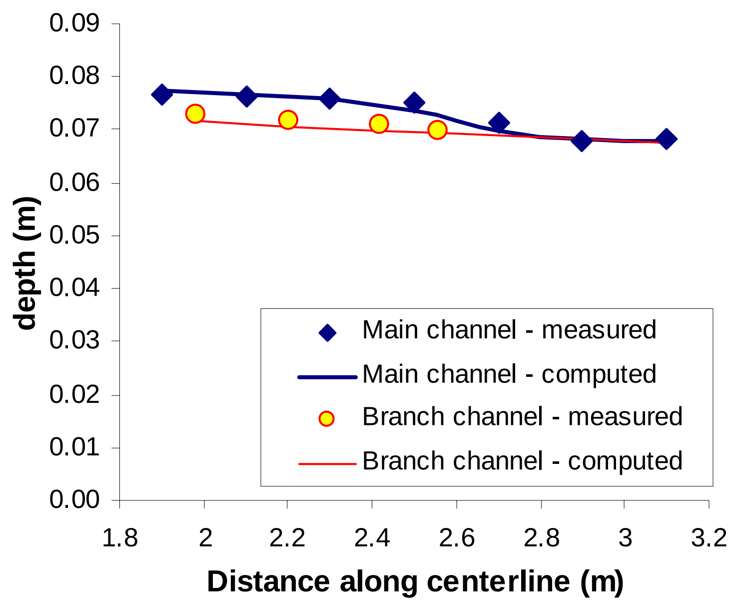

Figure 3. Measured and computed longitudinal water depth profiles along main and branch channels for 30^{o} diversion (Bulle 1926).

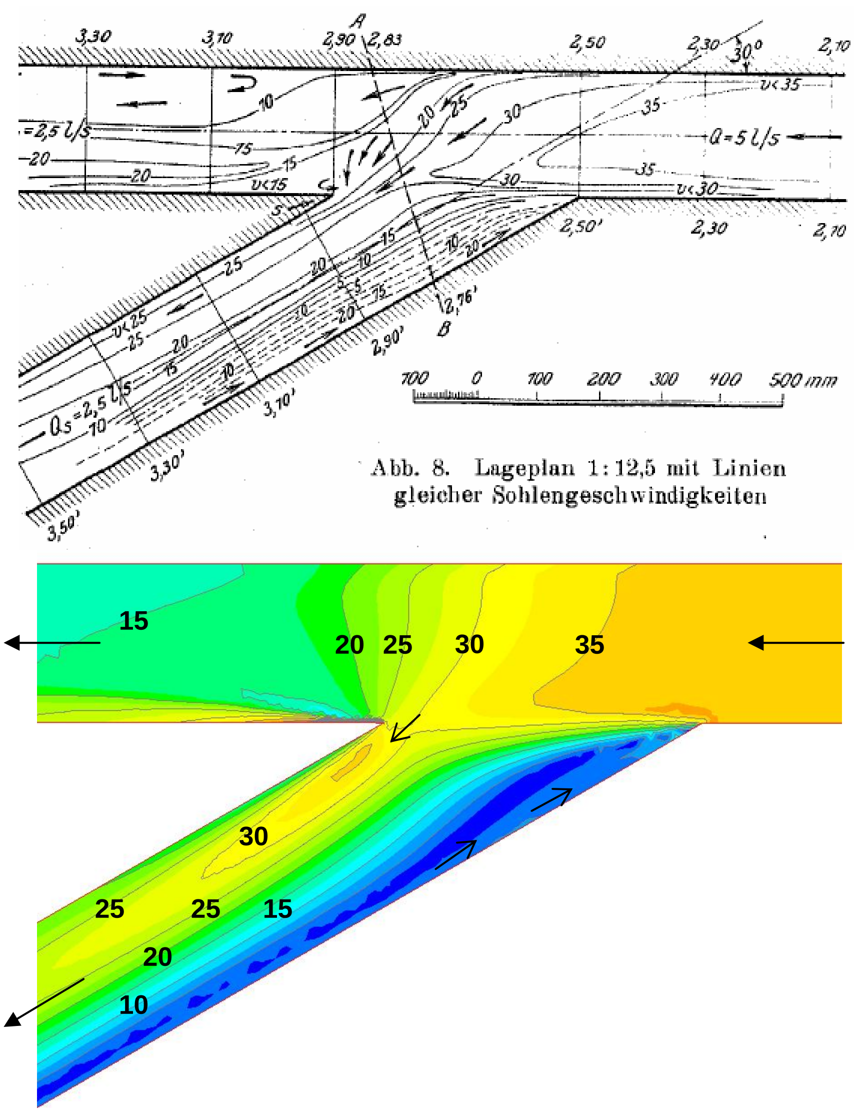

Figure 4. Near bed velocities measured by Bulle (top plot) and depth-averaged velocities predicted by River2D (bottom plot). Plotted contour lines are every 5 cm/s.

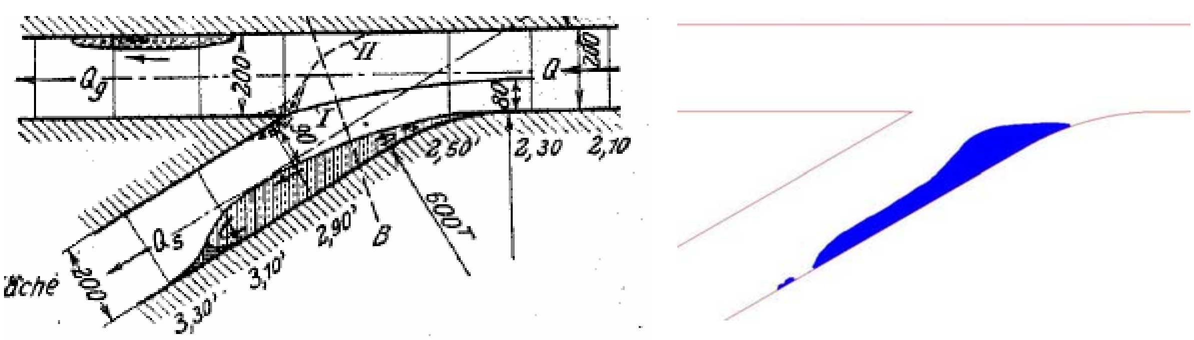

Figure 5. Reduction of the recirculation zone in the diversion channel by streamlining the entrance with a circular arc of 0.6 m radius: Measured by Bulle (left plot) and predicted by River2D (right plot).

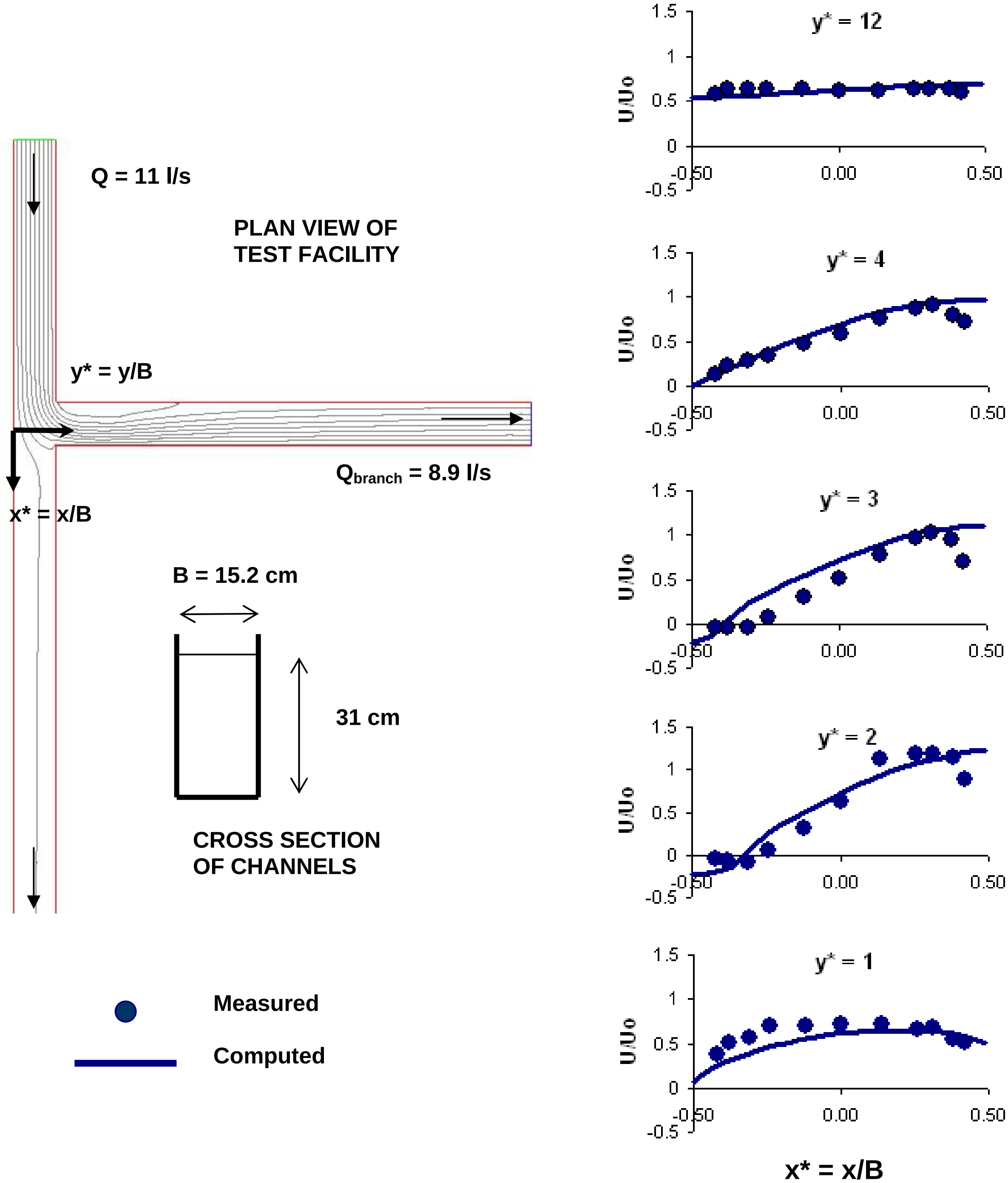

Figure 6. Layout of Barkdoll et al. (1998) test facility and experimental conditions, showing also the computed streamlines and a comparison between measured and computed velocity profiles along the branch channel.

4. DISCUSSION

4.1. Prediction capabilities of River2D

Despite the flow being highly three-dimensional in the diversion for the presence of a helical flow and recirculation zones (Bulle 1926, Neary and Odgaard 1993, Neary et al. 1999, Barkdoll 2004); River2D performed reasonably well. For the 30^o diversion, the model accurately reproduced the extension of the eddy in the branch channel (Fig. 2), the water depth in both the main and branch channels (Fig. 3) and at least qualitatively the distribution of horizontal velocity (Fig. 4). The small eddy in main channel was observed in some simulations with an uneven distribution of flow rates; but not in the final solution reported here where the branch channel diverts 50% of the incoming flow. However, that small eddy seems to be of secondary importance for the flow into the diversion. The effect of streamlining the entrance in the flow patterns is also correctly reproduced (Fig. 5).

For the 90^o diversion, there is not a very good agreement between the measured and computed velocity profiles along the branch channel (Fig. 6). However, there are good reasons for these results. Both the main and branch channels are extremely deep and narrow; the width being just half the depth (B/h = 0.5). This experiment does not comply with the general assumptions of shallow water flow used in 2D depth-averaged models. River2D only takes into account the friction of the bed. Friction of vertical walls cannot be specified. Despite those limitations, the general features of the flow were predicted correctly. Since practical applications usually imply large values of the width-depth ratio (B/h > 5); River2D should provide good results for most cases of flow diversions.

4.2. Eddy viscosity

The default value ε = 0.5 used by River2D in equation 2 seems adequate for most river applications where turbulence is bed generated (Steffler and Blackburn 2002). However, in the present application ε = 0.5 would require a substantial reduction of the bed friction (e.g. k_s =0.01 mm or Manning's n = 0.007) in order to accurately reproduce the size of the recirculation zone in the branch channel. Instead, the combination k_s =1 mm and ε = 0.2, which seems more realistic, was adopted with successful results. This was the only change made to the default values of River2D and is likely a result of a different turbulence generating mechanism in the diversion. What is a bit surprising is that the very simple turbulence model described by equations 1 and 2 provides such good results. This cast reasonable doubt in the need to use more sophisticated turbulence models (e.g. k-epsilon, LES) for this type of applications.

4.3. Unstructured mesh

Most of the numerical simulations of flow diversion reported in the literature rely on structured meshes in 2 or 3 dimensions based on quadrilateral elements (e.g. Shettar and Murthy 1996, Neary et al. 1999, Heer and Mosselman 2004); which is perfectly applicable for right-angle diversions. Very acute angles, like the 30^o diversion reported here, are challenging for structured meshes. In a recent publication, Heer and Mosselman (2004) reported that the 3D modeling system Delft3D underpredicted the length of the eddy for Bulle's 30^o diversion because the computational mesh was too round in the upstream corner of the diversion channel. River2D, which uses a flexible unstructured mesh based on triangular elements, was able to precisely map the geometry of the experimental layouts for both the sharp (Fig. 1) and rounded (Fig. 4) corners with successful results.

In fact, the main reason for adopting a Finite Element formulation like the one used by River2D is the increased geometric flexibility of the computational mesh that can adapt to almost any planform geometry. An important advantage of unstructured meshes is that the process of making the mesh is highly automated and almost effortless. Once the outside boundaries are defined, automatic mesh generating algorithms fill in the modeling area with triangular elements at a user-defined resolution. River2D also allows automatic mesh refining based on the computed flow field after a hydrodynamic solution has been achieved.

4.4. River bifurcations

Although the results reported here are for fixed-bed diversions, the results also have implications for alluvial diversions such as river bifurcations. Bulle (1926) demonstrated that because of the most of the diverted water comes from near-bed layers of the upstream channel; the branch channel receives a disproportionate amount of bed load sediment. He also showed that the eddy in the branch channel is an area of intense deposition. Barkdoll (2004) argues that these sedimentation areas may create bars in rivers that divert the flow causing attacks to riverbanks.

It is clear that a hydrodynamic model with enough capabilities to simulate the main flow patterns, such as the recirculation zone and the distributions of both velocity and depth, is a pre-requisite for any morphological model of river bifurcations. Simple 1D models for river bifurcations exist (Wang et al. 1995, Bolla Pittaluga et al. 2003), but they neglect the effects of upstream asymmetries, secondary flows or local eddies (Heer and Mosselman 2004). Given the similarities between flow pass diversions and bend flow, a 2D model with capabilities for simulating alluvial bend flow, such as River2D-Morphology (Vasquez et al. 2005), could possibly be adapted to study the morphology of river bifurcations.

4.5. Lateral intakes

Another application of open channel flow diversions are lateral intakes (Barkdoll 2004). In a physical model study of a run-of-the river intake with four parallel diversion channels, Vasquez (1993) observed sedimentation in the recirculation zones of all the diversion channels, similar to the patterns described by Bulle (1926). 2D depth-averaged models are of limited applicability in these cases because river intakes are normally located above the riverbed making the vertical component of velocity not negligible. However, 2D model still provide valid qualitative information to design the planform geometry and orientation of the intake (see www.PepeVasquez.com for details). A 2D analysis, which can be performed relatively quickly, can be used for sensitivity tests of a proposed design (Odgaard and Wang 1997) or feasibility studies of various pre-design alternatives before embarking on a physical model study or a full 3D simulation.

5. CONCLUSIONS

The two-dimensional Finite Element hydrodynamic model River2D has demonstrated that it can accurately reproduce the main flow features in fixed-bed diversions in cases with acute diversion angles and sharp corners, thanks to its flexible unstructured mesh. Even for a very deep and narrow diversion, which is at the limit of applicability for a 2D shallow water model, River2D was able predict the recirculation zones and the shape of the velocity profile along the branch channel.

These results show that River2D is a promising tool for the pre-design of lateral intakes and the study of river bifurcations.

6. ACKNOWLEDGEMENTS

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