Hydrodynamics in Kinoshita-generated meandering bends: importance for river-planform evolution

Jorge D. Abad
Graduate Research Assistant, Ven Te Chow Hydrosystems Laboratory. Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Av., Urbana, Il, 61801, USA. E-mail: abad@uiuc.edu

Marcelo H. García
Chester and Helen Siess Professor, Ven Te Chow Hydrosystems Laboratory. Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Av., Urbana, Il, 61801, USA. E-mail: mhgarcia@uiuc.edu

ABSTRACT: Most alluvial rivers have a tendency to meander as they flow downslope. This process of planform evolution is controlled by several components such as flow conditions, sediment, vegetation, and geological characteristics of the channel boundaries. The interactions of these components result in a complex system, which can not be completely described yet, even with the advance of computational, experimental and field resources. Several laboratory-based studies have dealt with periodic symmetric channel configurations and have described the importance of high-amplitude and high-curvature bends in terms of flow structure and sediment redistribution. However, most rivers present not only symmetric, but also asymmetric planform configurations. This study attempts to provide some insight into the hydrodynamic description of the flow in laboratory-scaled asymmetric meandering channels (Kinoshita-generated). Sediment transport and morphological evolution are not considered in this first stage of the study; thus, the meandering channels have been described topographically by using an empirical formulation based on local curvature and channel forming discharge. Four river stages (angular sinuosity: $\theta = 20°, 50°, 90°, 100°$) are simulated numerically with the help of a state-of-the-art three-dimensional CFD model. The results show the important role of convective accelerations, induced by point bars, in the redistribution of momentum, dynamics of secondary flows, and the distribution of bed shear stresses. Discussions about implications for sediment transport and river-planform evolution are presented.

1 INTRODUCTION

River evolution in time and space involves full spectrum variability of key components. To truly apply all of the components is not possible yet (in many cases they are unknown), even with the current advances on computational, experimental and field resources. Thus, scientists and engineers have incorporated assumptions and restrictions to their approaches depending on the objectives of the study. Several analytical, experimental and field studies for describing planform evolution have considered flow field, sediment transport and bank erosion processes in symmetric planform (e.g. sine-generated curves) configurations, Langbein and Leopold (1966). Indeed, several rivers manifest this type of winding, while others describe more complicated patterns as seen in Figure 1. Reviews about the complex patterns of river evolution are found in Hickin (1974), Hooke (1984, 1995) and Hooke et al. (1992). In rivers with high-amplitude and high-curvature bends, the asymmetric Kinoshita-type curves are found frequently (Parker et al., 1983; Parker and Andrews, 1986). Kinoshita-generated curves incorporate high order characteristics of river configuration (skewness and flatness) for high-sinuosity rivers, while reducing to almost sine-generated curves for low-sinuosity rivers. The life cycle of a river (youth, early maturity and full maturity as described by Mueller, 1968) shows two types of sinuosity: topographic and hydraulic. The former is associated with the delineation of the meander belt (valley) and the latter associated to the stream planform configuration. Herein, the term sinuosity is referred to the hydraulic case. To characterize these meandering rivers, several methodologies (Hooke, 1984; Oneill and Abrahams, 1986; Howard and Hemberger, 1991; MacDonald et al., 1992) and user-friendly tools (Lagasse et al., 2004; Abad and García, 2005) have been proposed. In this study, four river sinuosities (at different stages of river evolution prior to cut-off) are considered in an asymmetric Kinoshita-generated meandering channel. At this preliminary stage, sediment transport and morphological evolution are not considered, and then the Kinoshita-generated curves have been described topographically by using an empirical formulation developed by Beck (1988).

Figure 1: Meandering Alatna River, Alaska, USA (http://www.terragalleria.com)

2 METHODOLOGY

As stated before, no sediment transport and morphological evolution is performed in these preliminary simulations. This work has served primarily at the design stage of a laboratory-scale asymmetric meandering channel (Kinoshita-generated) where bed evolution and sediment transport will be considered. Herein, the bed topography is described by using empirical formulations based on field and experimental results. Then, a state-of-the-art three-dimensional CFD model is applied for each configuration at two different flow stages.

2.1 *Steady-state transversal bed slope parameter, A*

Based on the work of Yen (1967), Zimmerman and Kennedy (1978) and Odgaard (1981); Beck (1988) described the transversal bed slope parameter A by using the following empirical relationship:

$$A = 3.8\left(1.0 + \frac{B}{6.96H}Exp\left(\frac{-6.96H}{B}\right)\right) \qquad (1)$$

Where B and H are the half-width and water depth of the channel. In general, the parameter A is related to sediment characteristics, flow velocity and discharge variation, and therefore time variation. However, in the present analysis, since the simulations are performed by using the same hydraulic and sediment conditions, the parameter A can be assumed as constant.

2.2 *Transversal slope, S_t*

For low- and medium-sinuosity rivers, the maximum transverse bed slope is located downstream from the point of maximum channel curvature in a meander bend. Several empirical lag expressions have been presented in the past to account for such lag. Based on previous experiments (Hooke, 1974; Gottlieb, 1976; Hasegawa and Yamaoka, 1984; Yamaoka and Hasegawa, 1984 and Ikeda and Nishimura, 1986), Beck (1988) also presented an empirical formulation for the lag component, valid for mild- and high-sinuosities and not for intermediate–sinuosity cases. Herein, no lag component between the maximum transverse bed slope and the maximum channel curvature is considered. Thus, the transverse bed slope is directly related to the local channel curvature ($C = \partial\theta/\partial s$) as $S_t = -AHC$.

2.3 *Transverse bed elevation in a cross section*

Beck (1988) described three different empirical relationships for delineating the transversal bed elevation (linear, exponential and Beck's proposal). Herein, Beck's proposed empirical relationship is used. The bed elevation is given by $\eta = H - h$; h is the flow depth across the section (Equation 2) and $\tilde{h}_c$ is the depth at the center of the cross section (Equation 3), given by the following expression,

$$h = \left(1 - \frac{h_c}{S_t n}\right)\left\|-S_t n, 0\right\| + \frac{h_c}{S_t n}Exp\left(-S_t\frac{n}{H}\right)\left\|S_t n, 0\right\| \qquad (2)$$

$$\tilde{h}_c \approx \frac{4BH\,|S_t| - S_t^2 B^2}{2B\,|S_t| + 2H - 2HExp\left(-|S_t|\frac{B}{H}\right)} \qquad (3)$$

Finally, the bed elevation η is expressed as:

$$\eta = H - \left(1 - \frac{h_c}{S_t n}\right)\left\|-S_t n, 0\right\| + \frac{h_c}{S_t n}Exp\left(-S_t\frac{n}{H}\right)\left\|S_t n, 0\right\| \qquad (4)$$

where s and n are the streamwise and transversal coordinates and $\|A, B\|$ represents the greater value between A and B. For more information about the development of these relationships, the reader is referred to Beck (1988).

2.4 *Validation of Beck's relationship for mild- and high-sinuosity channels*

Beck (1988) presented a qualitative comparison of a mild-sinuosity, sine-generated channel bed elevation (Hooke, 1974) and his empirical relationship (Equations 2-4). Herein, an additional qualitative comparison for the case of high-sinuosity, Kinoshita-generated channel (Hills, 1987) is presented. These two qualitative comparisons are shown in Figures 2 a, b. Through a visual comparison for the case of high amplitude bends (Hills, 1987), it can be noticed in Figure 2b that upstream from the bend apex, the computed bed configuration does not reproduce well the existence of the pool along the inner bank. This issue suggests the existence of a lag component between the maximum transversal bed slope and the maximum channel curvature. However, downstream from the bend apex, the bed topography is quite well represented. Thus, herein, no lag component is assumed.

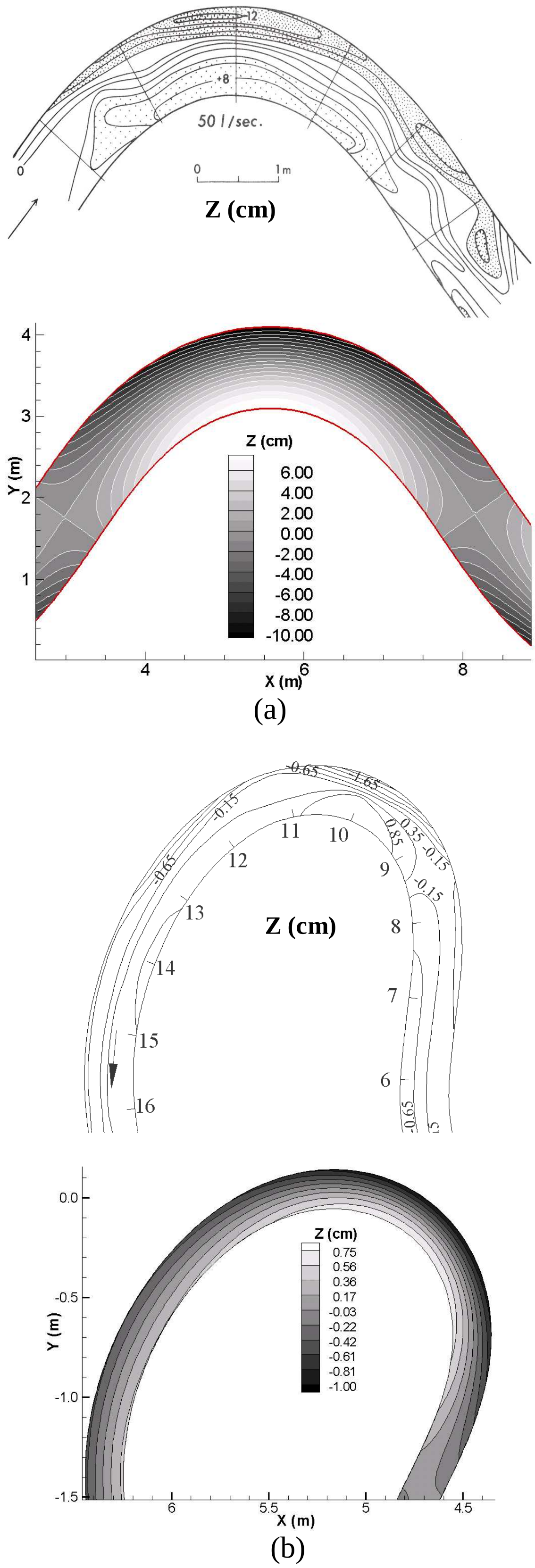


Figure 2: Comparison of experimental and computed bed elevation using Beck's empirical formulation. (a) Hooke (1974) (RUN 50); (b) Hills (1987) (RUN 3-2), original reference level for contours have been modified (from depth to bed elevation values) for comparison

2.5 *Planform configurations*

Several formulations for river planform configurations have been presented for symmetric (sine-generated curves: Langbein and Leopold, 1966) and asymmetric bends (Fourier series-based: Yamaoka and Hasegawa, 1984 and Kinoshita-generated: Kinoshita, 1961; Kinoshita and Miwa, 1974; Parker et al, 1983; Parker and Andrews, 1986). Herein, Kinoshita-generated meandering channels are used and described in intrinsic coordinates by:

$$\theta = \theta_0 Sin\left(\frac{2\pi s}{\lambda}\right) + \theta_0{}^3\left(J_s Cos\left(3\frac{2\pi s}{\lambda}\right) - J_f Sin\left(3\frac{2\pi s}{\lambda}\right)\right) \quad (5)$$

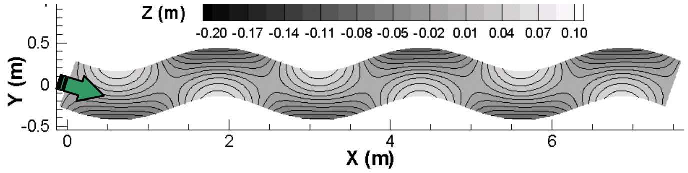
Where, J_s and J_f represent the skewness and flatness coefficients, θ_0 is the maximum angular amplitude, λ is the arc-wavelength of the channel, and s is the streamwise coordinate.

Four configurations ($\theta_0 : 20°, 50°, 90°, 100°$) are chosen to cover low-, medium- and high-sinuosity meandering channels before cut-off occurrence. By choosing the width ratio (β) equal to 3 (B=0.3 m and H=0.1 m), the transversal bed slope parameter A (given by Equation 1) results in 3.961. These four configurations are defined using the same wavelength, λ (around 8 times the width of straight channels), but different arc-wavelength, λ_c, resulting in a range of sinuosities ($S = \lambda_c/\lambda$) going from 1.03 to 2.69. The centerline slope was kept constant on equal to 0.001 for all runs.

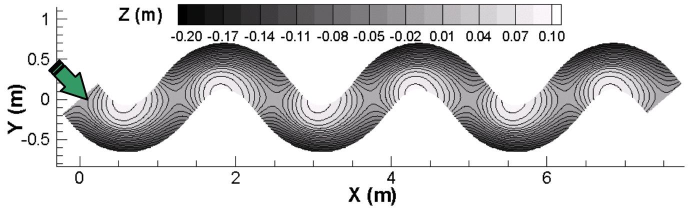
Parker and Andrews (1986) presented the required dimensioned time interval $\Delta t = (H_0 \Delta t^*)/(U_0 E_0 B)$ (the dimensionless time interval Δt^* is given by Equation 6) for computing the time required for a freely meandering bend to increase or decrease in angular amplitude from an initial value θ_I to a final value of θ_F, as follows:

$$\Delta t^* = \frac{1 + \frac{1}{2}A}{2k_c^2 A \theta_I^2} \frac{1}{\beta_t} \ln\left[\frac{(\theta_F/\theta_I)^2 (6\beta_t + 1)}{6\beta_t + (\theta_F/\theta_I)^2}\right] \quad (6)$$

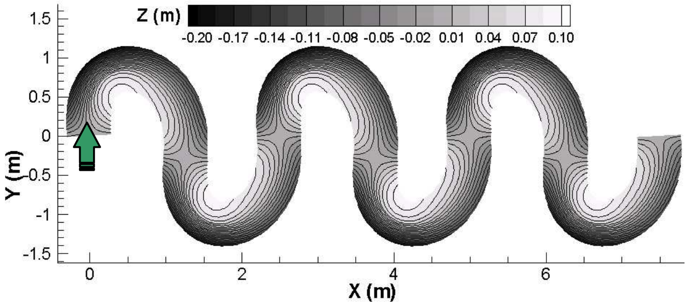
Thus, the time required to reach the configuration at 100° (considering the initial time at 20°) is approximately 320 years of river evolution (using k_c=0.031, β_t=3.0, E_0=1.0x10^{-8}) where k_c is the critical wavelength, and β_t is a parameter that controls growing or decaying of meander bends.



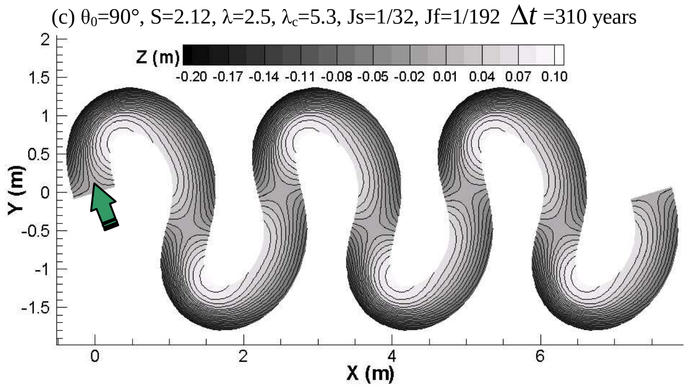
(a) θ_0=20°, S=1.03, λ=2.5, λ_c=2.58, Js=1/32, Jf=1/192, Δt =0 years



(b) θ_0=50°, S=1.22, λ=2.5, λ_c=3.05, Js=1/32, Jf=1/192, Δt =210 years



(c) θ_0=90°, S=2.12, λ=2.5, λ_c=5.3, Js=1/32, Jf=1/192 Δt =310 years



(d) θ_0=100°, S=2.69, λ=2.5, λ_c=6.73, Js=1/32, Jf=1/192 Δt =320 years

Figure 3: Bed elevation using Beck's empirical formulation, equations (2)-(4) (Beck, 1988)

3 FLOW FIELD MODELING

A state-of-the-art three-dimensional model FLOW-3D® developed by Flow Science Inc (2005) was used. This CFD model has been previously validated for river modeling by Rodriguez et al. (2004) and Abad et al. (2005a, b). FLOW-3D specializes in the accurate simulation of free surface flows, using the Volume of Fluid (VOF) technique. The model solves simultaneously the three-dimensional Navier-Stokes equation and the continuity equation (Equations 7 and 8).

$$\frac{\partial}{\partial x_i}(u_i A_i) = 0 \tag{7}$$

$$\frac{\partial u_i}{\partial t} + \frac{1}{V_f}\left(u_j A_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + G_i + f_i \tag{8}$$

Where u_i represents the fluid velocities in x, y and z Cartesian coordinates (u, v and w); A_i (A_x, A_y and A_z) are the fractional area open to flow in the x, y, and z directions; P is the pressure, G_i (G_x, G_y and G_z) are the body accelerations; and f_i (f_x, f_y and f_z) are the viscous terms. FLOW-3D can handle different turbulence closures such as Prandtl mixing length model, turbulent energy model, $\kappa-\varepsilon$ model, Renormalized Group (RNG) model and Large-Eddy simulation model. In the present study, the RNG model is used following previous studies (Lane et al., 1999 and Rodriguez et al., 2004, Abad et al., 2005a, b). More details about different turbulence closures can be found in Rodi (1993) and Pope (2000) among others.

3.1 *Computational grid and model setup*

Figure 3 shows four configurations without the streamwise slope (for visualization purposes), however during simulations, this slope was introduced (0.001). The empirical bed elevation is created using the channel forming parameters in which the average velocity and flow depth were estimated as U=0.3 m/s and H=0.1 m respectively ($Fr = U/\sqrt{gH}$ =0.303). Additional runs with H=0.15 m are performed by using the same bed configuration as in H=0.1 m. The spacing of the pools (3-5 times the channel width) along the meandering bends (Figure 3) is in accordance to previous studies (Whiting and Dietrich, 1993b; Zimmerman and Kennedy, 1966; Engelund, 1974; and Kikkawa et al., 1976). In these four configurations, similar boundary conditions are imposed. Pressure boundary conditions are introduced in the upstream and downstream ends. Bed and bank-side boundary conditions were considered as no-slip rough surfaces (k_s=0.013578). At the entrance and exit regions of the meandering configurations shown in Figure 3, straight channels, approximately 2.0 m long have been added in order to have a fully developed turbulent flow at the entrance and to avoid boundary effects at the exit region respectively.

4 RESULTS

Two flow cases β=3 (H=0.10 m) and β=2 (H=0.15 m) are simulated. Figures 4 and 5 show the spatial distribution of velocity magnitude throughout the middle bend for β=3 and 2 respectively. As expected, the water super-elevation is more pronounced for the case of high-curvature or high angular amplitude (Yen, 1965; Ippen et al. 1962).

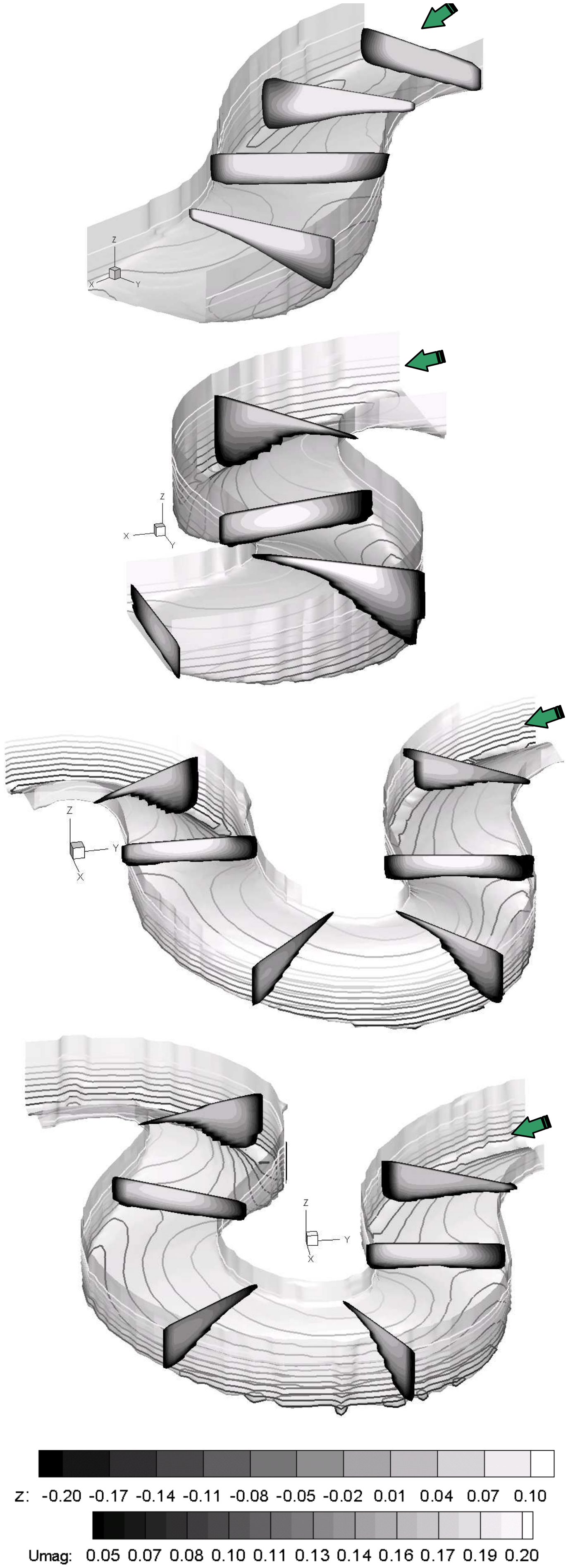


Figure 4: Velocity magnitude [ms^{-1}] at cross sections on middle bend. From top to bottom (Θ=20°, 50°, 90° and 100°).H=0.10 m

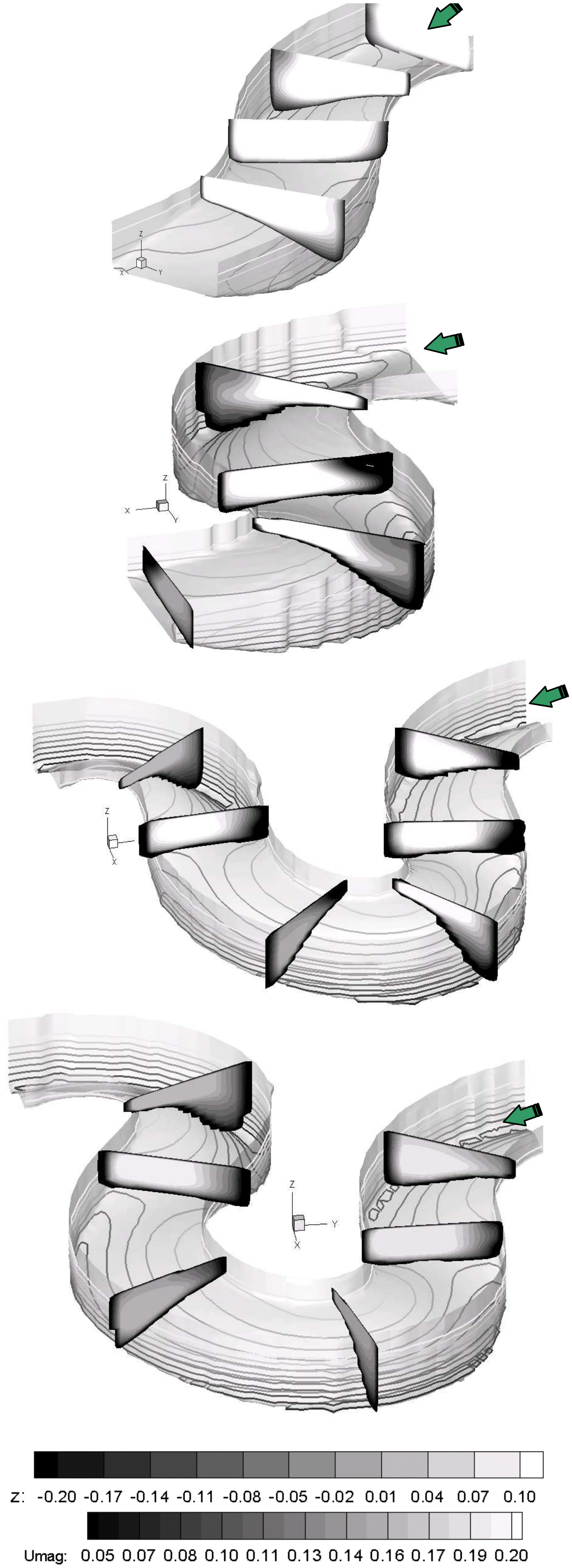


Figure 5: Velocity magnitude [ms^{-1}] at cross sections on middle bend. From top to bottom (Θ=20°, 50°, 90° and 100°). H=0.15 m

Results confirm previous studies (Ippen et al. 1962; Yen, 1965; Silva, 1995) that for low- and mild-sinuosity meandering channels (θ=20° and θ=50°), the flow with high velocities is concentrated near the inner bank, while for high-sinuosity channels (θ=90° and θ=100°), the flow with high velocity shifts from the inner bank to the outer bank. The latter is attributed to the flow redirection induced by the point bar at the inner bank near the apex (Dietrich and Smith, 1983; Dietrich, 1987 and Kawai and Julien, 1996). As expected, the velocity magnitudes for the case of β=2 (H=0.15 m) are higher than those for β=3 (H=0.10 m). However the patterns of velocity distribution are very similar in both cases.

Figures 6 and 7 show that the near-bed shear velocity is stronger in the bar crests (light regions), and it is weaker in the pools (dark regions). The distribution of near-bed shear velocities for low-sinuosity channels (θ=20°) are found to be higher in peak magnitude and mainly concentrated in the central region of the channel. For the case of intermediate sinuosity (θ=50°), the maximum near-bed shear velocity is found upstream from the bend apex. For high-sinuosity channels (θ=90° and θ=100°), an interesting behaviour is found. For the case of θ=90°, the peak shear velocity is found slightly upstream of the bend apex at the inner bank, however for the case of θ=100°, another region with high shear velocity of similar strength was found downstream of the bend apex near the inflection point. This suggests that even though the patterns for velocity magnitude are quite similar (Figures 4 and 5); the existence of an additional asymmetry on the channel planform configuration determines a major redistribution of near-bed shear velocities. However, the latter could also be related to the increment of channel amplitude (~ 2.5 times the channel width).

For both conditions (β=2 and 3), the patterns of shear velocity are quite similar, however, in the case of β=2, the magnitudes are one order higher of magnitude than those of β=3.

Figures 8 and 9 show the turbulent kinetic energy (TKE) for β=3 and β=2 respectively. In both cases the maximum TKE is found near the bed at the central region, however, near the apex the maximum TKE is found located near the inner bank due to the point bar effect which produces additional turbulence activity. Downstream of the bend apex, there is a region with high values of TKE near the outer bank, which gets weaker until the inflection point and again increases its value near the apex of the downstream bend.

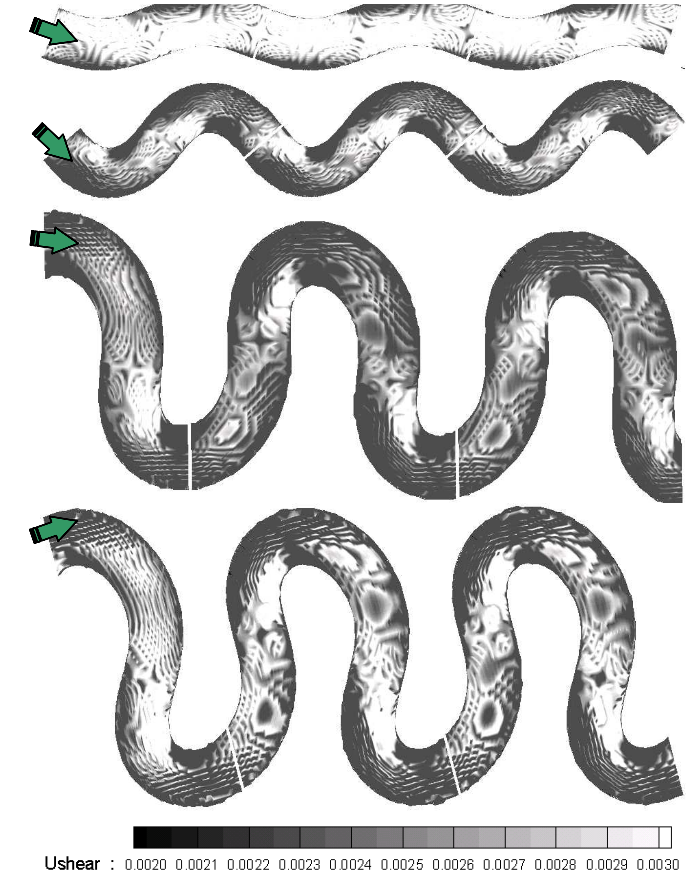


Figure 6: Near-bed shear velocity. From top to bottom (Θ=20°, 50°, 90° and 100°). H=0.10 m.

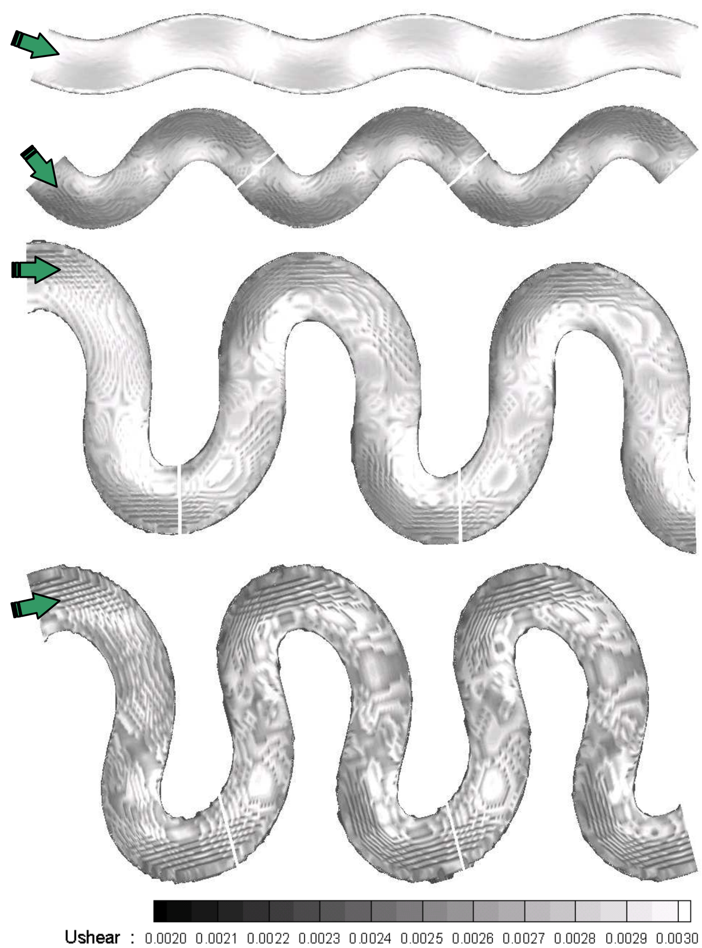


Figure 7: Near-bed shear velocity. From top to bottom (Θ=20°, 50°, 90° and 100°). H=0.15 m.

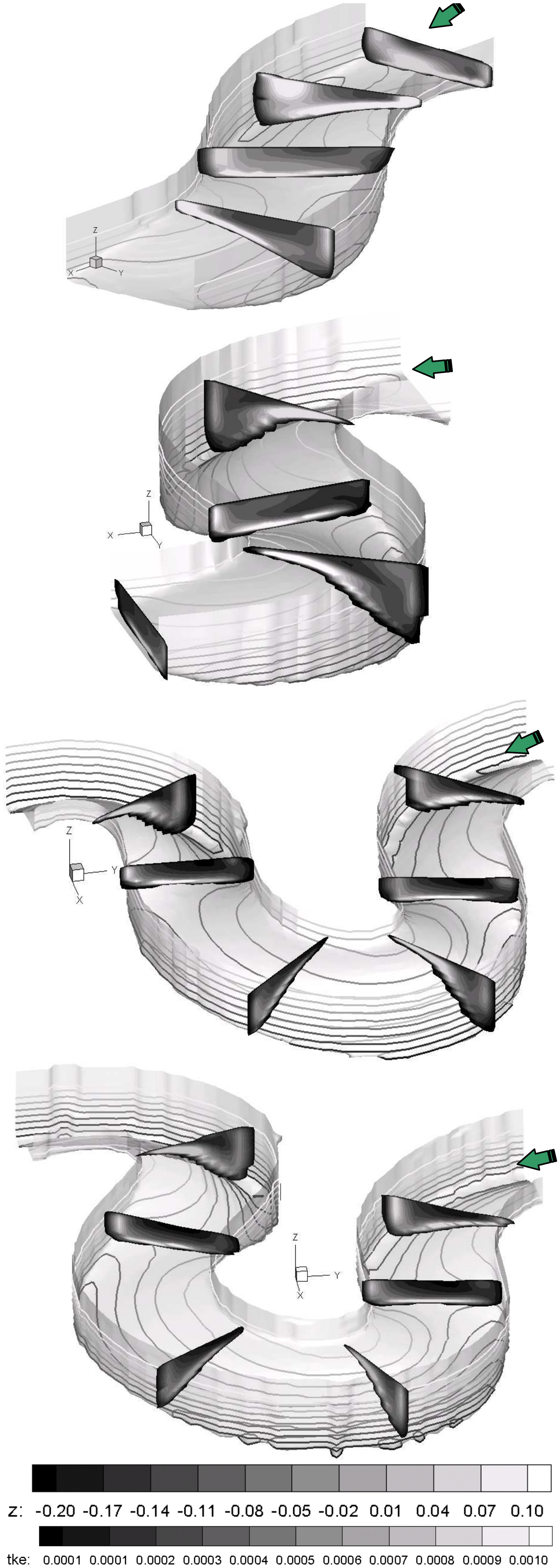


Figure 8: Turbulent Kinetic Energy [m^2s^{-2}] at cross sections on middle bend. From top to bottom (Θ=20°, 50°, 90° and 100°). H=0.10 m.

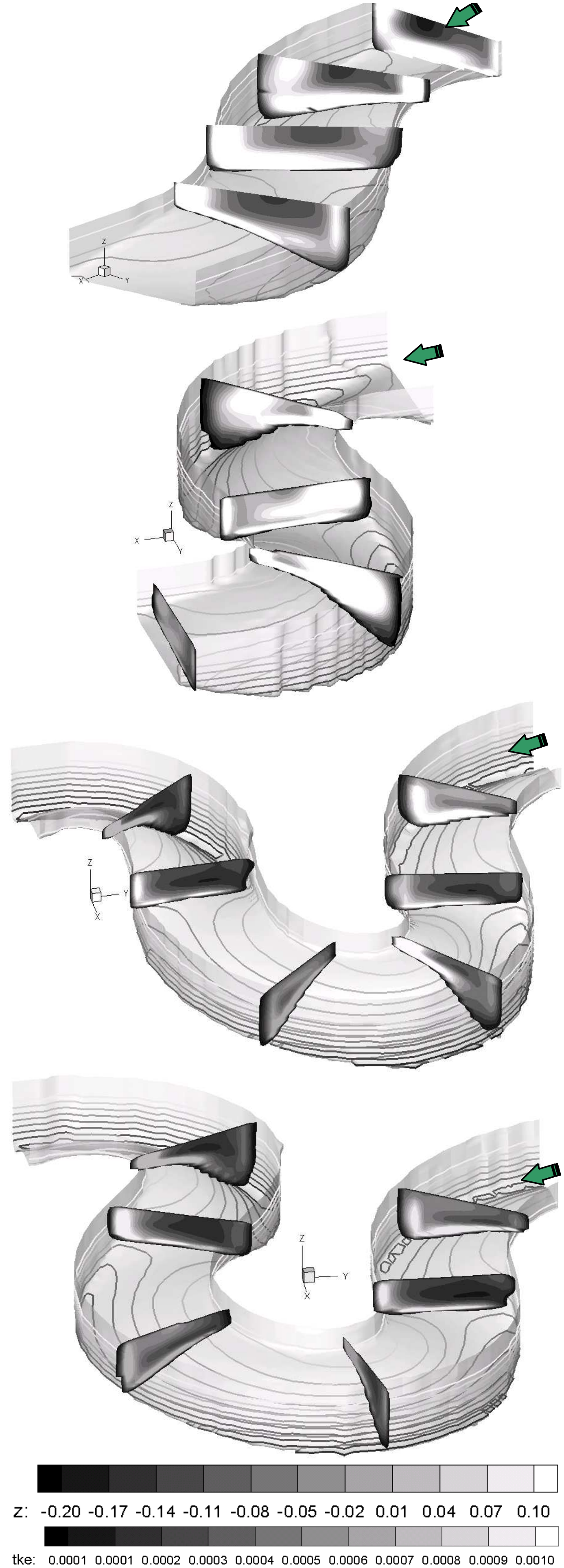


Figure 9: Turbulent Kinetic Energy [m^2s^{-2}] at cross sections on middle bend. From top to bottom (Θ=20°, 50°, 90° and 100°). H=0.15 m

Blanckaert (2002) and Blanckaert and de Vriend (2004) have presented detailed measurements of mean and turbulent quantities in a high-curvature experimental channel (sharp bend). It was mentioned the existence of two recirculating cells (center-region cell and outer-bank cell), in which, the turbulence activity in the outer bank was found to be smaller than in the case of straight channel due to streamline curvature effect. Indeed this reduction in turbulence activity has been described by Figures 8 and 9. However, there are certain region with peak values of TKE, mainly concentrated near the bed and near the inner bank upstream of the bend apex and near the outer bank downstream of the bend apex

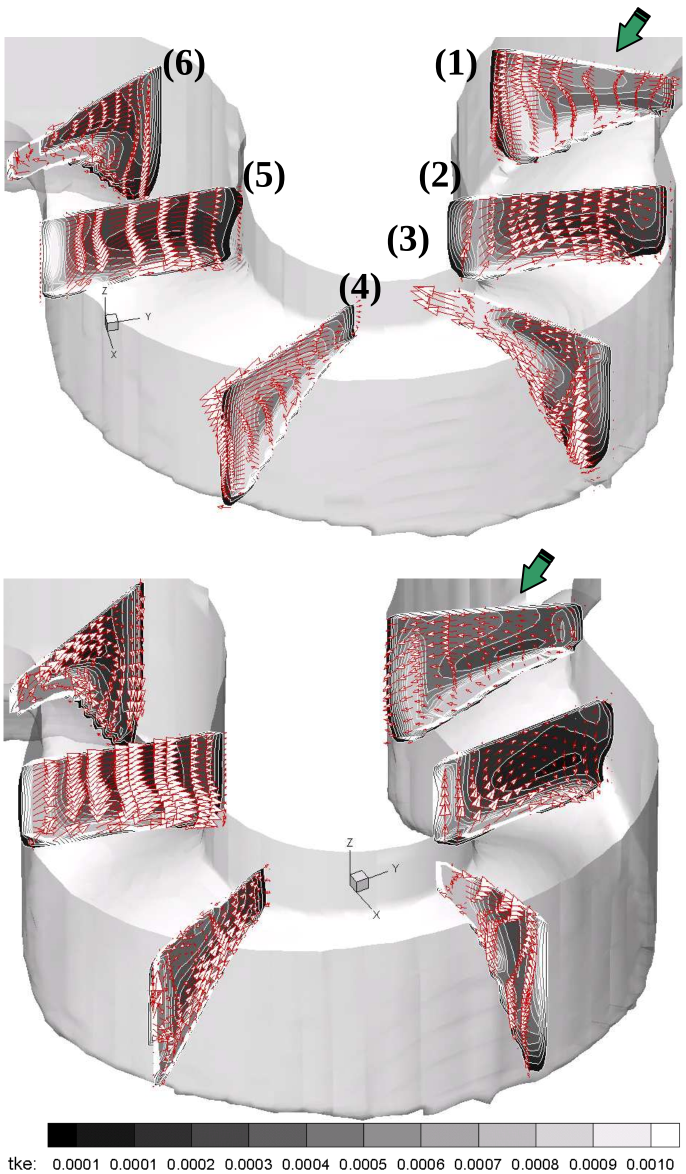


Figure 10: Turbulent Kinetic Energy [m^2s^{-2}] at cross sections on middle bend. From top to bottom (Θ=90° and 100°). H=0.15 m. Vectors describe recirculation cells.

Figure 10 shows detailed flow recirculation cells at different cross sections for H=0.15 m (some vectors are skipped for visualization purposes). These two configurations present some similarity in terms of recirculation cells. At section 1 (prior to the inflection point), the flow moves toward the outer bank, however near the inflection point (section 2), the flow starts to change in direction, but there is no defined transversal recirculation cells yet. In the case of section 3 and 4 (near the bend apex), the recirculation cell is defined quite well, however, the recirculation cell is weaker for section 4 than for section 3. Thus, at the next inflection point (section 5), the flow already has changed direction. In these simulations almost no additional recirculation cells have been found. The latter could be due to the necessity of increasing the resolution and to the use of RNG turbulence closure. Future work would incorporate the use of LES modeling which has been proved can described additional recirculation cells near boundaries, which indeed are quite important for bank and bed erosion.

5 DISCUSSION

The methodology of combining predefined planform and bed formulations presents some limitations such as the river bed is assumed to have pools are riffles under steady conditions and equilibrium, where no migrating bars are considered. However, migration of multiple bars is frequently observed in wide channels (large width ratio, β). Whiting and Dietrich (1993a, b) and Garcia and Niño (1993) described that depending on some parameters (e.g. sediment supply, sinuosity, etc), migrating bars are found along the outer bank in the nearly constantly curved region in a meandering channel. In the contrary, for narrow channels (low width ratio), Whiting and Dietrich (1993a, b) stated that these migrating bars are suppressed, but not eliminated, while, Yamaoka and Hasegawa (1984) showed that for a width ratio equal to 6, the migrating bars are completely eliminated. In fact, in Hills (1987)'s experiments, the width ratio was around 4~7 and in some runs no migrating bars were reported in the Kinoshita-type configuration. Another limitation of this methodology is that the water discharge that produce the equilibrium river bed is related to a steady condition by using the channel forming discharge concept (Ackers and Charlon, 1970; Biedenharn and Copeland, 2000; Shields et al., 2003 and Abad and García, 2004).

However this methodology could be useful for many situations such as in restoration and naturalization processes. In the past many streams have been channelized to improve channel conveyance and have ended with detrimental consequences in the downstream reach. A good example is given by the

Kankakee River that was straightened on the Indiana side and has exacerbated flooding problem as it flows though Illinois for more than a century. Nowadays there is a strong desire to restore streams to more natural conditions. However, not much is known about re-meandering of channelized streams and often times is not possible to go back to the original meandering pattern due to the development that has taken place along the river banks and its floodplain. In several meandering evolution models (e.g. Abad and García, 2004, 2005), the use of simplistic formulations based on bank erosion coefficients (e.g. Ikeda et al, 1981) is common; however, for determining the interaction of flow structure, bed and bank erosion, and how this interaction controls river evolution patterns such as cut-offs, double headings, as well as resonance between bar migration and channel sinuosity (García and Niño, 1993 and Seminara et al. 2001), the knowledge of the hydrodynamics at different morphological stages is required.

Another advantage of using idealized meandering channels could be for presenting more exhaustive validations and testing of numerical models, where special attention should be given to the use of turbulence closures. It is well known, that streamline curvature reduces turbulent activity (Bradshaw, 1969, 1973; Irwin and Smith, 1975; Chebbi et al., 1998; Holloway and Tavoularis, 1998). Blanckaert (2002) stated that streamline curvature affects turbulence in a similar fashion as stratification does. Several scientists have incorporated the effect of streamline curvature into standard RANS turbulence models (Howard et al., 1980; Launder et al., 1987; Younnis, 1993). Booij (2003) presented LES simulations for a rotating annular flume and for an experimental curved flume, where it was observed that LES models improve the representation of secondary recirculation cells in curved channels. However, an issue still pending is the resolution needed for LES models in order to cover a wide range of the flow energy spectrum. In the case of river mechanics, few experimental studies have covered a wide range of river sinuosities (Friedkin, 1945), while others have specified a sinuosity by having a movable bed with fixed banks (Whiting and Dietrich, 1993a, 1993b; García and Niño, 1993). Based on those experiments, good understanding on the morphology evolution process was acquired. Thus, recently, numerical efforts have attempted to simulate these morphological processes (Duan, 1998; Darby and Delbono, 2002; Jang and Shimizu, 2005) where mostly qualitative rather than quantitative agreements were reported. In order to improve this prediction of interaction of flow behavior and morphology evolution, there is a strong need for a better turbulence representation in meandering channels, thus the use of idealized meandering channels could provide an essential setup for testing different turbulent closures rather than using constant curvature channels or curved ducts where no free surface effects are considered.

Another application for these idealized meandering channels could be for gaining an insight into time- and spatial-scales related to flow and sediment transport processes, thus improving our morphological prediction capabilities. An applied application of these idealized meandering channels could be related to the study of the effects of instream structures (e.g. bendway weirs; Abad et al. 2005a, b) on bank erosion control and fish habitat enhancement as well as on the on flow structure and sediment transport patterns.

6 CONCLUSIONS

The combination of empirical formulations for river planform and bed configuration at equilibrium conditions makes it feasible to describe the spatial three-dimensional distribution of the flow structure in idealized symmetric and asymmetric meandering channels. These results have reflected the importance of the convective accelerations due to the presence of the point bar near the bend apex, which redistributes the primary and secondary flows as well the near-bed shear velocity. High turbulent kinetic energy is found near the bed, this is related to the rate of bed and bank-toe erosion that could in turn enhance the rate of bank erosion. Furthermore, a reduction on turbulence activity has been verified by increasing the sinuosity of the river. However, there are still regions with peak values which could enhance sediment erosion. At this stage of the study, it is necessary to perform detailed mean and turbulence measurements on this type of asymmetric meandering channels, which could help us to improve the predictions of river morphodynamics. This laboratory experiments are currently been prepared.

7 ACKNOWLEDGEMENTS

This research has been partially supported by the Illinois Water Resources Center (Grants: USGS Project 04, contract No. 14-08-0004-G2017 and 2001IL4321B) and the National Science Foundation (Grant No. 0097059).

Abad, J. D. & García, M. H. 2004. Conceptual and Mathematical Model for Evolution of Meandering Rivers in Naturalization Processes. *ASCE World Water & Environmental Resources Congress*, Salt Lake City, Utah, USA.

Abad, J. D. & García, M. H. 2005. RVR Meander: A toolbox for re-meandering of channelized streams. *In Press in Computers & Geosciences*. doi:10.1016/j.cageo.2005.05.006.

Abad, J. D., Rhoads, B. L. Guneralp, I., García, M. H. 2005. Effect of bendway weirs on low-stage flow structure: field measurements, modeling and importance for stream habitat enhancement. *Submitted to Journal of Hydraulic Engineering*.

Abad, J. D., Rhoads, B. L., García, M. H. 2005. Flow structure at different flow stages in a meander-bend with bendway weirs. In preparation.

Ackers, P. & Charlon, F. G. 1970. Geometry arising from varying flows. *Journal of Hydrology*, 11.

Biedenharn, D. S., Copeland, R. R. 2000. Effective discharge calculation. *Tech. rep., U.S. Army Corps of Engineers*, ERDC/CHL HETN-II-4.

Blanckaert, K. & de Vriend, H. J. 2004. Secondary flow in sharp open-channel bends. *Journal of Fluid Mechanics*, 498: 353-380.

Blanckaert, K. 2002. Flow and turbulence in sharp open-channel bends. PhD thesis, Ecole Polytechnique Federale de Lausanne, Lausanne, EPFL, Switzerland.

Beck, S. M. 1988. Computer-simulated deformation of meandering river patterns. *PhD Thesis*. Department of Civil Engineering, University of Minnesota, Minneapolis, Minnesota, USA.

Booij, R. 2003. Measurements and Large Eddy Simulations of the flow in some curved channels. *Journal of Turbulence*, 4.

Bradshaw, P. 1969. The analogy between streamline curvature and buoyancy in turbulent shear flow. *Journal of Fluid Mechanics*, 36: 177-191.

Bradshaw, P. 1973. Effects of streamline curvature on turbulent flow. *AGARDograpg*, NATO (169).

Chebbi, B., Holloway, A. G. L., Tavoularis, S. 1998. The response of sheared turbulence to changes in curvature. *Journal of Fluid Mechanics*, 358 (7).

Darby, S. E., Delbono, O. 2002. A model of equilibrium bed topography for meanders. *Earth Surface Processes and Landforms*, 27: 1057-1085.

Dietrich, W. E. & Smith, J. D. 1983. Influence of the point bar on flow through curved channels. *Water Resources Research*, 19 (5): 1173-1192.

Dietrich, W. E. 1987. Mechanics of flow and sediment transport in river bends. In K. Richards (Ed.). River Channel Environment and Process, Basil, Blackwell: 179-227.

Duan, J. G. 1998. Simulation of alluvial channel migration processes with a two-dimensional numerical model. *PhD thesis*, Engineering Science, Computational Hydroscience and Engineering Department, University of Mississippi, Mississippi, USA.

Engelund, F. 1974. Flow and bed topography in channel bends. *Journal of the Hydraulics Division*, 100 (HY11): 1631-1648.

Flow Science Inc. 2005. FLOW-3D version 9.0.

Friedkin, J. 1945. A laboratory study of the meandering of alluvial rivers. *Technical Reports, U. S. Waterways Experiment Station*, Vicksburg, Mississippi.

García, M. H. & Niño, Y. 1993. Dynamics of sediment bars in straight and meandering channels: experiments on the resonance phenomenon. *Journal of Hydraulic Research*, 31(6).

Gottlieb, L. 1976. Three-dimensional flow pattern and bed topography in meander channels. *ISVA Ser. Pap. 11*, Tech. Univ. Denmark, Copenhagen.

Hasegawa, K. & Yamaoka, I. 1984. Phase shifts of pools and their depths in meander bends. *In River Meandering, Proceedings of the Conference, Rivers '83*, edited by C. M. Elliot: 885-895, ASCE, New York.

Hickin, E. J. 1974. The development of meanders in natural river-channels. *American Journal of Science*, 274: 414-442.

Hills, R. A. 1987. Sediment sorting in meandering rivers. *Master thesis*. Department of Civil Engineering, University of Minnesota, Minneapolis, Minnesota, USA.

Holloway, A. G. L. & Tavoularis, S. A. 1998. A geometric explanation of the effects of mild streamline curvature on the turbulence anisotropy. *Physics of Fluids*, 10 (7).

Hooke, R. LeB. 1974. Shear-stress and sediment distribution in a meander bend. *Technical report*. University of Uppsala, Sweden..

Hooke, J. M. 1995. Processes of channel planform change on meandering channels in the UK. *In changing River Channels* (Ed: Gurnell, A. and Petts, G.), John Wiley & Sons Ltd.

Hooke, J. M. & Redmond, C. E. 1992. Causes and Nature of River Planform Change. *In Dynamics of Gravel-bed Rivers* (Ed: Billi, P., Hey, R. R., Thorne, C. R. and Tacconi, P.), John Wiley & Sons Ltd.

Hooke, J. M. 1984. Changes in river meanders: a review of techniques and results of analyses. *Prog. Phys. Geog*. 8: 473-508.

Howard, A. D. & Hemberger, A. T. 1991. Multivariate characterization of meandering. *Geomorphology*, 4, 161-186.

Howard, J. H. G., Patankar, S. V., Bordynuik, R. M. 1980. Flow prediction in rotating ducts using coriolis-modified turbulence models. *Journal of Fluid Engineering*, 102: 456-461.

Ippen, A. T., Drinker, P. A., Jobin, W. R. and Shemdin, O. H. 1962. Stream dynamics and boundary shear distributions for curved trapezoidal channels. *Tech. rep.*, Department of Civil Engineering, Massachusetts Institute of Technology.

Ikeda, S., Parker, G., Sawai, K. 1981. Bend theory of river meanders. Part 1. Linear development. *Journal of Fluid Mechanics*, 112: 363-377.

Ikeda, S. & Nishimura, T. 1986. Flow and bed profile in meandering sand-silt rivers. *Journal of Hydraulic Engineering*, 112 (7).

Irwin, H. P. & Smith, P. A. 1975. Prediction of the effect of streamline curvature on turbulence. Physics of Fluids, 18 (6): 624-630.

Jang, C-L. & Shimizu, Y. 2005. Numerical simulation of relatively wide, shallow channels with erodible banks. *Journal of Hydraulic Engineering*, 131 (7), 565-575.

Kawai, S. & Julien, P. Y. 1996. Point bar deposits in narrow sharp bends. *Journal of Hydraulic Research*, 34 (2).

Kikkawa, H., Ikeda, S. and Kitagawa, A. 1976. Flow and bed topography in curved open channels. *Journal of the Hydraulic Division*, 102 (HY9): 1327-1342.

Kinoshita, R. 1961. Investigation of channel deformation in Ishikari River. Report to the Bureau of Resources: 1-174.

Kinoshita, R. & Miwa, H. 1974. River channel formation which prevents downstream translation of transverse bars. ShinSabo, 94: 12-17.

Lagasse, P. F., Spitz, W. J., Zevenbergen, L. W., Zachmann, D. W. 2004. Handbook for predicting stream meander migration. *Report 533, National Cooperative Highway Research Program*, Transportation Research Board of the National Academies, Washington, DC, USA, 105 pp.

Lane, S. N., Bradbrook, K. F., Richards, K. S., Biron, P. A. and Roy, A. G. 1999. The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches. *Geomorphology*, 29, 1-20.

Langbein, W. B. & Leopold, L. B. 1966. River meanders, a theory of minimum variance. *U.S. Geol. Surv. Prof. Pap.*, 422-H, 15.

Launder, B. E., Tselepidakis, D. P., Younnis, B. A. 1987. A second-moment closure study of rotation channel flow. *Journal of Fluid Mechanics*, 183: 63-75.

MacDonald, T. E., Parker, G., Leuthe, D. 1992. Inventory and analysis of stream meander problems in Minnesota. Technical report., Department of Civil Engineering, University of Minnesota, Minneapolis, Minnesota, USA, 38 pp.

Mueller, J. E. 1968. An introduction to the hydraulic and topographic sinuosity indexes. *Annals of the American Geographers*, 58 (2): 371-385.

Odgaard, A. J. 1981. Transverse bed slope in alluvial channel bends. *Journal of the Hydraulic Division*, ASCE, 107 (HY12).

Oneill, M. P. & Abrahams, A. D. 1986. Objective identification of meanders and bends. *Journal of Hydrology*, 83, 337-353.

Parker, G. & Andrews, E. D. 1986. On the time development of meanders bends. *Journal of Fluid Mechanics*, 162: 139-156.

Parker, G., Diplas, P., Akiyama, J. 1983. Meander bends oh high amplitude. *Journal of Hydraulic Engineering*, 109 (10).

Pope, S. B. 2000.Turbulent Flows. *Cambridge University Press*, UK.

Rodi, W. 1993. Turbulence models and their application in hydraulics. *IAHR Monograph*, Delft.

Rodriguez, J. F., Bombardelli, F. A., Garcia, M. H., Frothingham, K., Rhoads, B. L., Abad, J. D. 2004. High-resolution Numerical Simulation of Flow through a Highly Sinuous River Reach. *Water Resources Management*, 18: 177-199.

Seminara G., Zolezzi G., Tubino M. and Zardi D. 2001. Downstream and upstream influence in river meandering. Part 2. Planimetric development. *Journal of Fluid Mechanics*, 438: 213-230.

Shields, F. D., Copeland, R. R., Klingeman, P. C., Doyle, M. W. and Simon, A. 2003. Design for stream restoration. *Journal of Hydraulic Engineering*, 129 (8).

Silva, M. 1995. Turbulent flow in sine-generated meandering channels. *PhD Thesis*, Queen's University, Ontario, Canada.

Whiting, P. J. & Dietrich, W. E. 1993a. Experimental studies of bed topography and flow patterns in large-amplitude meanders 1: Observations. *Water Resources Research*, 29 (11).

Whiting, P. J. & Dietrich, W. E. 1993b. Experimental studies of bed topography and flow patterns in large-amplitude meanders 2: Mechanisms. *Water Resources Research*, 29 (11).

Yamaoka, I. & Hasegawa, K. 1984. Effects of bends and alternate bars on meander evolution. *In River Meandering, Proceedings of the Conference, Rivers '83*, edited by C. M. Elliot, pp: 783-793, ASCE, New York.

Yen, B. C. 1965. Characteristics of subcritical flow in a meandering channel. *Institute of Hydraulic Research*, University of Iowa, Iowa City.

Yen, C. L. 1967. Bed Configuration and Characteristics of Subcritical Flow in a Meandering Channel. *PhD thesis*, University of Iowa, Iowa City.

Younnis, B. A. 1993. Prediction of turbulent flows in rotating rectangular ducts. *Journal of Fluid Mechanics*, 115:646-652.

Zimmerman, C. & Kennedy, J. F. 1978. Transverse Bed Slopes in Curved Alluvial Streams. *Journal of the Hydraulics Division*, ASCE, 104 (HY1): 33-48.