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Hydrodynamic processes in curved channels

Hydrolink

HYDRODYNAMIC PROCESSES
FROM BASIC RESEARCH TO ENGINE

BY KOEN BLANCKAERT

This article summarizes some research performed during the last 15 years on hydrodynamic processes and their implications for river morphology, ecology, engineering and management. The investigated processes include curvature-induced and turbulence-induced secondary flows, flow separation from boundaries, shear layers and turbulence. These processes do occur in natural rivers and channels and play a prominent role in, for example bends, confluences and bifurcations. Three-dimensional flow processes enhance mixing and transport processes, but they also enhance the energy losses and thereby reduce the conveyance capacity. They have an important influence on the sediment transport and lead to the formation of zones of deposition and scour, which may affect navigability or endanger structures like bridge piers, abutments and riverbanks. They also enhance heterogeneity in substrate, flow and morphology that may enrich habitat. On geological timescales, they affect the planform evolution of the river and the development of the floodplain stratigraphy, which is relevant with respect to the exploration of hydrocarbons. The research described in this article, was performed in a collaboration that exploits synergies between expertise in field experiments, laboratory experiments, analytical modelling, numerical modelling and ecological processes available in different groups at Ecole Polytechnique Fédérale de Lausanne (Switzerland), Delft University of Technology (The Netherlands), Leibniz Institute of Freshwater Ecology and Inland Fisheries (Germany), University of Iowa (USA), and Chinese Academy of Sciences (China). All colleagues who contributed to this joint research are acknowledged:
G. Constantinescu, V. Dugué, W. Ottevanger, M. Koken, W. Uijttewaal, W. van Balen, H.J. de Vriend, A. Schleiss, M. Ribeiro, I. Schnauder, F.X. Garcia, M. Pusch, A. Sukhodolov, R. Li, R. Han, Q. Chen.
The main objectives of the research were: to enhance insight in these hydrodynamic processes, to convert the new knowledge into practical tools for application in a wide range of spatial and temporal scales, and to transfer the knowledge to students, scholars and practitioners. The present article highlights some of the results on hydrodynamic processes in open-channel bends, and tries to identify some remaining directions for future research and application.

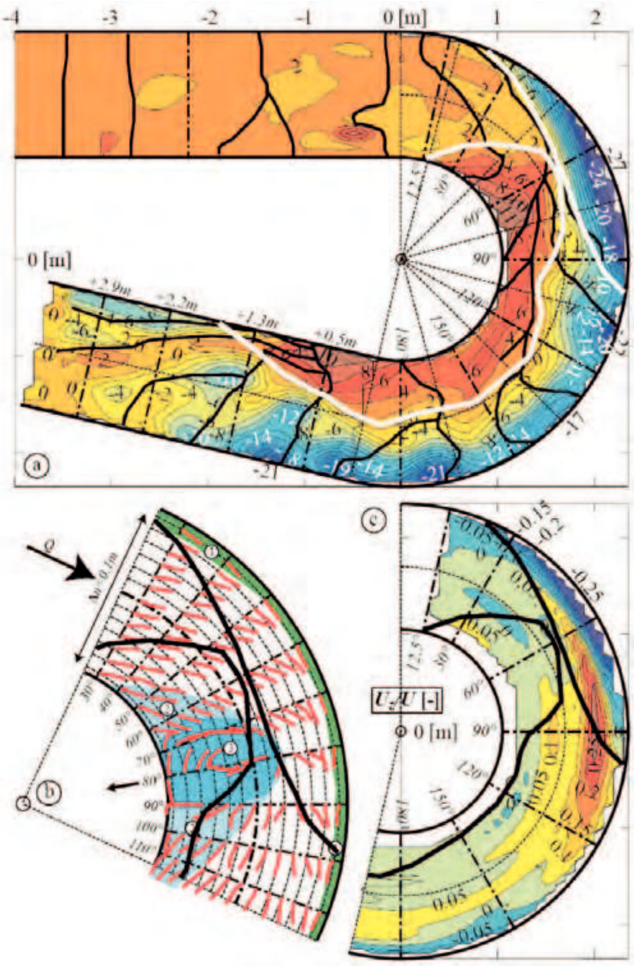

Figure 1. Mobile bed experiments in a curved laboratory flume. (a) Bed level with an interval of 0.02 m. The black lines indicate the position of dunes. The white lines delineate the point bar and pool. (b) Visualization of the flow at the water surface: (1) outer-bank cell of secondary flow; (2) zone of flow separation; (3) zone of flow recirculation. (c) Depth-averaged vertical velocity normalized with the flume-averaged velocity. Figure modified from Blanckaert (2010).

1 Experimental research

Laboratory experiments are being performed since 1998 at Ecole Polytechnique Fédérale de Lausanne in the flume shown in Figure 1, which was designed to be representative of sharply curved natural open-channel bends. This laboratory flume provides a setting with controlled flow and boundary conditions defined with an accuracy exceeding that which could possibly be obtained in a field study. A systematic series of experiments has already been performed that investigates the influence of parameters, such as the degree of curvature defined by the ratio of flow depth to centreline radius of curvature, the configuration of the bathymetry, the roughness of the banks, and the inclination of the banks.
Figure 1 shows some results in a live bed experiment with a typical equilibrium bathymetry that consists of a shallow point bar at the inner side and pronounced bend scour at the outer side of the bend. Figure 1b shows that horizontal flow recirculation occurs over the shallow point bar.

IN CURVED CHANNELS:
EERING APPLICATION

This flow separation captures fine sediments and plays an important role with respect to accretion at the inner bank. Moreover, it reduces the effective width and directs high velocity flow towards the outer bank, thus enhancing the flow attack on the outer bank. In spite of its importance, important knowledge gaps remain, such as the parameters of influence, the conditions of occurrence, the dependence on the geometry and roughness of the bank, and the underlying physical processes.

Figure 1c shows the depth-averaged vertical velocity, based on measurements in the indicated cross-sections. The flow cannot follow the abrupt change in direction at the bend entrance, and collides with the outer bank at an oblique angle near the cross-section at 60°, resulting in abrupt flow reversal and important vertical velocities that impinge on the channel bed and contribute to the formation of the maximum bend scour. The velocities impinging on the bed are deflected inwards near the bottom, and permit the sustaining of a transverse bed shape that is steeper than the angle of repose of the sediment. Zeng et al (2008) have satisfactorily predicted the flow and the macroscopic features of the bed morphology in this experiment with a 3D RANS flow model and Engelund-Hansen's sediment transport formula. The maximum bend scour and the maximum transverse bed slope, however, were underestimated. This indicates that the sediment transport formulae could be improved by including effects of vertical velocities impinging on the channel bed, which are found in a variety of other configurations, such as bridge piers, jets, etc.

2 Numerical research

In the experiment illustrated in Figure 1, about 50 vertical profiles of the three-dimensional velocity vector were measured at high temporal resolution in 12 cross-sections around the flume. In spite of this unprecedented detail, the measurements cannot provide all relevant information on the flow: the spatial resolution in streamwise direction is relatively low, important variables such as the boundary shear stress and pressure fluctuations are not measured, and information on coherent turbulence structures is incomplete. This information can be obtained from numerical simulations, after validation of the numerical model by means of the available experimental data. The hydrodynamics in the illustrated experiment have been numerically investigated by Van Balen et al. (2010) at Delft University of Technology, and by Constantinescu et al. (2011) at the University of Iowa, by means of so-called eddy-resolving techniques, which directly resolve the large scales of the turbulent motion.

Figure 2 illustrates some numerical results obtained by Constantinescu et al. (2011). Figure 2a shows an instantaneous pattern of the vertical vorticity at the free surface, i.e, vortices that rotate around a vertical axis. A shear layer characterized by high vorticity is clearly visible at the edge of the zone of horizontal flow recirculation over the shallow point bar (Figure 1b). Flow animations based on the simulation results show that vortices shedding from the downstream part of this shear layer, at times, impinge on the outer bank near the cross-section at 90° (Figure 2a). This results in large pressure fluctuations on the outer bank (Figure 2b). The effect of such pressure fluctuations on

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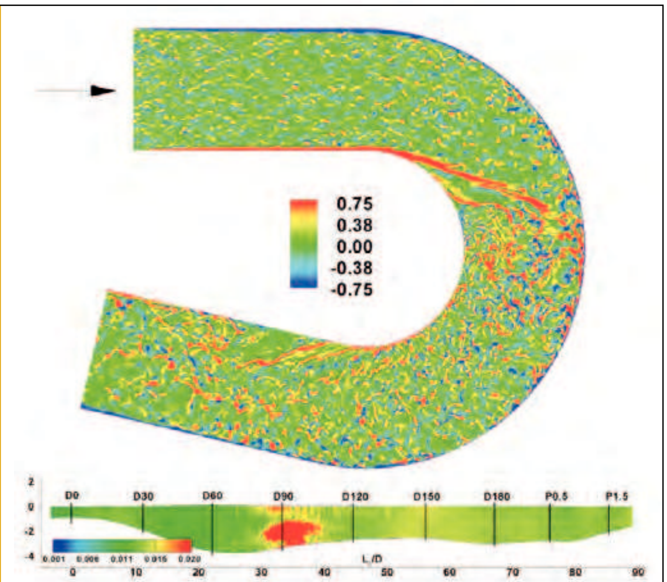

Figure 2. Results of numerical simulations by means of Detached Eddy Simulation. (a) Instantaneous pattern of the vertical vorticity at the water surface, normalized by U/H (U and H are the flume-averaged velocity and flow depth, respectively). (b) Distribution of the pressure RMS fluctuations at the outer bank, normalized by 2U4 where is the water density. Modified from Constantinescu et al. (2011).

the potential for bank erosion, and the inclusion of this effect in sediment transport models and in design methods for bank protection, would be challenging and highly relevant research topics. Numerical models are powerful tools for the broadening of the investigated parameter space and the generalization of the results. Changing the radius of curvature of the bend, for example, is practically not feasible in a laboratory flume, but straightforward in a numerical simulation.

3 Engineering tools and techniques

3.1 Model for flow and morphology in open-channel bends

The computational cost of eddy-resolving flow models is still prohibitive for most practical applications. Therefore, knowledge gained from the experiments and the numerical simulations needs to be converted into practical tools for engineering. Common one-dimensional models predict the average water depth and flow velocity in each cross-section of the river. For the case of meandering rivers, one-dimensional models exist that also predict the transverse gradients of the bed profile and the velocity (Figure 3a). A review of such models is given in Camporeale et al. (2007). Secondary flow, defined as the flow component perpendicular to the channel axis (Figure 3a), plays an important role in the transverse redistribution of the morphology and the velocities.

Most existing models for curved open-channel flow account for the effects of the secondary flow by means of a parameterization that is based on the hypothesis of mild curvature. This parameterization is known to overestimate the effects of the secondary flow in moderately and strongly curved bends. Based on the enhanced insight provided by laboratory experiments and numerical simulations, Blanckaert and de Vriend (2003, 2010) and Ottevanger et al. (submitted) have developed a parameterization for the secondary flow that remains valid for moderately and strongly curved bends. Figure 3b shows the evolution of the transverse bed slope around the flume for the experiment shown in Figure 1: it compares the measured evolution to predictions by mild-curvature models and the newly developed model without curvature restrictions. Mild-curvature models considerably overestimate the maximum transverse bed slope in sharply curved bends, which leads to an overestimation of the maximum bend scour and the flow attack on the outer bank. The newly developed model considerably improves the accuracy of the predictions, at only a marginal increase in computational cost. Obviously, such a one-dimensional model can only predict the macro-scale features of the flow field and the morphology, and is intrinsically unable to resolve features on a spatial scale smaller than the channel width. Such a model is, however, a valuable practical tool. With little input information and at a low computational cost, it allows estimating the morphology and flow field. Based on the river planform, provided for example by aerial images or the design of a re-meandering scheme, it allows identifying the regions with maximum scour depth and maximum velocity that will be most vulnerable to bank erosion. The low computational cost furthermore allows large-scale and long-term simulations. When coupled to a model for bank erosion and planform evolution, the model allows investigating meander dynamics at geological timescales, including processes occurring in sharp meander bends that are close to cut-off.

The combined experimental-numerically research is being pursued, and focuses on the improvement of the parameterization of the flow attack on the banks, by accounting for processes such as flow separation, pressure fluctuations, and turbulence-induced near-bank secondary flow cells.

3.2 Modifying flow in morphology by means of bubble screens

Curvature-induced secondary flow redistributes the flow and contributes to the development of the typical bar-pool morphology. Figure 1 illustrated that vertical velocities impinging on the channel bed contribute to the development of the maximum scour. Based on the insight gained in hydrodynamic and morphodynamic processes by means of the laboratory experiments and numerical simulations, a technique has been developed that consists in counteracting the curvature-induced secondary flow by means of a bubble screen situated near the outer bank. The rising air bubbles counteract the vertical velocities impinging on the bed. Figure 4 compares the flow field and the morphology in the cross-section at 180° in the laboratory flume shown in Figure 1 (Dugué et al. 2013). In the reference situation without bubble screen, a curvature-induced secondary flow cell occurs in the deepest part of the cross-section. Maximum scour depth is found where the vertical velocities associated with this secondary

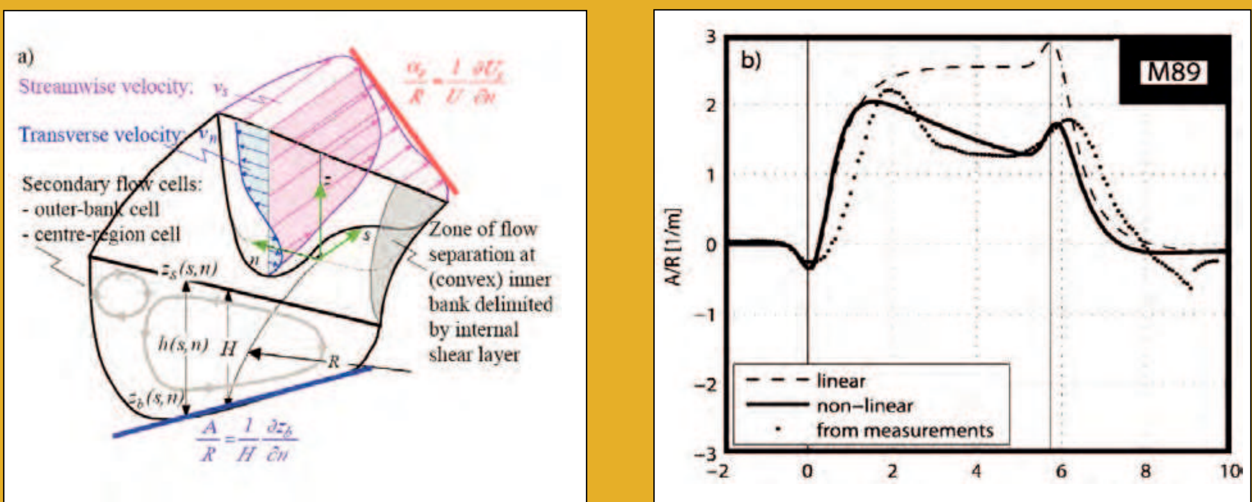

Figure 3. (a) Conceptual representation of flow and morphology in open-channel bends. (b) Evolution around the bend of the transverse bed slope, defined as A/R = H-1∂h/∂n in the experiment shown in Figure 1. Comparison of experimental data to simulation results with a weak-curvature model (labeled "linear") and a model without curvature restrictions (labeled "non-linear").

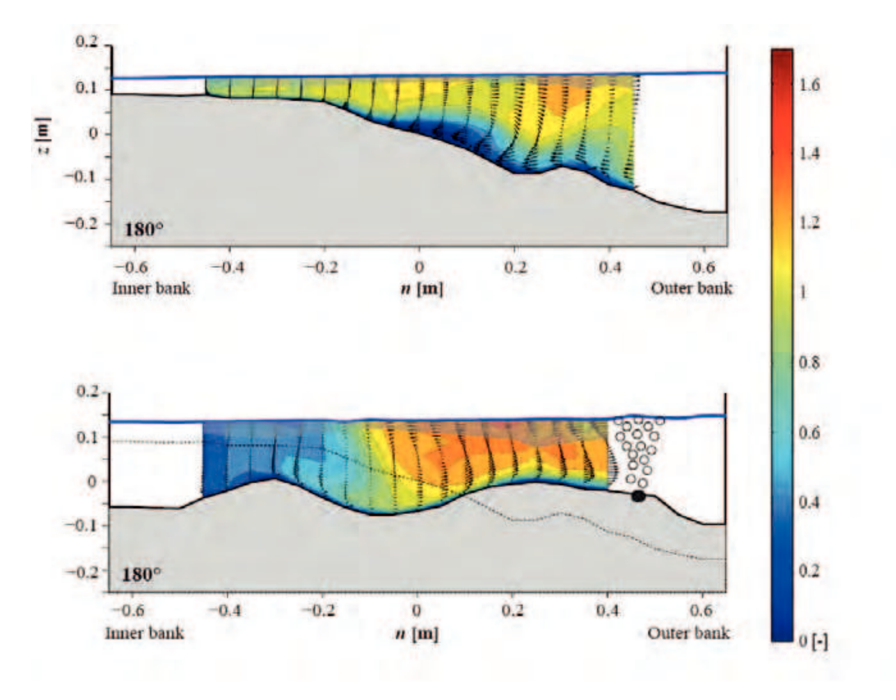

Figure 4. Cross-section at 180° in the bend shown in Figure 1. Bed morphology, streamwise velocity normalized by the cross-sectional averaged velocity (color contours indicate) and secondary flow (vector pattern). (a) Reference experiment without bubble-screen. (b) Experiment with bubble screen.

flow impinge on the bed. In the presence of a bubble screen, the rising air bubbles entrain fluid, and cause a secondary flow cell with a sense of rotation opposite to the curvature-induced secondary flow. This bubble-induced secondary flow redistributes the flow and shifts the core of highest velocities away from the outer bank. The maximum scour, core of vertical velocities impinging on the bed, and core of maximum streamwise velocities are all found near the junction of the curvature-induced and the bubble-screen induced secondary flow cells. Morphological gradients are considerably reduced, as illustrated by the reduced scour near the outer bank and the reduced deposition near the inner bank.

This laboratory experiment demonstrates the capability of the bubble-screen technique to modify the flow field and the morphology in rivers. The potential use of the technique is not limited to open-channel bends, but to configurations where local scour occurs due to vertical velocities impinging on the bed, such as bridge piers, abutments or obstacles in the flow. Further research is required to investigate scale effects, estimate the range of applicability, and develop the bubble-screen technique into a practically applicable tool.

4 Knowledge transfer

A list of publications related to the results described in the present article is available at: https://documents.epfl.ch/users/b/bl/blanckae/www/Blanckaert_Publications

Besides knowledge transfer by means of publications, it is important to promote collaboration between hydrologists, fluid mechanicians, hydraulic engineers, geomorphologists, geologists, ecologists, etc. Two events have been organized in the framework of the reported joint research program. In 2008, the International Summer School "Complex flows, turbulence, morphodynamics and ecology in rivers" was held at Delft University of Technology, The Netherlands. In 2011, the Euromech Colloquium 523 "Ecohydraulics: linkages between hydraulics, morphodynamics and ecological processes in rivers", was held in Clermont-Ferrand, France. A special issue of the Journal "Ecohydrology" will be devoted to it in 2013. These were stimulating events that promoted collaboration, multi-disciplinarity, and knowledge transfer, and provided optimal conditions for the germination of new ideas.

I take the opportunity to thank IAHR for supporting these events.

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