Topographic steering, flow recirculation, velocity redistribution, and bed topography in sharp meander bends

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1. Introduction

River meanders are major features on the Earth surface. Alluvial meanders are characterized by shallows at the inside and deep zones of scour at the outside of bends, which are called point bars and pools, respectively. The relative submergence of the point bar in natural meanders varies with the flow stage, giving rise to spatiotemporal variations in flow and sedimentologic characteristics that makes it a hot spot for biodiversity [e.g., Allan and Castillo, 2007; Nakano and Nakamura, 2008]. Colonization by vegetation at low-flow stages can assist in stabilizing the point bar and can play an important role in accretion at the inner bank. The location of the pool and the maximum bend scour within the pool are the major parameters with respect to erosion at the outer bank and meander migration [e.g., Ikeda et al., 1981; Camporeale et al., 2007; Crosato, 2008]. Meander migration continuously reshapes the land and rejuvenates the meander channel belts and floodplains. The shifting boundaries endanger property, lead to a loss of fertile soil, and are a legal concern. But the dynamical character is also of value: the meander belt offers a retention capacity during flood events, and it is a landscape element of ecological value that offers a potential for river restoration and revitalization [Tockner, 2007]. It is a challenge in river management and engineering to conciliate these threats and opportunities. Finally, the migration of channel belts across floodplains result in a heterogeneous sediment stratigraphy that complicates the exploitation of drinking water or hydrocarbons from paleochannel deposits [Cojan et al., 2005; Clevis et al., 2006].

Meandering rivers have fascinated a range of scientists and practitioners over many years, as testified by the abundant literature initiated by da Vinci (1508–1510) and followed by Fargue [1868], Boussinesq [1868], and Thomson [1876]. In spite of the abundant research on all aspects of meandering rivers by means of laboratory experiments, field investigations, and numerical modeling, insight in the relevant meander processes is still incomplete and the available engineering and management tools still predict flow, transport, morphological, and ecological processes with uncomfortable uncertainties. Fully 3-D models of flow and sediment transport in alluvial channels have recently become computationally feasible. Such models have been
applied to the case of moderately curved bends by Shimizu and Itakura [1989], Wu et al. [2000], Ruther and Olsen [2005], Zeng et al. [2008b], and Khosronejad et al. [2007] and to the sharply curved bend reported in the present paper by Zeng et al. [2008b]. These models are able to resolve the global characteristics of the flow and the bed topography but fail to predict accurately characteristics in the point bar and the pool zones. Moreover, the application of such models is still limited to small-scale and short-term configurations. 1-D and depth-averaged 2-D models will remain important tools for the investigation of large-scale and/or long-term problems in real meandering rivers [Frascati and Lanzone, 2009]. Thus, insight into the relevant flow and sediment transport processes is required to evaluate the capabilities and application range of different types of existing tools and models and to allow their improvement and validation.

The present paper reports on an investigation of the bed topography, the flow field and their interaction in a sharply curved laboratory flume. It focuses on the point bar and the pool zones and highlights processes that are relevant with respect to meander dynamics, including the topographic steering of the flow around the point bar, the curvature-induced secondary flow, and the horizontal flow recirculation. The laboratory environment provides a setting with controlled flow and boundary conditions defined with an accuracy exceeding that which could possibly be obtained in a field study. At the same time, the major control parameters in the reported experiment are representative for sharp natural meander bends. Laboratory investigations of the bed topography have often been carried out with small flow depths [Whiting and Dietrich, 1993] or under dynamic conditions with migrating bed forms [Abad and Garcia, 2009b] that do not allow for detailed velocity measurements, whereas investigations of the flow field have often been carried out over schematized bed topographies [Yen and Yen, 1971; de Vriend and Koch, 1978]. Laboratory investigations including detailed measurements of the flow and the bed topography are extremely scarce [Hooke, 1974; Kikkawa et al., 1976; Odgaard and Bergs, 1988] and are limited to weakly and moderately curved bends. The laboratory experiment reported herein reproduced successfully morphological features that are characteristic of sharp meander bends: the point bar, a pool-bar topography, and zones of horizontal flow recirculation. Moreover, recent progress in laboratory instrumentation has permitted measurement of the bed and water surface topographies and the 3-D flow field with sufficient spatial and temporal resolution to investigate the hydrodynamics by means of term-by-term evaluations of the mass and momentum equations.

The paper has the following objectives:

1. To report the experimental techniques, the data treatment procedures, and estimates of the uncertainty in the experimental data, which is essential for the appropriate use of the experimental data in research on hydrodynamic processes or in the validation of models (section 2).

2. To detail the bed and water surface topographies and the 3-D flow field in a sharp meander bend with an accuracy and a resolution that allow identifying the relevant processes (section 3) and investigating the underlying hydrodynamic processes of mass and momentum redistribution (section 4).

3. To investigate the interaction between the bed topography and the flow field and thus gain new insight in the development of the point bar and pool, the nature of topographic steering of the flow around the point bar, the secondary flow and the occurrence of horizontal flow recirculation (section 5).

4. To analyze the implications of the results for numerical modeling and to indicate how the experimental results can be applied to validate, evaluate, and improve different types of models (section 6).

2. Experimental Setup and Techniques

2.1. The Experimental Setup and Conditions

The large variety of planforms and scales encountered in natural river meanders renders the definition of a representative laboratory configuration impossible. Therefore, laboratory experiments are commonly performed in simplified schematized configurations that allow isolating and/or accentuating certain parameters and processes under controlled conditions. In 1998, the author has carried out one experiment in a sharply curved laboratory flume. Although the flow was only measured in the outer half of one cross section for one experimental condition, this experiment enhanced insight in the mechanisms underlying the velocity redistribution [Blanckaert and Graf, 2004], the secondary flow [Blanckaert and de Vriend, 2004], and the turbulence structure [Blanckaert and de Vriend, 2005a, 2005b]. On the basis of the results of this experiment, an optimized experimental facility has been constructed, whose dimensions were mainly dictated by the optimal use of a dedicated Acoustic Doppler Velocity Profiler (ADVP). This instrument measures velocities in a range of flow depths from 0.1 to 0.5 m with an optimum at about 0.15 m. The facility comprises a sharp 193° bend that is preceded by a 9 m long straight inflow reach that was installed in order to guarantee the full development of the boundary layer. In order to avoid narrow channel configurations, the maximum width of B = 1.3 m allowed by laboratory space was installed, resulting in a width-to-depth ratio on the order of 10. Finally, a straight outflow reach of 5 m was installed. The first half of the bend is representative of meander bends with a pronounced increase in curvature, the second half of the bend is representative of meander bends with a weak variation in curvature, and the bend exit and straight outflow reach are representative of meander bends with a pronounced decrease in curvature, as well as the recovery toward straight flow. The centerline radius of curvature was $R = 1.7$ m, resulting in a ratio of $R/B = 1.3$, which falls into the range of sharply curved bends [Hickin, 1977]. Since the overwhelming majority of foregoing research on meanders was limited to weakly or moderately curved bends, knowledge is particularly scarce for such sharp bends, although recent investigations have been carried out by Blanckaert and Graf [2001] and Abad and Garcia [2009a, 2009b]. Moreover, engineering tools are characterized by a particularly high uncertainty in this curvature range.

Blanckaert [2009] reports research on hydrodynamic processes over horizontal bed topography with identical boundary conditions in this laboratory flume. The present paper reports results from a mobile bed experiment with smooth vertical banks made from PVC. The bed consisted of nearly uniform sand with diameters in the range 1.6—
2.2 mm with an average \((D_{50})\) of about 2.0 mm, which permitted bed load transport without appreciable suspension of bed sediment. Beginning from an initial flat bed, sediment was continuously fed at the flume entrance at a rate of \(q_s = 0023 \text{ kg m}^{-1} \text{s}^{-1}\), resulting in bed load sediment transport. A state of dynamic equilibrium, characterized by migrating dunes superimposed on the steady macrofeatures of the bathymetry, was reached when the sediment feeding rate at the flume entrance was equal to the sediment settling rate at the flume exit (at a time scale long enough to filter fluctuations in sediment transport rate due to migrating dunes). Once a state of dynamic equilibrium was reached, sediment supply was stopped and the bathymetry was frozen by spraying paint on the bed which is able to both stabilize and preserve the boundary roughness and thus enable detailed velocity measurements over a stable bed topography. Obviously, this configuration does not allow investigating the evolving effect of dune migration on the bend morphodynamics [Abad and Garcia, 2009b].

Table 1 summarizes the experimental conditions. Flow was rough turbulent \((Re* = u_k^*/\nu > 70)\), where Nikuradse’s equivalent sand roughness \(k_s\) has been defined according to \(Ran\) [1984] as 3 times the sand diameter), subcritical \((Fr < 1)\), and very sharply curved \((R/B = 1.31\) and \(R/H = 12.1, H\) is the flume-averaged flow depth). Blanckaert and de Vriend’s [2010] 1-D hydrodynamic model for sharply curved meander bends has identified \(C_{f,1}^{-1/2} = U/\sqrt{gR}\) \(E_s\) is a Chézy-type friction coefficient based on the hydraulic radius \(R_s\). \(Re\) is the Reynolds number, and \(Fr = U/\sqrt{gH}\) is the Froude number.

### 2.2. Acoustic Measurements of Velocity, Water Surface Topography, and Bathymetry

The key to improving the understanding of the complex hydrodynamics in sharply curved open channel flow lies in the comprehension of the patterns of the 3-D velocity, the role of cross-stream currents, the interaction between mean flow and turbulence, and the interaction between flow field and mobile bed topography. This requires measurements of the 3-D velocity vector with high spatial and temporal resolutions, as well as detailed measurements of the bed topography. Detailed measurements of the water surface topography are also essential for understanding gravity-driven open channel flows and energy losses.

Nonintrusive measurements of velocity profiles were obtained with an Acoustic Doppler Velocity Profiler (ADVP) developed at Ecole Polytechnique Fédérale Lausanne (Switzerland). The working principle of the ADVP has been reported by Lemmin and Rolland [1997], Hurther and Lemmin [1998], Blanckaert and Graf [2001], and Blanckaert and Lemmin [2006]. The ADVP consists of a central emitter surrounded by four receivers, placed in a water filled box that touches the water surface by means of an acoustically transparent mylar film (Figure 1). It measures profiles of the quasi-instantaneous velocity vector, \(v_i(t) = (v_x(t), v_y(t), v_z(t))\), from which the time-averaged velocity vector, \(\overline{v} = (\overline{v}_x, \overline{v}_y, \overline{v}_z)\), the Reynolds stresses, \(\rho \overline{v}_i \overline{v}_j\) \((ij = x, n, z)\) and higher-order turbulent correlations can be computed. The velocity vector is decomposed in an orthogonal reference system with curvilinear streamwise \(s\) axis, transverse \(n\) axis pointing toward the outer bank, and vertically upward \(z\) axis (Figures 1). The bend entry defines the origin of the \(s\) axis. Measurements were made with a sampling frequency of 31.25 Hz and with a sampling period of 200 s. The experiment exploited the following methodological advantages of the ADVP:

1. Its profiling capacity, which enables measurements at high spatial resolutions. Measurements were made in 12 cross sections around the flume on a fine grid that typically consisted of 38 vertical profiles and refined toward the outer bank (Figure 1). The shallowness of the flow over the point bar did not allow measurements close to the inner bank in some regions of the flume.

2. Its four receivers enable improvement of the temporal resolution [Hurther and Lemmin, 2001; Blanckaert...
and Lemmin, 2006], which is sufficient to investigate the dynamic range of turbulence in laboratory open channel bends [Blanckaert and de Vriend, 2005a, 2005b].

[17] 3. Its flexibility to optimize the geometric configuration of the transducers is also an advantage. Blanckaert and Lemmin [2006] have shown that a configuration with a central emitter symmetrically surrounded by four receivers at an angle of 45° with respect to the principal flow direction gives redundant information in all three velocity components and is optimal with respect to noise reduction and temporal resolution. This symmetrical configuration, however, only allows measuring up to 0.15 m from the banks, as illustrated in Figure 1. An asymmetrical ADVP configuration (Figure 1) has been designed for the reported experiment that allowed measuring up to 2 cm from the banks, allowing investigating in detail the hydrodynamics in the near-bank region. This asymmetrical configuration, however, only gives redundant information in the streamwise velocity component and is characterized by a higher noise level than the symmetrical one. Due to the shallowness of the flow, no near-bank measurements have been made at the inner bank.

[18] 4. Finally the ADVP allows for accurate determination of the elevation of the bed from the intensity of the backscattered acoustic pulses.

[19] The accuracy of the ADVP measurements is known to be slightly reduced near the flow boundaries: at the water surface, the ADVP housing (Figure 1) perturbs the flow in a region of about 2 cm and in a flow layer of about 2 cm near solid boundaries, the ADVP seems to underestimate turbulent characteristics, which is tentatively attributed to the high-velocity gradients within the measuring volume and/or to parasitical echoes from the solid boundary [Hurter and Lemmin, 2001]. ADVP measurements seem to underestimate systematically the vertical velocity fluctuations. More information on the estimated uncertainty in measured quantities is given in section 2.4.

Figure 1. Measuring grid as well as symmetrical and asymmetrical configuration of the acoustic doppler velocity profiler (ADVP) illustrated in the cross section at 120° in the bend.
[20] Measurements of the bed and the water surface topography were made by moving a set of eight echosounders mounted on a carriage along the flume. The echosounders were mounted in the transverse positions \( n = [-0.6, -0.5, -0.3, -0.1, 0.1, 0.3, 0.5, 0.6] \) m (cf. Figure 1) and the measuring grid consisted of 992 measuring points (Table 2), which was refined near the bend entry and exit, where important water surface gradients exist due to the discontinuity in curvature. Additional measurements of the bed topography were given by the ADVP measurements. In spite of the dense measuring grid, the spatial resolution was not sufficient to resolve all details of the dunes superimposed on the macroscale topography, and these dunes were mapped by means of photographs.

2.3. Velocity Data Treatment Procedures

[21] This section reports procedures that are required to bring the data into a format convenient for research on hydrodynamics and/or model validation, for example, by means of term-by-term analysis of the governing flow equations (reported in section 4.2). The different steps in the data treatment are illustrated by means of the normalized transverse velocity component \( (v_z/L) \) in the cross section at 120° in the bend.

2.3.1. Extrapolations Near the Water Surface

[22] By touching the water surface, the ADVP housing (cf. Figure 1) perturbs the flow in a region of about 2 cm near the water surface. After defining manually the perturbed flow region for each of the measured velocity profiles, this region is bridged by means of extrapolation with the only aim of improving estimates of depth-averaged flow quantities. These extrapolations, indicated in Table 3, lead to an additional uncertainty in these depth-averaged flow quantities (see section 2.4). In order to avoid any confusion in the interpretation of measured data, the perturbed region bridged by means of these extrapolations is indicated by shading in all figures (cf. Figures 2, 3, 4, 5, and 19).

2.3.2. Assembling of Data Measured on Overlapping Grids

[23] Assembling of data measured with the symmetrical ADVP configuration in the central part of the cross section and with the asymmetrical ADVP configuration near the banks (Figure 1) is not straightforward, because of systematic errors induced by instrument misalignment and different noise characteristics of both configurations. In order to estimate and possibly minimize differences induced by such systematic errors, measurements have been made with both configurations in nine profiles in an overlapping zone \( n = \pm 0.3 \) to \( \pm 0.5 \) m (Figures 1 and 3). Since measurements with the symmetrical ADVP configuration are, in theory, of higher quality and characterized by lower noise levels, they have been retained in the overlapping zone.

[24] Cross-stream velocities \( (v_x, v_z) \) are typically an order of magnitude smaller that the streamwise velocity \( v_x \) and therefore very sensitive to instrument misalignment. For the transverse velocity \( v_z \) shown in Figure 3, the measurements in the overlapping zone allowed minimizing the systematic differences by a rotational correction of 1.45° around the \( z \) axis. A similar rotational correction of 2.05° around the \( n \) axis allowed minimizing the systematic differences in the vertical velocity component \( v_z \) (not shown). These correction angles are within the accuracy of the ADVP positioning.

2.3.3. Splining of the Measured Patterns

[25] Near-surface extrapolation and grid assembling provide the measured data in a convenient format for data

<table>
<thead>
<tr>
<th>Flow Reach</th>
<th>Position of Measured Cross Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight inflow (m)</td>
<td>( s = [-6.5, -6.3, -6.1, -5.9, -5.7, -5.5, -5.3, -5.1, -4.9, -4.7, -4.5, -4.3, -4.1, -3.9, -3.7, -3.5, -3.3, -3.1, -2.9, -2.7, -2.5, -2.3, -2.1, -1.9, -1.7, -1.5, -1.4, -1.3, -1.2, -1.1, -1.0, -0.9, -0.8, -0.7, -0.6, -0.5, -0.4, -0.3, -0.2, -0.1, -0.02] )</td>
</tr>
<tr>
<td>Bend reach (°)</td>
<td>([0, 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 182.5, 185, 187.5, 190, 193])</td>
</tr>
<tr>
<td>Straight outflow (m)</td>
<td>( s = [0.01, 0.035, 0.5, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.6, 0.7, 0.8, 0.9, 1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.9, 2.1, 2.3, 2.5, 2.7, 2.9, 3.1, 3.3, 3.5, 3.7, 3.9, 4.1])</td>
</tr>
</tbody>
</table>

*See Figure 6.

### Table 2. Cross Sections Where Measurements of Water Surface and Bed Topography Were Made by Means of Echosounders*

<table>
<thead>
<tr>
<th>Flow Reach</th>
<th>Position of Measured Cross Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight inflow (m)</td>
<td>( s = [-6.5, -6.3, -6.1, -5.9, -5.7, -5.5, -5.3, -5.1, -4.9, -4.7, -4.5, -4.3, -4.1, -3.9, -3.7, -3.5, -3.3, -3.1, -2.9, -2.7, -2.5, -2.3, -2.1, -1.9, -1.7, -1.5, -1.4, -1.3, -1.2, -1.1, -1.0, -0.9, -0.8, -0.7, -0.6, -0.5, -0.4, -0.3, -0.2, -0.1, -0.02] )</td>
</tr>
<tr>
<td>Bend reach (°)</td>
<td>([0, 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 182.5, 185, 187.5, 190, 193])</td>
</tr>
<tr>
<td>Straight outflow (m)</td>
<td>( s = [0.01, 0.035, 0.5, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.6, 0.7, 0.8, 0.9, 1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.9, 2.1, 2.3, 2.5, 2.7, 2.9, 3.1, 3.3, 3.5, 3.7, 3.9, 4.1])</td>
</tr>
</tbody>
</table>

*See Figure 6.

### Table 3. Extrapolations Used to Bridge the Perturbed Flow Region Near the Water Surface in Order to Improve Estimates of Depth-Averaged Flow Quantities

<table>
<thead>
<tr>
<th>Flow Quantity</th>
<th>Extrapolation Near the Water Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streamwise and transverse velocities, ( v_x ) and ( v_z )</td>
<td>Parabolic: tangential in uppermost unperturbed measuring point and zero gradient inspired by the no-shear condition at the water surface</td>
</tr>
<tr>
<td>Vertical velocity, ( v_z )</td>
<td>Linear from the uppermost unperturbed measuring point to ( v_z = 0 ) at the water surface imposed by the kinematic boundary condition</td>
</tr>
<tr>
<td>Turbulent normal stresses, ( v_z^n ) and ( v_z^n )</td>
<td>Parabolic: tangential in uppermost unperturbed measuring point and zero gradient at the water surface</td>
</tr>
<tr>
<td>Turbulent normal stress, ( v_zn )</td>
<td>Linear from the uppermost unperturbed measuring point to ( v_z^n = 0 ) at the water surface imposed by the kinematic boundary condition</td>
</tr>
<tr>
<td>Turbulent dissipation rate, ( \varepsilon )</td>
<td>Parabolic: tangential in uppermost unperturbed measuring point and zero gradient at the water surface</td>
</tr>
</tbody>
</table>
presentation and model validation. But research on hydrodynamics is performed by computing variables such as the vorticity (see further in section 3) or by making term-by-term analyses of flow equations, such as the momentum equation (see further in section 4.2). Experimental scatter makes it difficult to evaluate accurately the required derivatives of measured quantities directly from the raw data. Therefore, analytical surfaces have been fitted to the experimental data using 2-D smoothing splines with weight functions [de Boor, 1978] as described and illustrated by Blanckaert and Graf [2001]. Figure 4 shows the splined patterns of the normalized transverse velocity \( v_n/U \) measured in the cross section at 120°, whereas Figure 5 com-

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**Figure 2.** Extrapolation of measured vertical profiles in the near-surface region perturbed by the ADVP housing (Figure 1), illustrated by means of the normalized transverse velocity \( v_n/U \), measured in the cross section at 120° (undistorted scale).

**Figure 3.** Assembling of patterns measured on “central grid” and “outer bank grid,” illustrated by means of the normalized transverse velocity \( v_n/U \), measured in the cross section at 120° (undistorted scale).
Compares vertical and transverse profiles of the raw and splined data (indicated in Figures 3 and 4 by dashed lines).

2.4. Estimated Uncertainty in Main Quantities

Knowledge of the uncertainty in the experimental data is essential when using them for model validation or research on hydrodynamic processes. Uncertainty in the experimental data may be caused by a multitude of factors, which may vary in space and in time. For ADVP measurements, for example, potential causes include the inaccuracy in the positioning of the instrument, the geometric and electronic configurations, the acoustic scattering level of the fluid. Uncertainties may be caused by random (or indeterminate) errors, systematic (or determinate) errors, and illegitimate errors. The latter are clearly erroneous values which are easily identified. Spatial random errors occur, but they do not cause significant uncertainty in the spatial patterns because of the adopted dense measuring grid (cf. Figure 1).

Temporal random errors under the form of white noise characterize the velocity measurement carried out with high temporal resolution (sampling frequency of 31.25 Hz), and they do not affect time-averaged velocities and turbulent shear stresses (or any cross correlation of independent velocity components) but do appear as systematic errors in the turbulent normal stresses (or any autocorrelation of velocity components). Blanckaert and Lemmin [2006] have proposed methods to reduce the systematic overestimation of turbulent normal stresses due to the white noise. But this systematic noise contribution cannot entirely be eliminated. Moreover, the remaining systematic error in turbulent normal stresses measured with the symmetric and asymmetric ADVP configurations may significantly differ. The non-resolution of frequencies above the sampling frequency causes a systematic underestimation of turbulence quantities. But this systematic error is probably negligible. Weak cross-stream velocities ($v_n$, $v_z$) are very sensitive to systematic errors due to instrument misalignment. As explained

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**Figure 4.** Splined pattern, illustrated by means of the normalized transverse velocity $v_n/U$, measured in the cross section at 120° (undistorted scale).

**Figure 5.** Comparison of transverse and vertical profiles (indicated by dashed lines in Figures 3 and 4) of the raw data after grid assembling (Figure 3) to the data after splining (Figure 4), illustrated by means of the normalized transverse velocity $v_n/U$, measured in the cross section at 120° (undistorted scale).
in section 2.3, this systematic error is largely eliminated in the grid-assembling procedure because of the high spatial resolution of the measurements. Systematic errors are not prohibitive for research on hydrodynamics as long as they remain relatively constant in space. A systematic but quasi-constant overestimation of the turbulent kinetic energy due to white noise, for example, is not prohibitive for identifying and analyzing the influence of curvature on the distribution of turbulent kinetic energy around the curved flume.

[27] The uncertainty is not only difficult to estimate but can be difficult to define. The reported experiments, for example, aim at mapping spatial patterns of flow variables with high spatial and temporal resolution. But an accurately measured spatial pattern of a variable, such as a cross-sectional velocity distribution, does not exclude very large errors occurring in isolated points. Absolute errors are appropriate to estimate the uncertainty in the water surface and bed topography as less than 1 mm and less than 4 mm (2d), respectively. Similar to previous reports [Rolland, 1994; Hurther, 2001; Blanckaert and de Vriend, 2004]. the uncertainty in ADVP measurements will be defined by means of a relative error (percent discrepancy),

\[ \tilde{f} = 1 + \sigma_f, \]

where \( \tilde{f} \) is the measured or splined quantity, \( f \) is the real value, and \( \sigma_f \) is the uncertainty in \( f \). This definition is not appropriate for small values of the quantity \( f \), in which case an absolute error can be estimated as \( \sigma_f \tilde{f} \text{avg} \) where \( \tilde{f} \text{avg} \) is the average magnitude in the pattern of the quantity. Obviously, this kind of simple parameterization can only be approximately given the many factors that affect uncertainty in patterns of experimental data.

[28] Rolland [1994] and Hurther [2001] estimate the uncertainty in the time-averaged velocities as less than 4% and in the turbulent stresses as less than 10%. Given the approximate character of the uncertainty parameterization, rather (over)conservative estimates are retained for the presented experiment: 10% for the time-averaged cross-stream velocities \( \langle v_x, v_y \rangle \), 15% for the turbulent shear stresses, and 20% for the turbulent normal stresses. The uncertainty in the turbulent dissipation rate is estimated as \( \text{O}(100\%) \). This high uncertainty mainly concerns a systematic error, which is due to the fact that the measuring frequency is well below the frequency range where turbulent dissipation is dominant. As mentioned in section 2.3, the uncertainty in ADVP measurements and notably in turbulence measurements increases progressively toward the bottom in the lower 20% of the water column. The uncertainty in depth-averaged mean velocities is estimated as less than 10%; the reduction in uncertainty due to the integration is compensated by the increase caused by the extrapolation in the near surface region (cf. Figure 2).

[29] Blanckaert and de Vriend [2004] have estimated the uncertainty in quantities derived from the time-averaged velocities and turbulent stresses, such as the vorticity or terms in the flow equations, based on the following expression:

\[ \frac{\partial f_1}{\partial x}, \frac{\partial f_2}{\partial y} < 1 + \sigma_{f_1} + \sigma_{f_2}. \]

For the streamwise vorticity \( \omega_x \) (see section 3), for example, equation (2) yields an uncertainty estimated as 20%.

[30] The reported uncertainties apply to the measured data. Patterns of these measured data are often reported in the form of isoline plots (cf. figures in section 3), which are based on interpolation between measured profiles. Care should be taken with the interpretation of values outside the measuring grid.


[31] Figures 6 and 7 illustrate patterns of the bed topography \( z_b \) and the water surface topography \( z_w \), respectively, derived from measurements with the echosounders. The reference \( z_b = 0 \) coincides by definition with the flume-averaged bed level. As aforementioned, the spatial resolution of the echosounder measurements was not sufficient to resolve details of the dunes superimposed on the steady macrofeatures of the bathymetry; their position and characteristics (indicated in Figure 6) were obtained from photographs and manual measurements with a point gauge (Figure 8).

[32] Figures 6, 8, and 9a indicate a typical bar-pool topography with a transverse bed slope that evolves as a damped oscillation toward an equilibrium value, which is overshot in the first part of the bend. In this very sharp bend, the maximum flow depth is about 3 times higher than the flume-averaged flow depth and the equilibrium slope is around 0.23 (13°). This large-scale behavior has been attributed to the different adaptation lengths of the flow and the bed topography to changes in curvature and has been accordingly modeled by de Vriend and Struikema [1984], Struikema et al. [1985], Odgaard [1986], etc. But these models do not explain or resolve important features on a smaller spatial scale (cf. Figure 6). Just downstream of the bend entrance, some minor bend erosion occurs in the inner half of the cross section. Subsequently, a pronounced quasi-horizontal point bar develops in the inner half of the cross section, and a pronounced pool develops at the outer bank. The pool widens in streamwise direction to cover about half of the width in the cross section at 60° in the bend. It is characterized by a transverse slope of about 0.55 (30°) that reaches a maximum value of 0.7 (35°), which is slightly higher than the angle of repose of the bed sediment and requires an upslope drag force exerted by the flow. The cross-sectional profiles in the region covered by the point bar and pool are approximately bilinear with a pronounced knickpoint at the edge of the point bar (cf. Figure 6).

Downstream of the cross section at 90° in the bend, the transverse bed slope shows less variation over the width and the cross-sectional shape is about linear. Interestingly, the cross-sectional area increases considerably in the bend and the straight outflow reaches (Figure 9a), leading to a reduction of the cross-sectional averaged velocity and the corresponding energy losses.

[33] The water surface is accurately resolved on the measuring grid (Figure 7). The water surface topography is quite similar to the bed topography, although the amplitude of the variations is obviously much smaller. Figures 7 and 9 indicate that the water surface topography can be described by a quasi-constant streamwise slope of about \(-0.0017\) (Figure 9b) with a superimposed transverse tilting of the
Interestingly, the transverse tilting of the water surface in this constant-curvature bend is not quasi-constant but seems to evolve as an oscillation that leaps ahead of the oscillation of the transverse bed slope (Figure 9a). The water surface has a bilinear pattern in the region covered by the point bar and the pool: it is about horizontal over the point bar and characterized by maximum transverse slopes over the pool. Downstream of the cross section at 90° in the bend, the transverse slope is about constant over the width of the flume. Interestingly, the transverse tilting of the water surface already begins to decay in the cross section at 150° in the bend, well before the bend exit. Moreover, it decays much faster than the transverse tilting of the bed. Further interesting features of the water surface topography...
are the adverse water surface gradients ($\partial z_s/\partial s > 0$) that occur near the outer bank from the bend entry onto about 45° in the bend, where the water surface rises from 13.8 to 14.6 cm (cf. Figure 7), and near the inner bank between the cross sections at 150° and 180° where the water surface rises from 12.5 to 12.7 cm (cf. Figure 7).

Depth-averaged quantities are used to describe the flow field in depth-averaged numerical models, which are commonly used in morphodynamic calculations. These quantities can synthesize the global features of the flow field reasonably well and capture the velocity redistribution, even in complex 3-D flows. Figures 10 and 11 illustrate the patterns of the normalized depth-averaged streamwise and transverse unit discharges, $U_s/\bar{U}H$ and $U_n/\bar{U}H$, respectively, which computation requires extrapolations near the water surface (cf. section 2.3 and Table 3). Moreover, they illustrate the location of the first moment (center of gravity) of the $U/\bar{U}$ pattern as well as the vector ($\langle U_s/\bar{U} \rangle$, $\langle U_n/\bar{U} \rangle$) ($\langle \rangle$ represents cross-sectional averaged values). The bed topography (Figure 6) leaves a strong footprint on these distributions, which is indicative for an intricate interaction between the flow, the sediment transport and the bed topography. Just downstream of the bend entrance, $U_s/\bar{U}$ resembles a potential vortex distribution and increases from the outer to the inner bank. Due to mass conservation, this requires inward mass transport, $U_n/\bar{U} < 0$. From the cross sections at

![Figure 7](image-url)  
*Figure 7.* Isolines of the water surface level with an interval of 0.002 m derived from echosounder measurements. The flume-averaged bed level defines the reference level. The black lines delineate approximately the point bar and pool. The arrow indicates the highest water surface elevation in the bend. ADVP measurements of the velocities and the bed topography are available in the indicated cross sections.

![Figure 8](image-url)  
*Figure 8.* Photograph of the bed topography, with cross sections indicated at 105°, 120°, and 135° in the bend and lee sides of dunes accentuated by shading.

![Figure 9](image-url)  
*Figure 9.* (a) Streamwise evolution of the transverse bed and water surface slopes. (b) Streamwise evolution of the cross-sectional averaged bed and water surface levels.
transport occurs in the region $90^\circ$–$150^\circ$, where the streamwise flow occupies again the entire width. This is attributed to streamwise changes in the bed topography. From the cross section at $150^\circ$ onward, the transverse tilting of the water surface decays (Figure 9a), resulting in flow accelerations/decelerations in the outer/inner half of the cross section (Figure 10), corresponding outward mass transport (Figure 11) and pronounced erosion near the outer bank (Figure 6). Just downstream of the bend exit, a region of low streamwise unit discharge is observed over the point bar near the inner bank. In the absence of detailed flow measurements near the inner bank, it is not clear if flow only separates in this region or also recirculates. Downstream of it, streamwise “gullies” develop near the inner bank (Figure 6, numbers 21–23). In the straight outflow, the distribution of $U_h$ (Figure 10) homogenizes over the width and corresponding inward mass transport occurs (Figure 11). The transverse mass flux (Figure 11) behaves like a damped oscillation in streamwise direction, in close relation to the damped oscillation of the transverse bed slope (Figure 9a), as explained and quantified by models of de Vriend and Struiksma [1984], Struiksma et al. [1985], Odgaard [1986], etc.

The depth-averaged streamwise velocity $U_s$ (Figure 12) seems to be less dominated by the bed topography. Interestingly, its maximum values are not found over the deepest part of the cross section. Just downstream of the bend entry, $U_s$ is well approximated by a potential vortex distribution with maximum values near the inner bank. The maximum $U_s$ values are subsequently found over the pool, before moving again inward downstream of the cross section at $90^\circ$. A pronounced outward shift of the maximum $U_s$ occurs at the bend exit, before $U_s$ slowly tends toward a uniform distribution in the straight outflow reach. Interestingly, this pattern of the depth-averaged streamwise velocity $U_s/U$ (Figure 12) leaves a clear footprint on the observed dune pattern (Figure 6), which is representative for the migration speed of the dunes and the related sediment transport rate.
The pattern of depth-averaged streamwise unit discharge and velocity (Figures 10 and 12) suggest the existence of a zone of flow recirculation on the shallow point bar in the bend and possibly also on the shallow point bar just downstream of the bend exit. The accuracy of the velocity measurements is reduced over the shallow point bars because of the flow perturbation by the housing of the ADVP velocimeter that touches the water surface (cf. Figure 1). Therefore, the flow over the point bar in the bend has been visualized by means of wool threads floating on the water surface (Figure 13). Flow does not separate at the bend entry but at about 40° in the bend. This can be attributed to the sudden increase in curvature at the bend entrance, which leads to pronounced local accelerations/decelerations in the inner/outer half of the cross section and corresponding inward mass transport that opposes flow separation. From about 10° in the bend, the developing transverse bed slope causes outward mass transport (Figure 11), which promotes flow separation at the inner bank. A horizontal recirculation zone is observed over the shallow point bar between the cross sections at 40° and 120°, similar to recirculation zones observed in natural rivers [Leeder and Bridge, 1975; Frothingham and Rhoads, 2003; Ferguson et al., 2003]. This flow recirculation zone reaches its maximum width in the cross section at 80°, where it covers about 2/3 of the total width. The zone of flow separation just downstream of the bend exit has not been measured or visualized in detail. It can be attributed to the suddenly vanishing transverse tilting of the water surface, which creates outward mass transport and an adverse water surface gradient at the inner bank that both favor flow separation. These processes do occur in natural meander bends, which are often characterized by prominent breaks and peaks in curvature.

The flow visualization identifies inward velocities at the water surface adjacent to the outer bank that indicate the existence of an outer bank cell of secondary flow. It has a width of about 0.5H, which is considerably less than the width of at least 1H reported in other laboratory [Mockmore, 1943; Einstein and Harder, 1954; Blanckaert and Graf, 2001; Booij, 2003; Van Balen et al., 2009; Van Balen et al., 2010a] and field [Bathurst et al., 1979; Dietrich and Smith, 1983; de Vriend and Geldof, 1983] experiments. This narrowing can be attributed to the flow recirculation zone that directs the flow in an outward direction, which can act to compress the outer bank cell. Besides the outer bank cell, strong outward transverse velocities are observed at the water surface over the pool, indicating the existence of curvature-induced secondary flow.

Obviously, 3-D flow structures, such as secondary flow, play an essential hydrodynamic role. In order to describe 3-D flow structures, the velocity \( v_i \) is decomposed into depth-averaged quantities \( \langle v_i \rangle = U_i \) and local deviations from it \( v^*_i \),

\[
v_i = \langle v_i \rangle + v^*_i = U_i + v^*_i \quad (i = x, n, z),
\]

where \( \langle \cdot \rangle \) indicate depth-averaged values. Physically, \( U_i \) can be interpreted as translatory motion, whereas \( v^*_i \) gives rise to rotational motion. The typical signature of secondary flow \( (v^*_x, v^*_n) \) in a bend can be represented by the scalar streamwise vorticity component \( \omega_s \) defined as

\[
\omega_s = \frac{\partial v_n}{\partial z} - \frac{\partial v_z}{\partial n} = \frac{\partial v_z}{\partial n} - \frac{\partial v_n}{\partial z}
\]

Figure 14 illustrates the evolution of the secondary flow around the flume by means of the patterns of the normalized depth-averaged streamwise vorticity \( \langle \omega_s \rangle H/U \). The secondary flow is concentrated over the deepest part of the cross section and is negligible in the shallow inner half of the cross section. The secondary flow evolves around the flume as a damped oscillation in a similar way as the transverse bed slope (Figure 9a), but the overshoot in the cross section at about 60° is even more pronounced, with values that are more than 3 times higher than the equilibrium value in the downstream part of the bend. The outer bank cell of sec-
flow has been modeled by Blanckaert [2009] and will not be further considered here. Increased turbulence activity near the centerline downstream of the cross section at 60° and slightly outward of the centerline downstream of the cross section at 150° may be attributed to horizontal shear due to transverse gradients in $U_s$ and $U_h$ (cf. Figures 10 and 12). The turbulence activity over the point bar seems to be reduced.

4. Flow Redistribution

[a1] The present section analyses the mechanisms that redistribute the flow over a known topography based on the conservation equations of mass and momentum. Section 5 will focus on the interaction between the flow field and the topography.

4.1. Mass Redistribution

[a2] Figure 17 shows the evolution around the bend of the first moments (center of gravity of the distributions) of the streamwise unit discharge $U_h$ (curve shown in Figure 10), the bed topography $h$, and the depth-averaged streamwise velocity $U_s$ (curve shown in Figure 12). By definition, differences between the curves for $U_h$ and $h$ are due to the nonuniform distribution of $U_s$ over the width. The proximity of the curves for $U_h$ and $h$ suggests that the bed topography $h$ has a dominant role with respect to the flow redistribution. The major effect of the bed topography is due to the transverse mass redistribution $U_h$, caused by streamwise variations in streamwise unit discharge $U_h$, as quantified by means of the depth-averaged equation of mass conservation [cf. Blanckaert and de Vriend, 2003],

$$U_h = -\frac{1}{1 + n/R} \int \left( \frac{1 + n/R}{\partial h/\partial n} \right) \, dn. \quad (5)$$

Figure 15. Isolines of normalized depth-averaged vertical velocity $U_z/U$ [-]. Patterns are based on high-resolution measurements in the indicated cross sections. The black lines delineate approximately the point bar and pool.

Figure 16. Isolines of normalized depth-averaged turbulent kinetic energy $\langle \text{tke} \rangle/(1/2u^2)$ [-]. Patterns are based on high-resolution measurements in the indicated cross sections. The white lines delineate approximately the point bar and pool.
Downstream variations in $h$ are the dominant contribution in equation (5). This mass redistribution mainly affects the direction of the flow, as indicated by the vectors ($\langle\langle U_t h \rangle\rangle$, $\langle\langle U_s h \rangle\rangle$) in Figures 10 and 11. It explains why the flow tends to go straight on and collides with the outer bank in the region of pronounced curvature increase contrary to the inward shift of the locus of highest velocities observed over a horizontal bed topography (per Zeng et al. [2008a] for a flat bed experiment in the same laboratory flume under similar hydraulic conditions). It also explains why the flow tends to follow the deepest parts of the cross sections and why the deep scour pools tend to attract the flow.

Figure 17 may falsely give the impression that mass redistribution is the dominant process and that momentum redistribution only plays a secondary role. Although mass redistribution can, to a large extent, explain the discharge distribution over a known bed topography, it cannot explain the formation of that bed topography, which is due to an intricate interaction between the flow and the sediment transport. According to the majority of models, sediment transport is not primarily determined by the unit discharge $U_s h$ but rather by the local magnitude of the bed shear stress $\tau_{s0}$, which is determined by momentum transport and in first approximation (assuming a constant dimensionless Chézy friction coefficient $C_s$) proportional to $U^2_s$ (cf. equation (6)). This seems to be confirmed in the present experiment by the dune pattern (Figure 6) that suggests a relation between the dune celerity and the pattern of $U_s$ (Figure 12) but not the pattern of $U_s h$ (Figure 10).

Mass redistribution alone cannot explain the formation of the pronounced point bar and pool. The transverse bed slope in the pool was shown (Figure 6) to reach a maximum value of 0.7 (35°) that is higher than that of repose of the bed sediment and thus requires upslope (inward) drag forces to be exerted by the flow. These drag forces can only be caused by secondary flow, because outward mass transport $U_s h > 0$ occurs over a large part of the concerned pool region. Moreover, important features of the flow field, such as the horizontal flow recirculation over the point bar, cannot be explained by mass redistribution alone.

4.2. Momentum Redistribution

The redistribution of $U_s$ is governed by the depth-averaged streamwise momentum equation, which

$$ c_j U_s^2 \approx \frac{\tau_{s0}}{\rho} = \text{GRAV} + \text{INERT} + \text{VERT} + \text{TURB}, \quad (6) $$

$$ \text{GRAV} = \frac{1}{1 + n/R} g h \frac{\partial h}{\partial s}, \quad (7) $$

$$ \text{INERT} = - \frac{1}{1 + n/R} \frac{\partial}{\partial s} \left( U^2_s h \right) - \frac{\partial}{\partial n} \left( U_s h U_s h \right) - \frac{2}{1 + n/R} \frac{U_s U_s h}{R}, $$

$$ \approx -h \left[ \frac{1}{1 + n/R} U_s \frac{\partial U_s}{\partial s} + U_s \frac{\partial U_s}{\partial n} + \frac{1}{1 + n/R} U_s U_s h \right], \quad (8) $$

$$ \text{VERT} = - \frac{1}{1 + n/R} \frac{\partial}{\partial s} \left( \langle \nu^2 \rangle h \right) - \frac{\partial}{\partial n} \left( \langle \nu_s^2 \rangle h \right) - \frac{2}{1 + n/R} \left( \nu^2 \nu_s^2 \right) h, \quad (9) $$

$$ \text{TURB} = - \frac{1}{1 + n/R} \frac{\partial}{\partial s} \left( \langle \nu_s^2 \rangle h \right) - \frac{\partial}{\partial n} \left( \langle \nu_s^2 \rangle h \right) - \frac{2}{1 + n/R} \left( \nu_s^2 \right) h. \quad (10) $$

It identifies and quantifies in a transparent way the influence of different processes that contribute to the streamwise component of the bed shear stress $\tau_{bs0}$. The term $\text{GRAV}$ represents the gravitational forces driving the flow. It is modulated by the flow depth $h$, indicating that higher flow depths lead to higher bed shear stresses and higher velocities. This bed topography effect explains to some extent why the first moment of $U_s h$ is generally larger than the first moment of $h$ (Figure 17). The equation of mass conservation allows transforming the term $\text{INERT}$ into the second line in equation (8), whereas the third line in equation (8) gives a good approximation along an axis that follows the local depth-averaged streamline. It shows that $\text{INERT}$ mainly represents inertial effects and momentum redistribution that accompanies the mass redistribution. It is also modulated by

**Figure 17.** Evolution around the flume of the first moments of the streamwise unit discharge $U_t h$ (curve shown in Figure 10), the bed topography $h$, and the depth-averaged streamwise velocity $U_s$ (curve shown in Figure 12).
the bed topography and thus another effect of the bed topography on the flow field. The term VERT represents momentum redistribution due to the vertical nonuniformity of the flow \(v_s^*, v_n^*\) (cf. equation (3)), which includes the curvature-induced secondary flow. This is the major term in configurations with horizontal bed topography, which have commonly been used in laboratory investigations of meandering flow. To date, there is no consensus on the relevance of this term in natural meanders with mobile bed topography. The term TURB represents momentum redistribution by the turbulence. It is not expected to be of dominant importance, although it may play a role in the formation of zones of flow separation and recirculation.

Blanckaert and Graf [2004] made term-by-term analysis of equation (6) for the case of a strongly curved laboratory bend measured by means of the same ADVP velocimeter used in the present experiment. Their measurements were limited to the outer half of one cross section, however, which did not allow estimating terms related to streamwise nonuniformities. The present experiment allows estimating all terms in equation (6). Whereas transverse gradients can be estimated accurately because of the high spatial resolution in the measured cross sections, streamwise gradients are characterized by a relatively high uncertainty due to the spacing between the measured cross sections. Hence, care should be taken with the interpretation of patterns interpolated in between the measured cross sections. The spatial patterns of the terms in equation (6) are shown in Figure 18, except for the term TURB, which was found to be considerably smaller than the other terms. The flume is divided into three characteristic regions for the analysis of the flow dynamics. Each region is further divided in sub-regions as indicated in Figure 18d, including a subdivision over the width that is based on the position of the first moment of the distribution of \(U_s h / U_h\) (cf. Figures 10 and 11). Extrapolated regions outside the measuring grid near the inner bank are indicated by shading.

Table 4 summarizes averaged values of characteristics of the bed topography, the flow field, and the different terms in the depth-averaged streamwise momentum equation (6) in these regions and subregions. An indication of the accuracy in the evaluated terms is given by the following two observations (cf. Table 4): (1) the averaged value of the terms INERT, VERT, and TURB over the entire measuring
grid is small, which is required since these terms do not generate momentum but only redistribute it; (2) although the uncertainty in the individual terms adds up, their sum complies with the expected order of magnitude of the bed shear stress. The following analysis of equation (6) and the corresponding interpretation of the flow dynamics focus on first-order effects, which can be reliably deduced from the experimental data, taking into account experimental uncertainty.

[46] Region I (cf. Figure 18d and Table 4) from the bend entry onto 120° in the bend is representative for flows subject to a pronounced increase in curvature, such as found between the crossover and the apex in meandering rivers. A pronounced increase in curvature causes considerable momentum redistribution in a bend. Just downstream of the bend entry (regions Ia and Ib), the driving GRAV term is increased/decreased in the inner/outer part of the cross section by the increase of the transverse tilting of the water surface, which is in first approximation inversely proportional to the centerline radius of curvature. The decrease of the GRAV term at the outer bank is further accentuated by the flow that cannot follow the strong curvature increase and collides at an oblique angle with the bank (cf. Figure 10), thereby creating a stagnation point at about 50° at the outer bank (arrow in Figure 18a). In the investigated case, this even leads to an adverse water surface gradient in the outer part of the cross sections between the bend entrance and the stagnation point (upstream part of region Id). Nevertheless, the flow goes outward around the point bar and concentrates over the pool in this region and the streamwise velocities remain positive, which must be attributed to inertia. The term INERT is probably considerably underestimated in this region (cf. Figure 18b) due to the spacing between the measured cross sections that leads to rather inaccurate estimates of the streamwise gradients. The term VERT related to the vertical flow structure (cf. Figure 18c) is not negligible in this region. Downstream of the stagnation point (downstream part of region Id), GRAV strongly favors the flow over the deepest part of the pool. At the end of the pool zone, it is again opposed to the flow due to the decreasing flow depth. The terms GRAV, INERT, and VERT locally reach high magnitudes in the pool zone (region Id). When considering averaged values over the pool (cf. Table 4, region Id), VERT and especially INERT are mainly positive and are the dominant contributions to the flow redistribution.

[47] The strong deceleration of $U_s$ over the point bar between 30° and 60° in the bend (upstream part of region Ic) is mainly due to the strong negative values of the term INERT. The water surface is about horizontal on the point bar, leading to strongly reduced values of GRAV. The horizontal flow recirculation may be induced by the core of pronounced negative values of GRAV, which coincides with the center of the recirculation zone (cf. Figure 13). Flow accelerates over the point bar between 80° and 120° in the bend (downstream part of region Ic), which is mainly due to GRAV. The term VERT is generally small in region Ic, although a core of negative values occurs at the edge of the point bar.

[48] Region II from 120° to 165° is not affected by the abrupt curvature variations at the bend entry and exit and is characterized by relatively weak transverse velocities. Therefore, it is most representative for established curved flow with weak curvature variations. Interestingly, the maximum velocities do not occur over the deepest part of the cross section but over the shallower inner half (cf. Figure 12). This seems to be mainly due to the term INERT (Table 4), although also the relatively low/high values of GRAV in the outer/inner half of the cross section (despite their modulation with the flow depth $h$) contribute. Curvature-induced secondary flow, represented by VERT, is a mechanism of dominant order of magnitude that increases velocities in the outer half of the cross section. The effect of turbulence on the velocity distribution, quantified by TURB (Table 4), is not negligible in this region II.

[49] Region III from 165° in the bend to the exit of the flume is representative for flows subject to a pronounced decrease in curvature, such as found between the apex and the crossover in meandering rivers. Moreover, the straight outflow reach is representative for the recovery to straight flow. The influence of the bend exit already results in a decrease of the transverse tilting of the water surface well upstream of the bend exit at about 150° in the bend.
(cf. Figures 9a and 18a), which may be attributed to the pronounced point bar at the inner bank just downstream of the bend exit. This results in a considerable decrease/increase of the driving GRAV term in the inner/outer part of the cross section (cf. Table 4, regions IIIa and IIIb). The pronounced negative values of INERT in the outer part of the cross section in region IIIb largely balance GRAV, resulting in a relatively weak acceleration of the flow. Although weakening, curvature-induced secondary flow is still a mechanism of dominant order of magnitude that increases velocities in the outer half of the cross section in region IIIb. The absence of measurements over the shallow point bar just downstream of the bend exit did not allow estimates of the terms in equation (6). The flow remains considerably skewed in outward direction in the straight reach downstream of the bend exit (Figure 18d, regions IIIc and IIId). This is mainly due to the quasi-horizontal water surface over the point bar (cf. Figures 7 and 18a) that slows down the flow in the inner half of the cross section (region IIIc). The term INERT is mainly negative in regions IIIc and IIIId due to the decrease in cross sectional area and flow depth (cf. Figure 9b). Curvature-induced secondary flow decays and its effect is negligible at about one width downstream of the bend exit. The velocities only tend to uniformize at the downstream end of the flume under the influence of the uniformizing flow depth and corresponding GRAV term, as well as the term INERT.


5.1. The Hydrodynamics of Topographic Steering

[50] Attempts to clarify the flow redistribution in curved open channel flow by means of a term-by-term analysis of the depth-averaged streamwise momentum equation have been made by Yen and Yen [1971] (laboratory flume with idealized bed topography), Dietrich and Smith [1983] (meander bend on Muddy Creek), Odgaard and Bergs [1988] (laboratory flume over mobile bed), Nelson and Smith [1989] (meander bend on Muddy Creek), Dietrich and Whiting [1989] (meander bend on Muddy Creek). These analyses were based on measurements of the horizontal and transverse velocity components on rather coarse grids and did not allow evaluating all terms in equation (6), leading to a high uncertainty in the results. Odgaard and Bergs [1988] and Whiting and Dietrich [1993], for example, report conflicting findings on the importance of different terms/processes. The main controversy is about the role and relevance of the terms INERT and VERT with respect to the outward migration of the flow toward the deepest part of the cross sections. Classical models by Engelund [1974] and Ikeda et al. [1981] for flow and bed topography in open channel bends predict the core of maximum velocities at the inside of the bend in configurations with horizontal bed, which is in contradiction with experimental observations [Rozovskii, 1957; Kikawa et al., 1976; de Vriend, 1977]. Kalkwijk and de Vriend [1980] attributed this to the neglect of outward advective transport of momentum by the curvature-induced secondary flow, represented by the term VERT, which they successfully included in their model. Smith and McLean [1984] argue that these effects are only of second order in natural alluvial meander bends and should be neglected on theoretical grounds. They further argue that the key to successful simulation of the flow and bed topography in meanders is the inclusion of convective accelerations induced by cross-stream and downstream variations in the channel topography and by a changing radius of curvature, corresponding to the term INERT in the present paper. The seminal model of Engelund [1974] did not include all relevant contributions to INERT (cf. equation (8)). Results of field measurements in a bend on Muddy Creek by Dietrich and Smith [1983], Nelson [1988], and Dietrich and Whiting [1989] are summarized by the latter as follows: “Point bars force the flow over the bar toward the opposite bank, even at the bed. This effect, called quite graphically topographic steering by Nelson [1988], is linked to the convective acceleration terms. In essence, shoaling of the flow over the point bar generates convective accelerations that cause a pressure rise over the bar and drop over the pool such that, in the cross-stream direction, centrifugal force exceeds the opposing pressure gradient force and net outward flow occurs. Put more simply, the flow goes around the bar.”

[51] For the case of sharp meander bends, the reported experimental data and their analysis clarify some controversial issues, such as the roles of secondary flow (VERT) and convective accelerations (INERT), and provide new insight in the hydrodynamics underlying topographic steering. The reported experimental results indicate that the flow goes around the point bar mainly because of mass conservation requirements that determine the direction of the flow, whereas momentum redistribution that determines the magnitude of the velocity vector plays a less important role. Convective accelerations (INERT) and secondary flow (VERT) are both found to be processes of dominant order with respect to momentum redistribution. The conflicting results in the past on the importance of INERT can be attributed to the inherent difficulty to estimate this term from experimental data. The term INERT consists of two very large contributions that are opposed due to mass conservation and therefore lead to a high uncertainty. The patterns of INERT shown in Figure 18(b) are estimated from the second line of equation (8) whereby \( U_N \) and \( U_P \) respect mass conservation. Nelson [1988] and Dietrich and Whiting’s [1989] term “topographic steering” is adequate to describe the flow redistribution in meander bends, although their description of the underlying hydrodynamics appears to be inaccurate. The experimental results presented herein clearly show that the bed topography determines the mass redistribution and strongly influences all terms in the momentum equation (6).

5.2. Horizontal Flow Separation/Recirculation

[52] Horizontal flow separation and recirculation alter the velocity distribution and have important implications for sediment transport and meander migration. Recirculation zones also create distinctive ecological niches and are likely to reduce mixing and spreading of suspended matter, nutrients, oxygen, and pollutants. Yet little is known about the detailed flow structure of recirculation zones in open channel bends, their interaction with the topography, their conditions of occurrence, and the controlling factors. The reported experimental data and their analysis provide new insight in these issues that will now be presented and situated with respect to the state of the art. It can reasonably be
assumed that the existence of an adverse water surface gradient is a necessary but not a sufficient condition for the occurrence of flow separation and recirculation. Two different types of adverse water surface gradients occur in the investigated experiment, which will be analyzed separately.

[53] The first type concerns adverse water surface gradients occurring due to the adaptation of the transverse tilting of the water surface to pronounced changes in curvature. The adverse water surface gradient near the bend exit (cf. Figures 7, 9a, and 18a) causes a zone of flow separation over the shallow inner half of the cross section. The more pronounced adverse water surface gradient downstream of the bend entry (cf. Figures 7, 9a, and 18a), on the contrary, only causes a considerable deceleration of the flow, which remains however streamwise directed. Due to the effect of the upstream bend, the approaching flow at the outer bank in a meandering river is in general considerably slower than in the investigated laboratory flume with uniform inflow conditions, which favors flow separation and recirculation. Jackson [1992], for example, observed flow recirculation in the pool at the outer bank in the meandering Fall River in a region of increasing curvature. Hodskinson and Ferguson [1998] mention flow separation at the outer bank in a bend at Allt Dubhaig, Scotland, and carried out numerical investigations that confirm the dependence of outer bank flow separation on the inflow conditions. Furthermore, they assume that constriction of the flow near the outer bank by the recirculation zone over the point bar opposes the development of flow separation at the outer bank. The experiment reported herein suggests that this effect may be compensated by the increase in cross-sectional area and the deepening in the pool zone. Channel widening, on the contrary, reduces the velocities and promotes flow separation at the outer bank, but it is not clear if it is a required condition as suggested by Hickin [1977]. On the basis of the reported experimental data and their analysis, necessary conditions for the occurrence of an adverse water surface gradient due to changes in curvature will now be derived by expressing the water surface elevation as the sum of its value at the centerline and the curvature-induced transverse tilting (cf. Figures 9a and 9b),

\[ z_s = z_c(n = 0) + \frac{\partial z_c}{\partial n} n. \]  

In first approximation, the water surface gradient at the centerline and the transverse tilting of the water surface [Chow, 1959] can be estimated as

\[ \frac{\partial z_c(n = 0)}{\partial s} = -S_c = -C_f \frac{U^2}{gh}, \]  

\[ \frac{\partial z_c}{\partial n} = \frac{U^2}{gh} \]  

where the centerline radius of curvature \( R \) varies in streamwise direction. This leads to

\[ \frac{\partial z_c}{\partial s} = -C_f \frac{U^2}{gh} + \frac{U^2}{g} \frac{\partial}{\partial s} \left( \frac{1}{R} \right) n. \]  

Pronounced variations of \( R \) typically occur over streamwise distances on the order of \( R_{\text{min}} \), leading to the following estimation of \( \partial R^{-1}/\partial s \),

\[ \frac{\partial}{\partial s} \left( \frac{1}{R} \right) = \pm \left( \frac{1}{R} \right)_{\text{cross-over}} \frac{1}{R_{\text{min}}} \]  

and of the streamwise water gradient at the outer/inner bank in regions of increasing/decreasing curvature,

\[ \frac{\partial z_c}{\partial s} = -C_f \frac{U^2}{gh} + \frac{1}{2} \frac{U^2}{gR_{\text{min}}} \frac{B}{R_{\text{min}}} = -C_f \frac{U^2}{gh} \left( 1 - \frac{1}{2} \frac{H}{C_f B} \frac{B^2}{R_{\text{min}}^2} \right). \]  

Hence, a required condition for the occurrence of adverse water surface gradients is obtained as

\[ \frac{R_{\text{min}}}{B} < \left( \frac{1}{2} \frac{H}{C_f B} \right)^{1/22}. \]  

As aforementioned, Blanckaert (submitted manuscript, 2010) summarizes values of \( C_f^{-1} H/B \) for some natural meandering rivers, which are typically in the range between 5 and 10, leading to required values of \( R_{\text{min}}/B \) for the onset of flow separation of about 2. This is in agreement with Bagnold [1960] and Markham and Thorne [1992], who relate the observed decreasing meander migration rates in sharp meander bends with \( R_{\text{min}}/B \) smaller than a critical value of about 2 to the occurrence of flow separation. It also agrees with Hickin [1977], who suggested as threshold of \( R_{\text{min}}/B = 2 \) for the onset of flow separation. According to equation (17), adverse water surface gradients and flow separation/recirculation are favored in smooth and narrow rivers.

[54] The second type of adverse water surface gradient occurs in the horizontal flow recirculation zone over the point bar in the region of strong curvature increase. The experimental results and their analysis shed light on the mechanisms underlying this recirculation zone. The adverse water surface gradient seems to play a major role in the generation of the horizontal flow recirculation zone, although momentum redistribution represented by the terms INERT, VERT, and TURB also contribute considerably, mainly near the edge of the point bar (Figure 18 and Table 4). The contribution of the term TURB (Table 4) represents shearing induced by the transverse redistribution of mass associated with the topographic steering of the flow around the point bar (arrows in Figure 12). It can be represented by one-equation and two-equation turbulence closure as confirmed by successful simulations by Hodskinson and Ferguson [1998], Ferguson et al. [2003], and Zeng et al. [2008a, 2008b]. The experimental results indicate a positive feedback between the water surface elevation and the flow recirculation zone: a weak depression in the water surface elevation (cf. Figure 12) coincides with the center of the flow recirculation zone (cf. Figure 13) and is strengthened by centrifugal effects of the recirculating flow. It leads to a favorable adverse water surface gradient in the downstream part of the recirculation zone (cf. Figures 12 and 18a). Because of the low velocities, the water surface gradients in the recirculation zone are considerably weaker than those related to the curvature-induced transverse tilting of the flow over the deep pool. The topographic steering of the flow
around the point bar, and the resulting low velocities on the point bar seem to be necessary conditions for the occurrence of the flow recirculation zone. The observations suggest that the development of an equilibrium situation with a pronounced point bar characterized by flow recirculation and adverse water surface gradients is due to a subtle nonlinear interaction between sediment transport and the flow, whereby the parameters of influence remain to be identified and quantified. On the basis of field observations, Leeder and Bridge [1975] identified the Froude number and the curvature ratio $R/B$ as important parameter.

5.3. Secondary Flow, Topographic Steering, and the Formation of the Point Bar and Pool

[55] The foregoing analysis of hydrodynamics considered a known topography. The most relevant question in meander dynamics, however, is how the interaction between the flow and the sediment transport leads to this topography. In an experiment on an asymmetrical compound bend along the Embarras River, Frothingham and Rhoads [2003] observed that the flow collides with the bank at an oblique angle, resulting in abrupt reversal of flow near the bed downstream of the apex. Moreover, they observed that maximum rates of bank retreat occurred upstream of the apex and seemed to be related to this impingement of the flow on the outer bank. These observations point to the importance of the position of the point bar and pools with respect to meander dynamics. On the basis of data from laboratory experiments in various sine-generated meanders, Whiting and Dietrich [1993] observed that the first and most pronounced pool, opposite the first inner bank bar, is consistently positioned where the projection of the inner bank tangent at the upstream crossing intersects the outer bank. Hodkinson and Ferguson [1998] investigated a bend on the Dean River characterized by flow recirculation over the point bar and observed that down-welling became pronounced in the stagnation region where the main flow impinges on and turns against the outer bank. These results were confirmed by Ferguson et al. [2003] in a detailed investigation of two bends with flow recirculation on the Dean River, which led to the following observations: “The momentum of the near-bank flow causes it to continue in a fairly straight path, leaving a zone of low velocity in what is effectively a sudden lateral expansion. A second aspect of the morphology of both bends is a pronounced deepening of the channel from the inflow riffle to the apex pool. The outer bank helix is strongest proximally, where the bulk of the incoming flow converges on the outer bank not just passively as the bank starts to turn but also through the deflecting effect of the inner bank recirculation eddy.”

[56] The bed topography and flow in the reported experiment strongly resemble these observations and the reported experimental data provide more detailed observations of the relevant processes that allow clarifying the underlying physical mechanisms and their interactions. The detailed analysis of the redistribution of depth-averaged velocities (section 4.2) has shown that topographic steering imposed by mass conservation is the hydrodynamic mechanism underlying the tendency of the flow to go straight on and to collide with the outer bank. The deflecting effect of the inner bank recirculation eddy was found not to play a dominant role in the momentum balance. Moreover, it has shown that the reduction of velocities over the point bar is mainly due to inertia. Figure 19 provides a 3-D view of the patterns of normalized streamwise, transverse, and vertical velocities in the cross section at 30° in the bend. The bed in this cross section is about flat in the central region $n = -0.5$ m to $n = 0.5$ m, but the point bar and pool begin to develop near the
inner and outer bank, respectively. The pattern of transverse velocities in the central part of the cross section does not show any significant curvature-induced secondary flow. It is qualitatively very similar to the pattern of streamwise velocities, confirming the tendency of the flow to go straight on (cf. Figures 10 and 11). The reduced velocities near the inner bank (cf. Figure 12) cause a deposition of sediment that builds up the point bar, as indicated by the upward component of the velocities parallel to the bed near the inner bank (vertical velocities in Figure 19). The horizontal recirculation zone enhances the trapping of sediment on the point bar. The collision of the flow with the outer bank provokes a rise of the water surface elevation (Figure 7), which results in downwelling velocities that reach a magnitude as high as $v_0/U = -0.3$ (Figure 19). These pronounced downwelling velocities impinge on the bed and are clearly the main cause of the bed scour. They are inward deflected on the bed into transverse velocities. The pronounced inward near-bed velocities maintain a transverse bed slope of the pool zone that is steeper than the angle of repose of the sediment (cf. Figure 9a). Their collision with the pronounced outward mass transport over the point bar leads to quasi-bilinear bed profiles. The experimental data indicate positive feedback between these different processes. Between the cross sections at $30^\circ$ and $60^\circ$, the point bar and pool both widen and become shallower and deeper, respectively (Figure 6), resulting in enhanced topographic steering (Figure 11) and enhanced secondary flow at the outer bank (Figures 14 and 15), which in their turn enhance the development of the point bar and the pool. The point bar and pool zones (Figure 6) are confined by the inward mass transport that develops downstream of the stagnation point at the outer bank (Figure 18a) from about $70^\circ$ in the bend on (Figure 11). This alternating outward-inward mass redistribution is known to be due to the interaction between the flow and the bed topography at a larger spatial scale [de Vriend and Struiksm, 1984; Struiksm et al., 1985; Odgaard, 1986]. Curvature-induced secondary flow, characterized by inward near-bed velocities, is confined to the deepest zone of the cross section all around the bend (Figures 14 and 15). This leads quasi-bilinear bed profiles in zones characterized by outward mass transport and quasi-linear bed profiles in zones characterized by inward mass transport (cf. Figures 6 and 11).

6. Modeling Implications

[Z5] Van Balen et al. [2010b] and Zeng et al. [2008a, 2008b] have simulated the flow field in the reported experiment over the prescribed bed topography with a 3-D large eddy simulation (LES) code and a 3-D Reynolds Averaged Navier Stokes (RANS) code with Spalart–Almaras turbulence closure, respectively. Both codes resolved all relevant hydrodynamic processes. The small differences between the results of both codes confirm the results of section 4.2 that the velocity redistribution is dominated by the bed topography and that turbulence only plays a minor role. Simulations of the flow field over a horizontal bed in the same experimental flume revealed, however, that a detailed modeling of the turbulence by means of large eddy simulation is required to accurately resolve the horizontal flow separation at the inner bank, the outer bank cell of secondary flow, and the boundary shear stress [Van Balen et al., 2010a].

From these two extreme cases, it can be concluded that turbulence gains in importance with respect to the velocity redistribution in configurations with less pronounced bed topography, such as found in bends of milder curvature or rivers in less erodible alluvium. [Z58] Zeng et al. [2008a, 2008b] applied the same hydrodynamic code but also simulated the bed topography as part of the solution. Sediment transport was modeled by means of the formula of Engelund and Hansen [1967], which was originally derived and validated for straight uniform shear flows. It was extended by means of the ad hoc model of Sekine and Parker [1992] to account for the influence of the streamwise and transverse bed slope on the rate and direction of sediment transport. This morphodynamic model was able to resolve essential features such as the bilinear bed profiles in the point bar–pool region, but the maximum scour depth near the outer bank and the transverse bed slope in the pools were considerably underestimated. The reported experimental data allows identifying as principal knowledge gap the neglect of the influence of the pronounced vertical velocities impinging on the bed (cf. Figures 15 and 19) and the increased turbulence levels (cf. Figure 16) in the sediment transport formula. These hydrodynamic processes typically occur in local scour configurations, such as found at bridge piers or abutments. The reported experiment constitutes an appropriate benchmark case for the validation of new concepts/models for sediment transport that account for these hydrodynamic processes.

[Z59] Even though 3-D hydrodynamic models are able to resolve all relevant hydrodynamic processes, depth-averaged 2-D and cross-sectional averaged 1-D models will remain an important tool for the investigation of large-scale and/or long-term problems in real rivers due to limitations in computational capacity. The key for success in such models is the parameterization of the secondary flow and its effects on the momentum redistribution and the direction of the sediment transport vectors. Secondary flow in bends of mild curvature and weak curvature change is commonly parameterized as increasing proportionally to the curvature ratio $H/R$ [Van Bendegom, 1947; Rozovskii, 1957; Engelund, 1974: de Vriend, 1977],

$$v^*_0(z) = U(H/R)f_n(z, C_f).$$  \[18\]

from which follows in a straightforward way that $\langle \omega_0 \rangle H/U = (H/R)f_n(z, C_f)$. In the region of mild curvature change between the cross sections at $120^\circ$ and $165^\circ$ in the reported experiment, this formula predicts a value in the bend of about $\langle \omega_0 \rangle H/U = -0.5$, which is significantly higher than the observed value of about $-0.1$ (cf. Figure 14). This so-called saturation of the secondary flow in sharp meander bends is known to be due to the nonlinear interaction of the secondary flow with the streamwise flow component [de Vriend, 1981; Yeh and Kennedy, 1993]. Blanckaert and de Vriend [2003, 2010] have developed a parameterization of the secondary flow in sharply curved bends that account for the nonlinear hydrodynamic interactions and successfully reproduces the saturation of the secondary flow. The validity of both the parameterizations for mildly and sharply curved bends is still limited to regions of weak curvature variations, however, since they are based on the same simplified transverse momentum equation that expresses the near equilibrium of the outward centrifugal force and the inward
pressure gradient induced by the transverse tilting of the water surface. This simplified transverse momentum equation is based on the hypothesis that (1) no cross flow \( U_n \) occurs, implying that outward mass transport in the upper part of the water column and inward mass transport in the lower part are in equilibrium and (2) upwelling at the inside edge of the secondary flow well and downwelling at its outside edge are in equilibrium in each cross section. These hypotheses are clearly not satisfied in the region of strong curvature increase. A pronounced outward cross flow \( U_n \) exists (Figures 11 and 15) and downwelling velocities are dominant in the measured cross sections at 30° and 60° (Figures 15 and 18). Pronounced inward cross flow and dominant upwelling velocities occur in the measured cross sections at 90° and 120° downstream of the point bar and pool. It is only downstream of the cross section at 120° that the simplified transverse momentum equation accurately describes the hydrodynamics of the secondary flow. Moreover, commonly used parameterizations of the curvature-induced secondary flow prescribe it to extent over the entire width of the river. This is in contradiction with the observed confinement to the deeper part of the cross section, which was found to lead to the quasi-bilinear transverse bed profiles in zones of strongly increasing curvature. The reported experimental results may lead to the improvement of the parameterization of the curvature-induced secondary flow based on a more complete transverse momentum equation and a more accurate description of its transverse extent.

7. Conclusions

[60] This paper has investigated the bed topography and its interaction with the flow field in a sharply curved laboratory flume, characterized by control parameters \( C_f H/B \) and \( R/B \) that are representative for sharp natural meander bends. The transverse bed slope evolves around the bend as a damped oscillation in line with 1-D theoretical models [de Vriend and Struiksma, 1984; Struiksma et al., 1985; Odgaard, 1986]. Streamwise variations of the bed topography give rise to mass redistribution. Regions of inward mass transport are characterized by a quasi-linear transverse bed profile, whereas regions of outward mass transport are typically characterized by a quasi-bilinear transverse bed profile: the point bar in the inner part of the cross section is nearly horizontal and shallow, whereas the pool in the outer part of the cross section is deep and characterized by a pronounced transverse bed slope that is produced by inward near-bed velocities created by secondary flow. Positive feedback occurs between these different types of transverse bed profiles and the outward/inward patterns of mass redistribution. Outward mass transport typically occurs in regions of pronounced curvature increase, where the flow tends to go straight on. It also occurs in regions of pronounced curvature decrease, where the decreasing curvature-induced transverse tilting of the water surface gives rise to flow acceleration/deceleration in the outer/inner half of the cross section. In general the cross-sectional area increases in regions of pronounced curvature change, leading to a reduction of the cross-sectional averaged velocities and the corresponding energy losses.

[61] Topographic features, such as oblique dunes and the quasi-bilinear bed profiles over the point bar and pool, leave a strong footprint on the discharge distribution and the patterns of streamwise velocity, secondary flow, and turbulence. The flow goes around the shallows and the major part of the discharge concentrates over the deepest zones of the bend. This effect, commonly called topographic steering, is mainly due to mass redistribution required by the principle of mass conservation. The maximum depth-averaged velocities, however, do not systematically occur over the deepest part of the cross section. The velocity (re)distribution is relevant with respect to the development of the bed topography, as testified by the relation between the dune pattern and the distribution of the depth-averaged velocities.

[62] A term-by-term analysis of the depth-averaged streamwise momentum equation revealed that the water surface gradient is the principal mechanism with respect to velocity (re)distribution, although inertia and secondary flow are also processes of dominant order of magnitude. Turbulence seems to play a minor role. All processes are strongly influenced by the bed topography. The transverse water surface slope, for example, follows a damped oscillation that leaps ahead of the transverse bed slope oscillation.

[63] A required condition for the occurrence of adverse water surface gradients at the outer/inner bank due to the adaptation of the transverse tilting of the water surface in zones of pronounced curvature increase/decrease has been estimated as a function of the two major control parameters as \( R_{min}/B < 0.5(C_f H/B)^{1/2} \). In the reported experiment, the adverse water surface gradient leads to the formation of flow separation over the shallow point bar in the region of pronounced curvature decrease. In the region of pronounced curvature increase, it only leads to a considerable flow deceleration in the outer half of the cross section. This indicates the importance of the inherent inflow conditions, which are typically determined by upstream meander bends. The development of the point bar, the adverse water surface gradient, and the horizontal flow recirculation at the inner bank in the zone of pronounced curvature increase seem to be the result of a subtle feedback, whereby also mass redistribution by topographic steering and momentum redistribution by inertia, secondary flow, and turbulence are of importance.

[64] The curvature-induced secondary flow is restricted to the deepest outer part of the cross sections. Although it contributes significantly to momentum redistribution, its major role is with respect to the development of the bed topography. When the flow cannot follow pronounced increases in curvature, it collides at an oblique angle with the outer bank, thereby creating vertical downwelling velocities that are subsequently inwardly directed near the bed. The development of the pool scour can be attributed to these vertical velocities impinging of the bed, whereas the inward near-bed velocities can maintain transverse bed slopes that are steeper than the sediment’s angle of repose. Secondary flow is significantly stronger over the deep pool zones in regions with a quasi-bilinear bed topography that in zones with a quasi-linear one. A small and weak outer bank cell of secondary flow occurs at the outer bank near the water surface.

[65] Turbulence is not a dominant mechanism with respect to the development of the bed topography and the flow redistribution. The maximum turbulence activity is not found over the deepest parts of the cross sections, although the shallow point bars seem to be characterized by a reduced turbulence activity. Three processes were found to increase
considerably the turbulence activity: the flow that collides with the outer bank in the zone of pronounced curvature increase, the additional shear due to the secondary flow, and the additional horizontal shear due to transverse flow gradients, such as provoked by the horizontal flow recirculation zones.

[66] 3-D hydrodynamic models can successfully resolve all relevant hydrodynamic processes. The reported experiment identified the neglect of the effect of vertical velocities impinging on the bed and the accompanying increased turbulence activity on the sediment transport as the main knowledge gap in morphodynamic models. Moreover, the reported experimental results indicated ways to improve the parameterization of the curvature-induced secondary flow in depth-integrated 2-D or cross-sectional integrated 1-D models, which are commonly used in long-term and/or large-scale problems.

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