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ESEX Commentary

Form roughness and the absence of secondary flow in a large confluence–diffluence, Rio Paraná, Argentina

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Abstract

Confluence–diffluence units are key elements within many river networks, having a major impact upon the routing of flow and sediment, and hence upon channel change. Although much progress has been made in understanding river confluences, and increasing attention is being paid to bifurcations and the important role of bifurcation asymmetry, most studies have been conducted in laboratory flumes or within small rivers with width:depth (aspect) ratios less than 50. This paper presents results of a field-based study that details the bed morphology and 3D flow structure within a very large confluence–diffluence in the Río Paraná, Argentina, with a width:depth ratio of approximately 200. Flow within the confluence–diffluence is dominated largely by the bed roughness, in the form of sand dunes; coherent, channel-scale, secondary flow cells, that have been identified as important aspects of the flow field within smaller channels, and assumed to be present within large rivers, are generally absent in this reach. This finding has profound implications for flow mixing rates, sediment transport rates and pathways, and thus the interpretation of confluence–diffluence morphology and sedimentology. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: confluence; diffluence; large river; secondary flow; Paraná River

Introduction

The splitting and joining of individual channels is a common feature of many rivers, with ‘confluence–diffluence’ units comprising a key element within many braided, anastomosed and distributary systems. Research investigating the processes of flow at river channel confluences has highlighted the possible importance of secondary flows and their controls on channel geometry, channel dynamics, sediment transport and flow mixing (e.g. Ashmore *et al.*, 1992; Best, 1986, 1987, 1988; Best and Reid, 1984; Best and Roy, 1991; Biron *et al.*, 1993, 1996; Bradbrook *et al.*, 1998, 2000, 2001; Lane *et al.*, 2000; McLelland *et al.*, 1999; Mosley, 1976; Rhoads and Kenworthy, 1998; Rhoads and Sukhodolov, 2001). The classical model of flow at a confluence involves divergence between near-bed and near-surface flows as a result of the interaction between pressure gradient forcing and bed topographic steering. This may lead to the formation of twin, ‘back-to-back’, helical secondary flow cells, with a zone of downwelling over a central scour hole (see, e.g., Mosley, 1976; Best, 1986; Rhoads and Kenworthy, 1998). These features can be significantly modified by differences in bed elevation (discordance) between the two confluent channels (Best and Roy, 1991; Biron *et al.*, 1993) and the effects of shear between the confluent flows (Sukhodolov and Rhoads, 2001). The discordance in bed height between the combining flows is known to produce a zone of negative dynamic pressure in the lee of the shallower channel, resulting in downstream advection and upwelling of fluid from the deeper channel into the waters of the shallower channel. Shear-generated turbulence at the mixing interface of the flows may lead to the formation of two-dimensional vortices with near vertical axes that translate and merge as they are advected downstream, producing time-averaged secondary flow cells (Best and Roy, 1991; Lane *et al.*, 1999, 2000).

Much less is known about the nature of, and controls upon, flow structure at open-channel diffluences, although there is recent recognition of the important influence of diffluences in controlling the partitioning of flow and hence diffluence erosion/sedimentation (see, e.g., Pittaluga *et al.*, 2001; Frederici and Paola, 2003). There is currently an incomplete understanding of the confluence–diffluence unit, including the transition from confluence to diffluence, and the flow characteristics that are inherited at, and downstream of, these sites (see, e.g., Nicholas and Sambrook Smith, 1999; Richardson and Thorne, 2001). The morphology of the diffluence will control the character of flow in the downstream distributaries, and therefore play a critical role in the movement of sediment through the confluence–diffluence unit, governing the development and maintenance of mid-channel bars that are a central part of this unit in braided rivers.

Additionally, the vast majority of the past work outlined above has been conducted in laboratory flumes, within small rivers (depths less than 3 m and widths less than 100 m, with width:depth (aspect) ratios invariably less than 50), and in experimental models scaled on these dimensions. There is almost no knowledge of how the processes observed at these smaller sites scale to larger, wider, rivers (Yalin, 1992), and this represents a fundamental gap in current understanding of how continental-scale river systems function. Notable exceptions are the studies of Richardson *et al.* (1996), McLelland *et al.* (1999) and Richardson and Thorne (2001), who examined secondary flows at bifurcations and around a braid bar in the Jamuna River, Bangladesh. However, these studies did not concern flow within a connected confluence–diffluence unit, which is the focus of the research presented herein. The present paper therefore has two main aims: (1) to describe the bed morphology and related 3D flow structure within a very large confluence–diffluence unit in a river with a width:depth (aspect) ratio approaching 200 and (2) to compare the features of mean flow identified with studies from smaller river channels.

Field Site Methods

The study area is a confluence–diffluence unit in the Río Paraná, approximately 16 km north of the city of Corrientes, NE Argentina (Figure 1). The Paraná River is the sixth largest in the world when rated by water discharge, with a mean annual discharge of ~17 000 $m^3 s^{-1}$ (Orfeo and Stevaux, 2002), and draining an area of 2 600 000 km^2, mostly within Southern Brazil and Argentina. At the field site, the width of Río Paraná varies from about 600 m to 2·5 km and its mean depth varies from 5 to 16 m, leading to a width:depth (aspect) ratio that is normally greater than 100, and averages ~200 in the study reach. The confluence angle is approximately 35 degrees whilst the diffluence angle approaches 80 degrees (Figures 1 and 2). At the time of surveying in May 2004, the discharge of the full river section was ~12 000 $m^3 s^{-1}$.

The field methodology involved survey of the bed morphology using a RESON™ digital, dual frequency, single beam echo-sounder deployed from a small survey vessel. Data were acquired along 36 individual cross-stream traverses, orientated approximately perpendicular to the true channel banks and spaced an average of 150 m apart (Figure 2). These bed surveys were accompanied by simultaneous broadband acoustic Doppler current profiling (aDcp), using an RD Instruments™ RioGrande® 600 kHz aDcp. The aDcp has a four-beam (transducer) system, each with an orthogonal angle of 20 degrees in the vertical (RD Instruments, 2001), and emits acoustic pulses of energy that are backscattered by particles in the water column. The backscattered signal was split into equally spaced 0·5 m vertical bins, and the Doppler shift principle used to convert the change in phase within these bins into weighted averages of components of

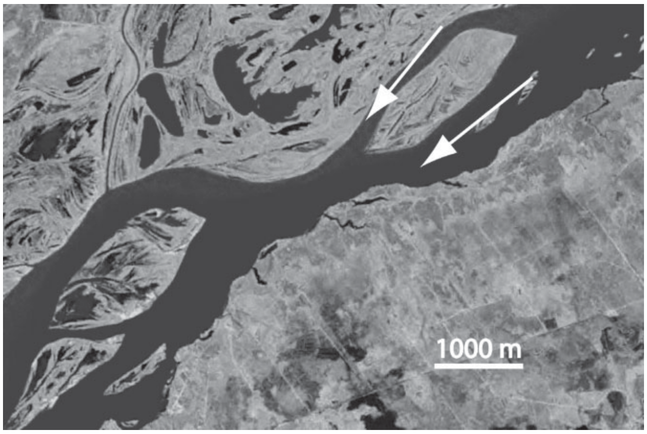

Figure 1. Remotely sensed image of the study reach (taken on 19 June 2000). White arrows indicate flow direction.

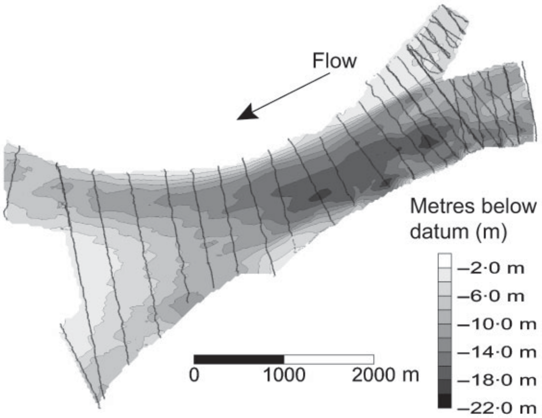

Figure 2. Bed morphology of the confluence–diffluence unit as measured by echo sounder survey and regular grid kriging. Black lines indicate the survey transects.

flow velocity within each depth range bin (RD Instruments, 2001). The aDcp was set to pulse (or 'ping') at ~5 Hz, although measurements were then averaged over five pulses to increase the signal:noise ratio to acceptable levels. Both the echo sounder and aDcp measurements were located using a Leica real-time kinematic (RTK) differential global positioning system (dGPS), which allowed precise differential positioning of the survey (to ±0·02 m and ±0·03 m in the horizontal and vertical dimensions respectively).

Since all flow velocities measured by the aDcp are relative to the aDcp, and hence the boat velocity, the measured aDcp velocities must also be corrected for this boat motion by removing the dGPS-derived boat velocity, thereby producing measurements of the flow velocity (cf. Yorke and Oberg, 2002; Muste *et al.*, 2004). Flow velocities for each position were finally converted from beam coordinates into an Earth referenced co-ordinate system, using the simultaneous measurements made by the aDcp's 'on-board' attitude and gyro sensor. In order to reduce potential aDcp-derived errors in flow velocity, a six profile (or ensemble) running average was used along each individual transect to determine the final 3D velocity profiles. Such spatial and temporal 'double' averaging across each section was used in an attempt to remove some of the higher frequency turbulence and dGPS positional variations from the final aDcp results. Although using only one transect per section, with such double averaging, may have some drawbacks with regards to reducing spatial resolution and obtaining fully time-averaged results (see, e.g., Muste *et al.*, 2004; Dinehart and Burau, 2005), Szupiany *et al.* (submitted) show that single transects with suitable averaging intervals are adequate to describe the flow through a section, including the larger scale secondary flow fields. The boat velocity and track position along each of the survey lines were monitored online during the survey and were held as constant as possible by the helmsman during surveying, with the boat velocity being approximately 1 m s^{-1}.

Results and Discussion

Bed morphology

The river bed surveys (Figure 2) show that the maximum depth at the confluence, and through the nodal area of maximum flow constriction, is up to 22 m, with a scour up to 12 m below upstream bed levels. The survey also reveals a pronounced bed discordance at the confluence with the true right, smaller, tributary being up to 6 metres shallower than the larger, deeper tributary. This morphology thus represents a discordant confluence with a mouth bar extending from the smaller tributary and dipping steeply, at up to 14 degrees, into the central scour (Figure 2). The thalweg from the true left upstream channel crosses the confluence–diffluence unit and extends further into the larger downstream diffluent (true right) channel, which is on the opposite side of the reach to the upstream confluence. Such asymmetry in the diffluence planform has also been noted by Zolezzi *et al.* (2006). Dune bedforms through the reach mostly scale, as expected, with the flow depth, with dunes up to 4·0 m high being present through the central scour, which is up to 22 m deep. These dunes reduce in amplitude through the diffluence but remain roughly scaled with the flow depth, with maximum heights approaching 2·2 m in a flow depth of ~7·5 m. There also appears to be no inlet step in bed height in either of the diffluent channels, as has been reported in some gravel-bed diffluences (Bolla Pittaluga *et al.*, 2003; Zolezzi *et al.*, 2006).

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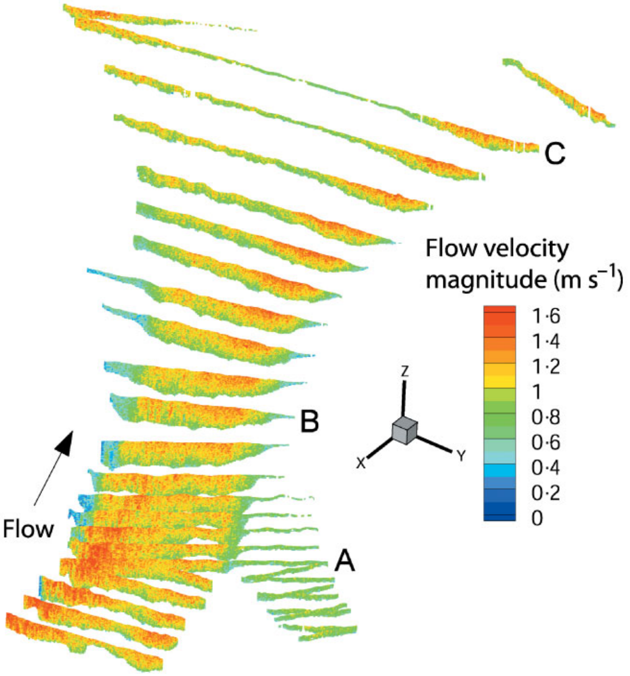

Figure 3. Perspective view of transects contoured by velocity magnitude through the confluence–diffluence unit. The black arrow indicates the general downstream flow direction. A, B and C denote the locations of sections shown in Figures 5 and 6.

Flow structure

At the flow stage investigated (12 000 $\mathrm{m^3\,s^{-1}}$), the true left channel was dominant in its discharge contribution to the confluence (Figure 3), with a discharge ratio (minor:major (right:left) confluent channels) of ~0·15. As the flows combined though the confluence, there was a slight overall acceleration of flow (Figure 3) produced by the reduced cross-sectional area of the downstream nodal constriction. As the deeper channel thalweg crossed the main channel downstream of the confluence, more of the flow discharge was routed into the true right diffluent channel. The diffluence discharge ratio (minor:major (left:right)) was approximately 0·6, thus showing a more equal distribution of flow between the two channels than at the upstream confluence.

The aDcp survey (Figure 4) shows the progressive division of flow upstream of the diffluence, as revealed by the horizontal directions of the flow velocity vectors along each of the surveyed transects from the nodal scour through to

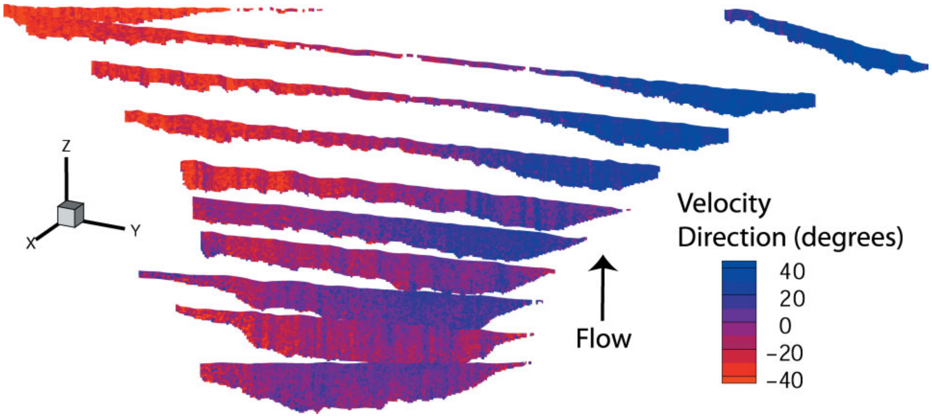

Figure 4. Perspective view of transects contoured by the direction of the horizontal velocity vector through the diffluence unit. Flow directions were determined as differences from the section-averaged mean flow direction within the central scour.

the bifurcation. The division of flow begins close to where the central scour begins to shallow (Figure 4), and well upstream of the downstream mid-channel bar. Since the division of flow begins before the actual diffluence, the position and orientation of the central scour would seem to both link and govern the confluence–diffluence unit, in particular with respect to the downstream division of flow. Given this finding, exploration of how bedload sediment is routed though these nodal scour holes would provide greater insight into the processes of flow division at diffluences more generally.

Secondary circulation

Secondary currents are generally classified into two main types: those generated by interactions between centrifugal and pressure gradient forces and those produced by the heterogeneity and anisotropy of turbulence. Two issues arise in defining such secondary currents: (1) definition of a suitable frame of reference (Rhoads and Kenworthy, 1999) and (2) correct interpretation of the differences between permanent and turbulence-driven secondary flows (see Lane *et al.*, 2000). In the present paper, the secondary flows along each aDcp cross-sectional transect were calculated using the Rozovskii (1957) method, which involves depth-integrating each velocity profile in the section to obtain the depth-averaged velocity vector. The differences from this depth-averaged velocity for all measurements within the profile are then computed to provide an indication of secondary motions in the plane perpendicular to the average velocity direction in the profile. Although the Rozovskii method for determination of secondary currents is problematic (cf. Rhoads and Kenworthy, 1999; Lane *et al.*, 1999, 2000), it was chosen herein since, if there is any type of secondary circulation present, this rotation method will identify it.

Figure 5 shows the calculated secondary flow vectors superimposed on the downstream flow contours at three sections through the confluence–diffluence unit. Section A is close to the confluence zone, showing higher downstream velocity within the true left channel and an area of lower velocity flow in a stagnation zone between the two flows. The vectors show no real pattern of secondary flow, with no helical circulation apparent, as has been reported from smaller channel confluences (see, e.g., Ashmore *et al.*, 1992; Rhoads and Kenworthy, 1998), some laboratory experiments (see, e.g., Mosley, 1976) and numerical simulations (see, e.g., Bradbrook *et al.*, 2000, 2001). Similarly, there appears to be no clear influence of bed discordance on secondary flow generation through this zone. At section B within the zone of the central scour, there is some evidence of a weak, but definable, channel-scale pattern of secondary flow, with flow generally moving towards the right bank at the bed and towards the left bank at the surface, thus defining a possible single cell of secondary circulation. However, it is again clear that no classical 'back-to-back' helical circulation is apparent, as found in studies from smaller confluences. At the downstream flow divergence at section C, again no channel-scale pattern of secondary flow is present, with a general scattering of secondary flow velocities throughout the section.

The absence of secondary circulation may appear surprising: the channels are curved with significant convergence and divergence, and it may be expected that flow direction at the surface would differ from that at the bed, as the latter is more strongly steered by bed topography (see, e.g., Rhoads and Kenworthy, 1998). The fact that there is a near-uniform flow direction throughout the flow depth (Figure 4) suggests that the steering of flow at the bed is readily transmitted throughout the flow depth, preventing channel-scale differences between near-bed and near-surface flow directions. Figure 6 shows the vertical velocities in the left channel at the diffluence section (section C in Figure 5) and indicates a strong correlation between zones of downwelling flow and the positions of the dune lee sides, with fluid upwelling being associated with the dune stoss sides. These dunes appear to scale approximately with the flow depth, with dune heights approaching 2·2 m, similar to those found in past studies (see Bridge, 2003; Best, 2005; Parsons *et al.*, 2005). Thus, although the flow depth in these large rivers is obviously greater than in smaller rivers, which should encourage greater divergence between near-bed and near-surface flows, the fact that the dune roughness scales with the flow depth allows the effects of the bed topography to be transmitted through the flow depth, therefore assisting with the steering of flow throughout the vertical. Thus, a preliminary conclusion is that the principal control on the potential absence of secondary circulation in large rivers, and why there is none in this confluence–diffluence unit, appears to be the extent to which form roughness is present that is capable of transmitting near-bed steering of flow throughout the flow depth. The potential role of bed roughness in negating the production of secondary flows was also invoked by McLelland *et al.* (1999) in their study of flow around a large braid bar. The question thus arises as to why this may not also be the case in smaller rivers, since dune height scales with flow depth irrespective of channel size. Two factors may be important. First, the lower width:depth (aspect) ratios in smaller rivers may produce channels that are more likely to develop channel-wide secondary flows (Nezu and Nakagawa, 1993; Yalin, 1992; McLelland *et al.*, 1999). Second, the effects of hysteresis in the response of dunes to changing flow stage may be more significant in larger channels, where the sediment volumes within the bedforms are larger, and hence their migration rates will be smaller. For instance, ten Brinke *et al.* (1999) and Julien *et al.* (2002) show that dune height may be larger after, rather

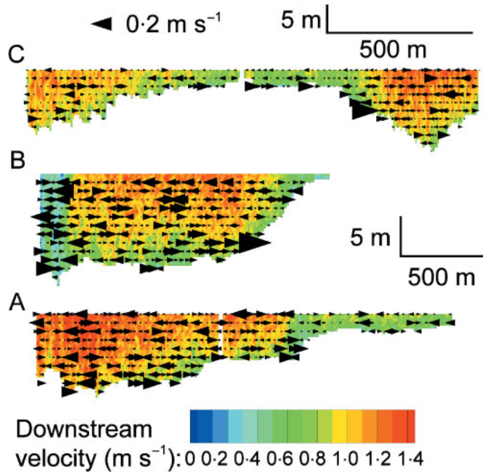

Figure 5. Secondary velocity vectors, derived using the Rozovskii method, and contours of downstream velocity for three sections through the confluence–diffluence. Flow is into the page. See Figure 3 for positions of sections A–C.

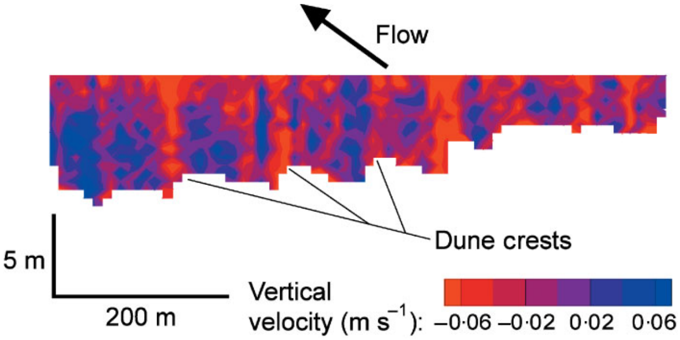

Figure 6. Contours of vertical velocity for the left branch of the diffluence at section C (see Figure 5 for location). Positive and negative values indicate flow away from and towards the bed respectively, and are seen to correspond to the position of the dune stoss and lee sides respectively. Downstream flow is obliquely to the left and into the page.

than before, the peak discharge and thus such hysteresis in dune response to changing flow stage may yield dunes that have a larger effect throughout the flow depth at lower flow stages. Both of these factors suggest the need for studies such as that reported herein to be conducted at the highest flow stages. At high flow stages, width:depth ratios are likely to decline (Yalin, 1992), the momentum ratios at the confluence may alter and the influence of form drag might diminish (Julien *et al.*, 2002). The findings of the present study, that such large confluence–diffluence units may not possess channel-scale secondary flow cells, may have profound implications for the rate and location of fluid mixing as well as the paths of sediment transport in such large rivers.

Conclusions

The findings presented herein indicate that caution must be applied in assuming that processes observed in small channels can be scaled up linearly with increasing channel size. Study of bed morphology and flow within a large confluence–diffluence unit, Paraná River, Argentina, reveals the presence of a large central scour between a discordant confluence and downstream diffluence. The central scour and its position and orientation appear to play a crucial role in governing flow division at the downstream diffluence. The flow field within the confluence–diffluence unit is dominated by simple convergence and divergence through this nodal area, and at this flow stage and discharge ratio no coherent, channel-scale secondary flow cells appear to exist at the confluence as has been proposed from smaller rivers. Although there is a suggestion of one, full-width, cell over the central scour, there is no evidence of coherent

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secondary cells as flow shallows at the diffluence. It is evident that at these flow levels in this very wide river, flow mixing and secondary flows are almost completely dominated by bedform roughness. As a result, the coherent secondary flow cells that have been identified in smaller channels, and often assumed to be present within large rivers, are generally absent through this large confluence–diffluence unit. These results suggest the need for a re-thinking of how river processes scale with channel size, including investigation of the relative form roughness, the width:depth (aspect) ratio of the channels and the influence of form hysteresis on flow structure. It is clear that there is a pressing need to repeat these measurements at both different flow stages and flow discharge ratios, to investigate under what conditions, if any, the development of secondary cells may become apparent.

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References

Ashmore PE, Ferguson RI, Prestegaard KL, Ashworth PJ, Paola C. 1992. Secondary flow in anabranch confluences of a braided, gravel-bed stream. *Earth Surface Processes and Landforms* **17**: 299–311.

Best J. 2005. The fluid dynamics of river dunes: A review and some future research directions. *Journal of Geophysical Research* **110**: F04S02. DOI: 10.1029/2004JF000218.

Best JL. 1986. The morphology of river channel confluences. *Progress in Physical Geography* **10**: 157–174.

Best JL. 1987. Flow dynamics at river channel confluences: implications for sediment transport and bed morphology. In *Recent Developments in Fluvial Sedimentology*, SEPM Special Publication 39, Etheridge FG, Flores RM, Harvey MD (eds). SEPM: Tulsa, OK, U.S.A.; 27–35.

Best JL. 1988. Sediment transport and bed morphology at river channel confluences. *Sedimentology*, **35**: 481–498.

Best JL, Reid I. 1984. Separation zone at open-channel junctions. *Journal of Hydraulic Engineering* **110**: 1588–1594.

Best JL, Roy AG. 1991. Mixing layer distortion at a confluence of unequal depth. *Nature* **350**: 411–413.

Biron P, Roy AG, Best JL. 1996. Turbulent flow structure at concordant and discordant open-channel confluences. *Experiments in Fluids* **21**: 437–446.

Biron P, Roy AG, Best JL, Boyer CJ. 1993. Bed morphology and sedimentology at the confluence of unequal depth channels. *Geomorphology* **8**: 115–129.

Bolla Pittaluga M, Repetto R, Tubino M. 2003. Channel bifurcation in braided rivers: equilibrium configurations and stability. *Water Resources Research* **39**: 1046–1059.

Bradbrook KF, Biron PM, Lane SN, Richards KS, Roy AG. 1998. Investigation of controls on secondary circulation in a simple confluence geometry using a three-dimensional numerical model. *Hydrological Processes* **12**: 1371–1396.

Bradbrook KF, Lane SN, Richards KS. 2000. Numerical simulation of three-dimensional, time-averaged flow structure at river channel confluences. *Water Resources Research* **36**: 2731–2746.

Bradbrook KF, Lane SN, Richards KS, Biron PM, Roy AG. 2001. Role of bed discordance at asymmetrical river confluences. *Journal of Hydraulic Engineering* **127**: 351–368.

Bridge JS. 2003. *Rivers and Floodplains*. Blackwell: Oxford.

Dinehart RL, Burau JR. 2005. Averaged indicators of secondary flow in repeated acoustic Doppler current profiler crossings of bends, *Water Resources Research*, **41**. DOI: 10.1029/2005WR004050

Federici B, Paola C. 2003. Dynamics of channel bifurcations in noncohesive sediments, *Water Resources Research*, **39**. DOI: 10.1029/2002WR001434

Julien PY, Klaassen GJ, ten Brinke WBM, Wilbers AWE. 2002. Case study: bed resistance of Rhine River during 1988 flood, *Journal of Hydraulic Engineering* **128**: 1042–1050.

Lane SN, Bradbrook KF, Richards KS, Biron PM, Roy AG. 1999. Time-averaged flow structure in the central region of a stream confluence: a discussion. *Earth Surface Processes and Landforms* **24**: 361–367.

Lane SN, Bradbrook KF, Richards KS, Biron PM, Roy AG. 2000. Secondary circulation cells in river channel confluences: measurement artefacts or coherent flow structures? *Hydrological Processes* **14**: 2047–2071.

McLelland SJ, Ashworth PJ, Best JL. 1999. Flow structure and transport of sand-grade suspended sediment around an evolving braid bar, Jamuna River, Bangladesh. In *Fluvial Sedimentology VI*, International Association of Sedimentologists Special Publication 28, Smith, N.D., Rogers, J. (eds). Blackwell: Oxford; 43–57.

Mosley MP. 1976. An experimental study of channel confluences. *Journal of Geology* **84**: 535–562.

Muste M, Yu K, Spasojevic M. 2004. Practical aspects of ADCP data use for quantification of mean river flow characteristics; part I: moving-vessel measurements. *Flow Measurement and Instrumentation* **15**: 1–16.

Nezu I, Nakagawa H. 1993. *Turbulence in Open-Channel Flows*. Balkema: Rotterdam.

Nicholas AP, Sambrook Smith GH. 1999. Numerical simulation of three-dimensional flow hydraulics in a braided channel. *Hydrological Processes* **13**: 913–929.

Orfeo O, Stevaux J. 2002. Hydraulic and morphologic characteristics of middle and upper reaches of the Paraná River (Argentina and Brazil). *Geomorphology* **44**: 309–322.

Parsons DR, Best JL, Orfeo O, Hardy RJ, Kostaschuk R, Lane SN. 2005. The morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: results from simultaneous multibeam echo sounding and acoustic Doppler current profiling. *Journal of Geophysical Research* **110**: F04S03. DOI: 10.1029/2004JF000231.

Pittaluga MB, Federici B, Repetto R, Paola C, Seminara G, Tubino M. 2001. The morphodynamics of braiding rivers: experimental and theoretical results on unit processes. In *Gravel-Bed Rivers V*, Mosley MP (ed.). New Zealand Hydrological Society: Wellington, NZ; 143–180.

RD Instruments. 2001. *Acoustic Doppler Current Profilers, Principles of Operation: a Practical Primer*, user manual report. San Diego.

Rhoads BL, Kenworthy ST. 1999. On secondary circulation, helical motion, and Rozovskii-based analysis of time-averaged 2-D velocity fields at confluences. *Earth Surface Processes and Landforms* **24**: 369–375.

Rhoads BL, Kenworthy ST. 1998. Time-averaged flow structure in the central region of a stream confluence. *Earth Surface Processes and Landforms* **23**: 171–191.

Rhoads BL, Sukhodolov AN. 2001. Field investigation of three-dimensional flow structure at stream confluences: 1. Thermal mixing and time-averaged velocities. *Water Resources Research* **37**: 2393–2410.

Richardson WR, Thorne CR. 2001. Multiple thread flow and channel bifurcation in a braided river: Brahmaputra-Jamuna River, Bangladesh. *Geomorphology* **38**: 185–196.

Richardson WRR, Thorne CR, Mahmood S. 1996. Secondary flow and channel changes around a bar in the Brahmaputra River, Bangladesh. *Coherent Flow Structures in Open Channels*, Ashworth PJ, Bennett SJ, Best JL, McLelland SJ. (eds). Wiley: Chichester; 459–490.

Rozovskii IL. 1957. *Flow of Water in Bends of Open Channels*. Academy of Sciences of the Ukrainian SSR: Kiev (translated from Russian by the Israel Program for Scientific Translations, Jerusalem, 1961).

Sukhodolov AN, Rhoads BL. 2001. Field investigation of three-dimensional flow structure at stream confluences: 2. Turbulence. *Water Resources Research* **37**: 2411–2424.

Szupiany RN, Amsler ML, Best JL, Parsons DR. A comparison of fixed- and moving-vessel flow measurements with an acoustic Doppler profiler (aDp) in a large river. *Journal of Hydraulic Engineering* submitted.

ten Brinke WBM, Wilbers AWE, Wesseling C. 1999. Dune growth, decay and migration rates during a large-magnitude flood at a sand and mixed sand–gravel bed in the Dutch Rhine river system, In *Fluvial Sedimentology VI*, Special Publication of the International Association of Sedimentologists 28, Smith ND, Rogers J. (eds). Blackwell: Oxford; 15–32.

Yalin MS. 1992. *River Mechanics*. Pergamon: Oxford.

Yorke TH, Oberg KA. 2002. Measuring river velocity and discharge with acoustic Doppler profiler. *Flow Measurement and Instrumentation* **13**: 191–195.

Zolezzi G, Bertoldi W, Turbino M. 2006. Morphological analysis and prediction of river bifurcations, In *Braided Rivers: Process, Deposits, Ecology, and Management*, Special Publication of the International Association of Sedimentologists 36, Sambrook Smith GH, Best, JL, Bristow CS, Petts GE. (eds). Blackwell: Oxford; 233–256.