Hydro-morphodynamic evolution in a 90° movable bed discordant confluence with low discharge ratio

Sebastián Guillén-Ludeña,^{1,2*} Mário J. Franca,¹ António H. Cardoso² and Anton J. Schleiss¹

¹ Laboratory of Hydraulic Constructions (LCH), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

² Instituto Superior Técnico (IST), Universidade de Lisboa (UL), Portugal

Received 4 February 2014; Revised 3 June 2015; Accepted 4 June 2015

*Correspondence to: Sebastián Guillén-Ludeña, Laboratory of Hydraulic Constructions (LCH), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. E-mail: sebastian.ludena@epfl.ch

ESPL

Earth Surface Processes and Landforms

ABSTRACT: Confluences with low discharge and momentum ratios, where narrow steep tributaries with high sediment load join a wide low-gradient main channel that provides the main discharge, are often observed in high mountain regions such as in the upper-Rhone river catchment in Switzerland. Few existing studies have examined the hydro-morphodynamics of this type of river confluence while considering sediment discharge in both confluent channels. This paper presents the evolution of the bed morphology and hydrodynamics as observed in an experimental facility with a movable bed. For that purpose, one experiment was carried out in a laboratory confluence with low discharge and momentum ratios, where constant sediment rates were supplied to both flumes. During the experiment, bed topography and water surface elevations were systematically recorded. When the bed topography reached a steady state (so-called equilibrium) and the outgoing sediment rate approximated the incoming rate, flow velocity was measured at 12 different points distributed throughout the confluence, and the grain size distribution of the bed surface was analyzed. Typical morphodynamic features of discordant confluences such as a bank-attached bar and a flow deflection zone are identified in this study. Nevertheless, the presence of a marked scour hole in the discordant confluence and distinct flow regimes for the tributary and main channel, differ from results obtained in previous studies. Strong acceleration of the flow along the outer bank of the main channel is responsible for the scour hole. This erosion is facilitated by the sediment discharge into the confluence from the main channel which inhibits bed armoring in this region. The supercritical flow regime observed in the tributary is the hydrodynamic response to the imposed sediment rate in the tributary. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: river confluences; river morphology; sediment transport; open channel junctions

Introduction

River confluences are characterized by complex morphodynamic patterns, where flow dynamics and bed morphology closely interact to accommodate abrupt changes in flow and sediment transport. From an environmental standpoint, confluences are considered hot spots within the fluvial network (Benda *et al.*, 2004). They enhance the river ecosystem by providing ecological connectivity and heterogeneity in flow, water quality and bed substrate (Leite Ribeiro *et al.*, 2015). Confluences also play a major role in the variability of fluvial transport at the network scale, and it is through the confluence of tributaries with main rivers that flow and sediments are provided to the latter.

Although flow dynamics of confluences have been widely investigated (Mosley, 1976; Best, 1987; Fujita and Komura, 1989; Biron *et al.*, 1996b, 2002; Rhoads and Kenworthy, 1995; Bradbrook *et al.*, 1998, 2001; Weber *et al.*, 2001; Parsons *et al.*, 2007, among others), the interaction between flow dynamics and bed morphology is not yet completely understood because bed morphology in river confluences is characterized by complex erosion and deposition processes.

These processes are controlled by a wide range of factors such as confluence planform, varying slope of the confluent channels, confluence angle, bed discordance, discharge and momentum flux ratios, bed material caliber and sediment supply (Mosley, 1976; Best, 1987, 1988; Best and Rhoads, 2008; Leite Ribeiro *et al.*, 2012a; Leite Ribeiro *et al.*, 2012b).

Among the most notable studies concerning confluence morphodynamics are those of Best (1988), Best and Rhoads (2008), and Leite Ribeiro *et al.* (2012a), which describe the main morphological features using conceptual models based on experimental tests, and those of Biron *et al.* (1993), Rhoads and Kenworthy (1995, 1998), Leclair and Roy (1997), Rhoads and Sukhodolov (2001), Biron *et al.* (2002), Boyer *et al.* (2006), and Rhoads *et al.* (2009), which were carried out on natural confluences.

Best and Rhoads (2008) built on Best's (1988) morphological model to describe the bed morphology of river confluences through five zones: (i) scour hole linked to increased velocities and turbulence intensity within the junction and to the transport pathways of sediment; (ii) tributary-mouth bars that form at the mouth of one or both channels; (iii) a mid-channel bar within the post-confluence channel; (iv) bank-attached lateral

bar in the post-confluence channel, corresponding to a flow separation or recirculation zone; and (v) zone of sediment deposition at the upstream corner of the confluence, associated with the flow stagnation zone.

Leite Ribeiro *et al.* (2012a), inspired by the Upper-Rhone river confluences in Switzerland, focused on systems characterized by low discharge and momentum ratios, defined as $Q_r = Q_t / Q_m$ and $M_r = (\rho QU)_t / (\rho QU)_m$, respectively. Here, Q denotes the flow discharge upstream of the confluence, M refers to the momentum flux, ρ is the water density, U is the mean flow velocity upstream of the confluence, and the sub-indexes r , t , and m refer to ratio, tributary and main channel, respectively. In this type of confluence, the main stream provides the dominant discharge and the sediments are predominantly and abundantly supplied by the tributaries, whose bed level is higher than the bed of the main channel (bed discordance). Tributaries are narrower but steeper than the main stream, and such steep slopes and sediment loads often result in supercritical flows in the tributaries. The sediment provided by the tributaries is coarser than that supplied by the main stream and consists of poorly sorted gravel with high gradation coefficients. Aside from the upper-Rhone river basin, these characteristics are typically observed in other high-mountain streams such as those studied by Miller (1958) at the Sangre de Cristo Range in the Rocky Mountains (USA).

To examine such confluences, Leite Ribeiro *et al.* (2012a, 2012b) carried out experiments with low discharge and momentum ratios ($Q_r = 0.11$ and $M_r = 0.22$) in a laboratory confluence where sediment was only supplied to the tributary. The lack of sediment discharge in the main channel induced an artificial bed armoring that may not occur in nature.

Based on these experiments, Leite Ribeiro *et al.* (2012a) described the bed morphology of the upper-Rhone river confluences through five morphological features. These features are: (i) bed discordance, which corresponds to the difference between tributary and main channel bed levels; (ii) bank-attached bar, which forms along the inner bank downstream of the confluence; (iii) avalanche faces of the bank-attached bar, which constitute the coarse sediment corridor; (iv) fine sediment corridor formed along the crest of the bank-attached bar; and (v) a zone of minor scour along the outer bank, associated with the zone of maximum flow velocity.

Bed discordance was identified by Kennedy (1984) as a common feature in natural confluences. This discordance affects the flow, sediment transport and bed morphology as confirmed by laboratory tests (Biron *et al.*, 1996a; Leite Ribeiro *et al.*, 2012a; Leite Ribeiro *et al.*, 2012b), by field measurements (Biron *et al.*, 1993; Boyer *et al.*, 2006), and through numerical modeling (Bradbrook *et al.*, 2001; Biron *et al.*, 2004). Biron *et al.* (1993) associated the absence of a marked scour hole and the absence of a recirculation zone at the Bayonne–Berthier confluence in Canada with bed discordance. Subsequently, Biron *et al.* (1996a) documented that discordance reduces deflection of the near-bed flow and enhances upwelling of flow at the downstream junction corner, which in turn contributes to the absence of flow recirculation. Boyer *et al.* (2006) highlighted the role of the shear layer in discordant confluences, which was identified as responsible for the variability of flow in the confluence and the spatial distribution of sediment transport rates. Leite Ribeiro *et al.* (2012a, 2012b) suggested that bed discordance originates from the distinct flow regimes and sediment transport rates in both channels.

Apart from the work by Leite Ribeiro *et al.* (2012a), in which the sediment discharge in the main channel was neglected, few experimental studies have examined mobile bed conditions at discordant confluences with low discharge and momentum ratios, especially where steep lateral tributaries with abundant

and coarse sediment load join nearly flat fine grained main channels at high junction angles.

With the aim of widening the existing knowledge of the hydro-morpho-sedimentary processes found in river confluences, an experimental study was carried out in a laboratory confluence with low discharge and momentum ratios ($Q_r = 0.11$ and $M_r = 0.16$), where a narrow steep tributary intersects a wider nearly flat main channel at a right angle. To build on the work by Leite Ribeiro *et al.* (2012a) and to better approximate conditions observed in nature, sediments were supplied to both the tributary and the main channel during the experiment. These experimental conditions correspond to the predominant key features in the river confluences found in the upper-Rhone valley. Systematic bed topography and water surface surveys illustrate the evolution of the bed morphology and hydrodynamics during the experiment. To characterize the main hydrodynamic features, the flow velocity was measured at 12 different points distributed throughout the confluence. Sediment patterns and bed material texture at equilibrium were also analyzed. The results of this study are compared with previous studies concerning the hydraulics, morphology and sedimentology in river confluences.

Experimental Set-Up and Procedure

Experimental confluence

The laboratory confluence consisted of an 8.5 m long and 0.5 m wide rectangular glass flume corresponding to the main channel, and a tributary formed by a 4.9 m long and 0.15 m wide rectangular PVC-channel (Figure 1). Both channels joined at 3.60 m downstream of the main channel inlet at an angle of 90°. The results in this paper are referred to the reference axes X, Y and Z as indicated in Figure 1.

Experimental parameters

The adopted discharge ratio ($Q_r = 0.11$) is representative of the upper-Rhone river confluences, where the main channel provides the dominant flow. To ensure adequate sediment transport capacity along the main channel, the adopted total discharge (Q_{p-c} post-confluence) was set at 30 L/s in this study.

Two different types of sediments were independently supplied during the experiment at the inlet of the main channel and tributary. For both sediment mixtures, the dimensionless

Figure 1. Plan view of the laboratory confluence. The gray-shaded area represents the measurement domain.

grain size distribution with respect to the mean diameter was representative of the Upper-Rhone river confluences (Leite Ribeiro, 2011). For the tributary, the sediments consisted of a poorly sorted mixture, where a 0.1–4.0 mm sand-gravel mixture constituted 80% of the sediment and 4.0–8.0 mm gravel constituted 20%. For the main channel, the sediments were composed of the 0.1–4.0 mm sand-gravel mixture supplied to the tributary, which means that the coarser part of the tributary mixture (4.0–8.0 mm gravel) was removed to reproduce the grain size distribution (GSD) relationship between the main channel and the tributary observed at the upper-Rhone river in Switzerland. The gradation coefficient σ , defined as $\sigma = 0.5 \times (d_{84}/d_{50} + d_{50}/d_{16})$, was 4.51 for the tributary and 3.15 for the main channel. The main characteristics of the supplied sediments are detailed in Table I, and the GSDs are depicted in Figure 2.

The sediment discharges for the tributary (Q_{st}) and main channel (Q_{sm}) were defined by assuming, as an initial hypothesis, that the longitudinal bed slope and GSDs were in the range of those observed in the upper-Rhone river confluences. Hence, the hypothetical bed slopes under equilibrium conditions were assumed to be approximately 1.0% for the tributary and within the range of 0.3–0.4% for the main channel. By assuming uniform flow in both channels for such slopes and for the defined discharge ratio, the sediment discharges for both channels were estimated using the sediment transport formula developed for gravel bed rivers by Smart (1984). Based on this estimation, the sediment transport rates supplied to the main channel (Q_{sm}) were fixed at 0.3 kg min^{-1} and 0.5 kg min^{-1} for the tributary (Q_{st}).

Procedure and measurements

Before the experiment, the initial movable bed was prepared using the same sediment mixtures that subsequently were

Table I. Main characteristics of the supplied sediment

Channel	ρ_s [kg/m ³]	σ [-]	d_{30} [mm]	d_{50} [mm]	d_{65} [mm]	d_{90} [mm]
Main channel	2650	3.15	0.4	0.8	1.4	3.0
Tributary	2650	4.51	0.4	0.8	2.3	5.7

ρ_s is the grain density, σ is the gradation coefficient, and d_x are the characteristic grain diameters of the mixtures, where the sub-index x represents the percentage of sediment mixture by weight, which have smaller diameters.

Figure 2. Grain size distributions (GSD) for sediments supplied to the tributary and main channel.

supplied to each channel. To accelerate the bed topography evolution in the tributary, a small bed discordance of approximately 0.03 m was imposed at the tributary mouth, together with a bed slope of 0.5%. This initial bed morphology did not affect the final topography because, as verified later, the initial slope and the initial discordance were smaller than those reached at equilibrium.

Once the channel beds were prepared, the model was slowly filled with water, and both bed topographies (for the tributary and for the main channel) were recorded before the beginning of the experiment ($t = 0 \text{ h}$). Later, topographic surveys were taken after 1 h ($t = 1 \text{ h}$), at seven hours ($t = 7 \text{ h}$), and at equilibrium, which was reached after 14 hours ($t = 14 \text{ h}$).

Bed topography measurements, made with a mini-echo-sounder with $\pm 1 \text{ mm}$ accuracy, consisted of nine longitudinal profiles laterally spaced along the main channel by $\Delta Y = 0.05 \text{ m}$ ($Y = 0.05$ to 0.45 m) with a spatial resolution of $\Delta X = 0.01 \text{ m}$, and one profile along the tributary axis ($X = 0.60 \text{ m}$) with a spatial resolution of $\Delta Y = 0.05 \text{ m}$.

Because the mini-echo-sounder is an intrusive device that needs to be slightly submerged for measuring, to perform topography surveys the downstream tailgate was raised to increase the water level and to stop the sediment transport by decreasing the flow velocity. Tributary and main channel discharges were reduced and the sediment feeders were switched off. Under these conditions, bed topography was measured. To restart the model, the discharges were adjusted according to the set values, the downstream water level was established, and the sediment feeders were turned on. The stop and re-start processes were verified to not affect the bed topography.

Water level was measured after 1 h and at equilibrium by an ultrasonic limnimeter with $\pm 1 \text{ mm}$ accuracy. For these measurements, three longitudinal profiles located at the outer bank ($Y = 0.05 \text{ m}$), at the main channel axis ($Y = 0.25 \text{ m}$) and at the inner bank ($Y = 0.45 \text{ m}$) were recorded along the main channel, and one profile was recorded along the tributary axis ($X = 0.60 \text{ m}$).

At the end of the experiment, the installation was slowly emptied by a bottom outlet to keep the bed topography intact. Four sediment samples were taken to analyze the GSD of the bed surface at different places within the confluence. The samples were obtained using adhesive paper. These samples were weighed and sieved to obtain the GSDs.

At equilibrium, flow velocity was measured at 12 points distributed throughout the confluence (V_1 to V_{12} in Figure 3). The measurements were taken at half water depth by means of a micro-propeller Schiltknecht with $\pm 0.01 \text{ m/s}$ accuracy.

To determine when the experiment reached equilibrium, the sediment transport at the downstream end was evaluated by weighing the outgoing sediment after 1, 5, 10, 11, 12, 14 and 15 h. In addition, equilibrium was also checked by measuring

Figure 3. Positions of the velocity measurements. (a) plan view; (b) coordinates.

the channel bed level evolution at five different positions (P_1 to P_5 in Figure 4) after 1, 7, 10, 12, 13, 14 and 15 h.

When the outgoing sediment discharge was equal to or larger than 90% of the incoming sediment discharge (cf. Figure 5) and the rate of change of the bed elevation evaluated by $r(t_i) = 100 [Z(t_i) - Z(t_{i-1})] / Z(t_{i-1})$ was less than 2% at each of the five control points (cf. Figure 6), the experiment was considered to be at equilibrium and was stopped. In this equation $Z(t_i)$ denotes the bed topography elevation measured at $t = t_i$, and $Z(t_{i-1})$ is the bed topography elevation measured previously, at $t = t_{i-1}$.

Figure 4. Position of control points used to verify the topography evolution.

Figure 5. Ratio of outgoing/incoming sediment during the experiment. Dashed line represents the equilibrium threshold.

Figure 6. Bed level evolution at the control points (cf. Figure 4). Dash-dotted line represents the equilibrium threshold.

Results

Bed morphology and water surface evolution

The bed morphology and the water surface evolved from the beginning of the experiment until reaching equilibrium. At the beginning ($t = 0$ h), the bed was fairly horizontal in the main channel, whereas the tributary bed had a slight slope and a small step at the mouth (see Figures 7(a) and 8).

After one hour ($t = 1$ h), a scour hole formed at the tributary mouth while the eroded material deposited downstream at about $X = 2.50$ m (cf. Figures 7(b) and 8(a)). The maximum depth of the scour hole was $Z = -0.04$ m located at $X = 0.70$ m, $Y = 0.45$ m.

In the tributary, during the first hour, the supplied sediment formed a wedge that gradually progressed downstream (cf. Figures 7(b) and 8(c)), raising the level of the bed. At $t = 1$ h, the front of this wedge was located at $Y \sim 1.00$ m (cf. Figures 7(b) and 8(c)). The position of this wedge at $t = 1$ h reveals that the scour hole was excavated in the initial bed of the main channel.

The water surface gradient at $t = 1$ h was relatively mild in both channels (see Figure 8). In the main channel and at the inner bank, an abrupt increase in water-surface elevation related to the tributary inflow was measured at the confluence (cf. Figure 8(a)). In the tributary, the water level profile rose from $Y = 2.00$ m to $Y = 0.50$ m, which revealed the presence of an M1-type backwater curve (Chow, 1959) imposed by the elevated water level in the main channel (see Figure 8(c)).

After 7 hours ($t = 7$ h), the tributary attained a quasi-equilibrium bed morphology consisting of a steep bed slope, a raised bed elevation and a well-developed bed discordance with the main channel (see Figures 7(c) and 8(c)).

At the inner bank of the main channel (cf. Figure 8(a)), downstream of the confluence, the sediment coming from the tributary in the form of a migrating wedge filled the initial scour hole and created a bar, commonly termed a bank-attached bar (Best and Rhoads, 2008). In addition, a new scour hole extended from the tributary mouth to the outer bank of the main channel, flanking the bar. The alignment of the new scour bisected the junction angle until reaching the outer bank, at which point it paralleled the orientation of the outer bank (cf. Figures 7(c) and 8(b)).

From seven hours ($t = 7$ h) until reaching equilibrium ($t = 14$ h), the bed morphology in both channels experienced only minor changes, including a small increase in the height of the bank-attached bar (cf. Figure 8).

At equilibrium, the tributary had a nearly constant longitudinal slope of approximately 1.6% (Figure 8(c) and detail in Figure 9). The transition between the tributary and main channel was characterized by a steep wedge front or avalanche slope, with an average inclination of approximately 44% that partially penetrated into the main channel (cf. Figure 9). This morphological feature is herein considered as the inception of a tributary mouth-bar, which is commonly observed in river confluences (Best and Rhoads, 2008).

At the inner bank of the main channel ($Y = 0.45$ m, Figure 8(a) and detail in Figure 11(a)) the bed remained nearly flat until reaching the confluence ($X \approx 0.53$ m), where the inception of the scour hole was observed at the tributary mouth as a small depression (Figure 11(a)). Downstream of the confluence, the bank-attached bar rapidly reached its maximum level ($Z = 0.108$ m at $X = 1.00$ m) through a steep slope (approximately 30%). Downstream of this maximum, the bar height gradually decreased through a slope of approximately 3%. The steeper slope of the upstream face of the bank-attached bar is the result of the strong upwelling flow observed at the downstream junction corner (cf. Figure 12).

Figure 7. Bed topography, with bed-level contours spaced $\Delta Z = 1$ cm: (a) at the initial state ($t = 0$ h); (b) after one hour ($t = 1$ h); (c) after 7 hours ($t = 7$ h); and (d) at equilibrium ($t = 14$ h).

Figure 8. Longitudinal profiles of bed level and water surface: (a) at the inner bank of the main channel; (b) at the outer bank of the main channel; and (c) at the tributary axis.

At the outer bank ($Y = 0.05$ m, Figure 11(b)), upstream of the confluence, the bed level started to decrease progressively until reaching a minimum at $X \approx 1.20$ m. Downstream of this low point, the bed level increased, until converging to the same

level as upstream of the confluence (cf. Figure 8(c) and detail in Figure 11(b)).

The water level profile measured in the tributary at equilibrium (see Figure 9) showed a steep and nearly constant slope

Figure 9. Bed level and water surface profiles along the tributary axis at equilibrium ($t = 14$ h).

until reaching the confluence. At the mouth, an abrupt increase in water surface elevation revealed the presence of a hydraulic jump. Moreover, in the tributary, the water level profile was parallel to the bed, indicating that the flow was nearly uniform.

In the main channel, at the inner bank ($Y = 0.45$ m) upstream of the confluence ($0.00 < X < 0.60$ m), the water level profile (Figure 11(a)) exhibited an upstream-oriented slope. At a distance of $X = 0.60$ m, the water surface reached a maximum level ($Z = 0.160$ m). This water level profile corresponds to a M1-type backwater curve (Chow, 1959) induced by the tributary inflow. The local water level increase may be associated with the presence of a stagnation zone, which was visually

observed at the upstream corner of the confluence. At the downstream junction corner ($X = 0.68$ m in Figure 11(a)), the water surface exhibited a drop revealing a low pressure zone, which was caused by the abrupt change of direction of the tributary flow (90°). Downstream of the confluence, the flow accelerated and the slope of the water surface increased due to the flow constriction exerted by the bank-attached bar and the fixed lateral banks.

At the outer bank of the main channel ($Y = 0.05$ m), upstream of the confluence ($0.00 < X < 0.60$ m), the water level profile (Figure 11(b)) was nearly horizontal, which again corresponds to a M1-type backwater curve (Chow, 1959) induced by the tributary inflow. As observed at the inner bank, the water level gradient increased downstream of the confluence, corresponding to flow acceleration.

Figure 13 depicts the cross-sectional average (CSA) values of bed elevation, water level and water depth along the main channel at equilibrium. Upstream of the confluence ($0.00 < X < 0.60$ m), the water depth increased until reaching its maximum at $X \sim 0.68$ m. Such an increase confirms the presence of a M1-type water curve in the upstream region. Consequently, the mean velocity in the main channel decreased. Downstream of the confluence, between $0.70 < X < 1.50$, the water depth rapidly decreased because of the flow acceleration; and for $X > 1.50$ m, the flow became nearly uniform, as confirmed by the constant CSA water depth.

Figure 10. Bed morphology at equilibrium: (a) downstream view from the main channel; (b) frontal view of the tributary mouth.

Figure 11. Bed level and water surface profiles at equilibrium ($t = 14$ h): (a) along the inner bank ($Y = 0.45$ m); and (b) along the outer bank of the main channel ($Y = 0.05$ m).

Figure 12. Frontal view of the tributary mouth.

Figure 13. Cross-sectional average (CSA) values of bed elevation, water surface elevation and water depth along the main channel at equilibrium.

Table II. Main hydraulic variables for the confluence physical system at equilibrium

h_{mu} [m]	h_{md} [m]	h_t [m]	U_{mu} [m/s]	U_{md} [m/s]	U_t [m/s]	Fr_{mu} [-]	Fr_{md} [-]	Fr_t [-]
0.109	0.075	0.028	0.50	0.80	0.72	0.48	0.93	1.37

h_{xx} , U_{xx} and Fr_{xx} refer to the CSA values of water depth, flow velocity and Froude number, respectively. Subscripts mu, md and t refer to main channel upstream, main channel downstream and tributary, respectively.

Velocities

At equilibrium, using the CSA water depths, the mean velocities were computed upstream of the confluence at $X=0.30$ m for the main channel (U_{mu}), at $Y=2.00$ m for the tributary (U_t), and downstream of the confluence in the main channel ($X=3.00$ m, U_{md}). The values obtained are shown in Table II together with their respective water depths and Froude numbers.

Froude numbers show the existence of two different flow regimes in the confluence. In the main channel upstream of the confluence, flow is subcritical ($Fr < 1$), whereas downstream of the confluence, the flow was trans-critical ($0.7 < Fr < 1.0$). Supercritical flow ($Fr > 1$) occurred in the tributary. These differences in flow regimes, which were also observed by Leite Ribeiro *et al.* (2012a), resulted in a hydraulic jump at the junction, which can be observed in Figure 9 by an abrupt increase of the water level, at approximately $Y = 0.50$ m, in the transition between the tributary and the main channel.

The point-velocity values measured at equilibrium in the main channel upstream of the confluence (V_7 to V_9 in Figure 14) reveal a fairly uniform distribution of the flow velocity across the section, which is in agreement with the observation of a fairly uniform bed and water surface across the section (see Figure 11) and with the computed CSA velocity (U_{mu}) shown in Table II. The nearest point-velocity value to the upstream junction corner (V_7 in Figure 11) was measured 12 cm upstream of the confluence and thus does not show any evidence of a stagnation zone, although the existence of a stagnation zone was inferred from the local water level increase at $X=0.60$ m (Figure 11(a)).

At the downstream corner of the junction (V_4 in Figure 14), the presence of a zone of reduced velocities, which favored the deposition and growth of the bank-attached bar, was observed. The positive velocity value at this point, together with the steep slope of the water surface (see Figure 11(a)), indicates the absence of a recirculation zone at equilibrium. At the outer bank downstream of the confluence, the flow was concentrated in the region of the main scour hole (V_5 and V_6 in Figure 14).

Farther downstream, where the scour hole and the bank-attached bar vanished, flow velocities increased, indicating a general convective acceleration of the flow between $X=0.80$ m and $X=2.20$ m, and trending again toward a uniform distribution of the velocity across the section. These velocities (V_1 to V_3 Figure 14) are representative of the recovery zone, and they are close to the computed cross-average velocity $U_{md}=0.80$ m/s.

In the tributary, the velocity measured at the point V_{10} (see Figure 14) is similar to the value U_t computed in Table II. However, V_{11} to V_{12} appear to be unreliable because the low values of velocity at these locations are not consistent with the constant water depth observed in the longitudinal profile depicted in Figure 9. The poor quality of these velocity readings may be due to the shallow water depth (0.028 m) compared with the size of the micro-propeller.

Sediment transport

Observations during the experiments provide insight into the dynamics of bedload in the confluence (Figure 15). At equilibrium, the spatial distribution of bed sediments downstream of the confluence reveals segregation between those coming from the tributary and those from the main channel. The tributary

Figure 14. Point velocity measurements over the bed topography at equilibrium (see Figure 3 for measuring position). Velocities are shown in the table in m/s.

Figure 15. Downstream view of the main channel bed.

bed load was conveyed along the inner part of the main channel, whereas the sediment supplied to the main channel was transported along the outer bank (Figure 15). Selective paths for the sediment originating from the tributary were observed: the finer portion of sediment coming from the tributary moved through a corridor along the crest of the bank-attached bar, whereas the coarser sediment was transported along the avalanche face of this bar (Figure 15).

The GSD of the bed surface was analyzed by four representative samples taken at different places within the confluence system (Figure 16).

In the main channel, the GSD of S1 indicates a slight coarsening ($d_{50} \sim 1$ mm) with respect to the initial bed ($d_{50} = 0.8$ mm) as shown in Figure 17.

In the tributary bed (S2), the bed surface was covered by a coarse armor layer with $d_{50} \sim 1.5$ mm (cf. Figure 16(a)), which was considerably larger than the initial mixture ($d_{50} = 0.8$ mm). A lack of the small size fractions in the sediment mixture was particularly evident for sizes smaller than 2 mm (Figure 17).

The GSD corresponding to S3, taken at the top of the bank-attached bar, fits well with the GSD of the tributary bed surface (S2), indicating that the bar was fed mainly by the tributary. The larger amount of fine sediment in sample S3 than in sample S4 confirms the presence of a corridor of fine sediment at the top of the bank-attached bar.

At the lateral slope of the bank-attached bar (S4), the GSD reveals armoring ($d_{50} \sim 3.7$ mm) with respect to the initial sediment supplied into the tributary ($d_{50} \sim 0.8$ mm). This armoring is in agreement with the observation of a coarse sediment corridor at this position (cf. Figure 15).

Discussion

Bed morphology

The initial state ($t = 0$ h) corresponds to a fairly planar channel bed for the main channel and a relatively steep bed for the tributary (slope $\sim 0.5\%$).

After one hour ($t = 1$ h), a scour hole at the channel junction was observed (Figures 7(b) and 8(a)). This scour hole was eroded in the initial bed of the main channel because the front of the sediment wedge from the tributary had not yet reached the confluence. This initial scour hole is a typical feature observed either in symmetrical or asymmetrical concordant confluences (Mosley, 1976). Similar confluence scour holes were also reported by other authors such as Ashmore and Parker (1983); Best (1988) and Ghobadian and Bajestan (2007). That initial scour hole was progressively filled with sediment coming from the tributary until reaching equilibrium, whereas the tributary bed increased in elevation above the bed of the main channel.

The discordance between the tributary and main channel beds, observed at equilibrium, was due to the dominant sediment load in the tributary compared with that of the main channel, and it was considerably larger than the one initially

Figure 16. Bed surface: (a) in the tributary; and (b) at the confluence under equilibrium conditions.

Figure 17. GSD of the initial sediments and samples at different position after equilibrium was reached (see Figure 16(b) for sample positions).

imposed. The avalanche slope observed in the tributary mouth facilitates the transport of coarse tributary sediment into the confluence. Best and Roy (1991), Biron *et al.* (1993, 1996a, 1996b), Boyer *et al.* (2006), Best and Rhoads (2008) and Leite Ribeiro *et al.* (2012a) documented the important influence of the bed height discordance on the bed morphology and flow dynamics within the confluence.

The bank-attached bar is associated with the reduced velocity zone observed at the downstream junction corner. This feature was also observed by Mosley (1976), Best (1988), Biron *et al.* (1993), Rhoads and Kenworthy (1995), and Leite Ribeiro *et al.* (2012a, 2012b), in asymmetrical confluences. Although the bar is typically associated with flow separation at the downstream junction corner, it may also form in regions of flow deceleration without actual flow separation (Best and Rhoads, 2008).

At equilibrium, a final scour hole formed in the main channel whose alignment bisected the junction angle (Mosley, 1976; Ashmore and Parker, 1983). The scour became parallel to the outer bank (see Figures 7(d) and 10(b)). This erosion is mainly motivated by net outward flow in the main channel. Due to lateral deflection of the main-channel flow by the tributary and by the bank-attached bar, the flow in the main channel is confined to the outer bank, where it accelerates and erodes the bed. The tributary inflow influences the upper-part of the main flow because of the bed discordance, whereas the near-bed flow of the main channel is steered to the outer bank by the bank-attached bar. When both deflected flows (upper and lower) converge in the outer bank, the unitary flow discharge increases, leading to flow acceleration. Moreover, the turbulence associated with the shear/mixing layer present at the flow deflection zone contributes to this erosion (Best, 1987). A similar scour hole, confined to the outer bank of the main stream, was observed by Rhoads (2006) in a natural concordant confluence with $M_r > 1$. In this case, the deflection of the flow of the main channel, along with the consequent flow concentration at the outer bank, was mostly caused by the tributary inflow. Biron *et al.* (1993) noted an absence of marked scour holes at discordant confluences and Leite Ribeiro *et al.* (2012a), who also studied discordant confluences, reported only weak erosion associated with the convective flow acceleration at the outer bank. In the case of Biron *et al.* (1993), the absence of a marked scour hole at the Bayonne–Berthier confluence in Canada may be a consequence, on the one side, of a weak flow deflection exerted by both the tributary inflow and the bank-attached bar and, on the other side, of a low unit discharge apparently due to a wide effective flow section. In the case of Leite Ribeiro *et al.* (2012a), though the bank-attached bar considerably reduced the effective flow section in the main channel, the acceleration experienced by the flow did not produce significant erosion, possibly due to armoring.

The hydrodynamics

The flow patterns observed in this study agree with the two-layer flow structure reported by Leite Ribeiro *et al.* (2012a), and Biron *et al.* (1993, 1996). In discordant confluences, the tributary flow deflects the upper part of the main channel flow towards the outer bank, whereas the lower part of the main flow, protected by the bed discordance, flows unimpeded downstream until reaching the bank-attached bar. This bar steers the flow toward the outer bank of the channel producing flow convergence and acceleration.

The hydrodynamic features inferred from the present experiment at equilibrium consisted of: (i) a reduced-velocity zone instead of a flow separation zone at the downstream junction corner; (ii) the presence of upwelling flow also at the downstream junction corner; (iii) a flow deflection zone associated with a shear layer; (iv) an acceleration zone created by the flow-constriction exerted by the bank-attached bar and the lateral banks of the main channel; and (v) a zone of flow recovery downstream of the confluence where the flow tends to recover a uniform distribution along the cross-section (see V_1 to V_3 in Figure 14); and (vi) a hydraulic jump at the tributary mouth, which was also observed by Leite Ribeiro *et al.* (2012a, 2012b).

The absence of flow separation and the presence of upwelling flow at the downstream junction corner were identified by Biron *et al.* (1993, 1996a, 1996b), Biron *et al.* (1996a), and Biron *et al.* (1996b) as typical flow patterns in discordant confluences. The low-pressure zone observed at the downstream junction corner ($X = 0.68$ m in Figure 11(a)) attracted the non-deflected near-bed flow of the main channel, which upwelled towards the surface (cf. Figure 12). This flow-upwelling inhibited the formation of flow recirculation (Biron *et al.*, 1996b).

In addition, the local water level increase observed at the upstream junction corner (see Figure 11(a)) may correspond to the stagnation zone that Leite Ribeiro *et al.* (2012a) and Rhoads and Sukhodolov (2001) observed at the same location. This local water level increase, caused by the tributary inflow, induced an M1 backwater curve (Chow, 1959) in the main channel upstream of the confluence.

The water surface profile along the tributary, where the flow was supercritical, exhibited an abrupt elevation increase in the water surface at the junction with the main channel ($Y = 0.50$ m in Figure 9). This abrupt increase in the water surface elevation corresponds to a hydraulic jump as supercritical flow joins the subcritical flow of the main channel. Thus, a change of flow regime occurred as tributary flow entered the main channel flow. Supercritical flow regime in the tributary at equilibrium was also observed by Leite Ribeiro *et al.* (2012a). This regime seems to be the result of the hydrodynamic adjustment to the imposed sediment load to the tributary.

Sedimentology

The sediment segregation observed in the main channel at equilibrium is consistent with data from Best (1988) that indicates that segregation becomes more pronounced with the increase of the confluence angle, the flow deflection and the depth of the scour hole.

Despite the different discharge ratios between this study and that of Best (1988) (0.11 in this study and 0.93 to 1.08 in Best, 1988) and the different confluence angles (90° in this study and 70° and 105° in Best, 1988), the patterns of sediment transport observed in this study are quite similar to those reported by Best (1988). The sediment movement originated in the main channel concentrated at the outer bank, whereas the load from

the tributary was conveyed along the bank-attached bar, which occupied the inner part of the main channel.

Bed morphology and sediment patterns observed in this study at equilibrium are in good agreement with those documented by Rhoads *et al.* (2009) for a natural asymmetrical concordant confluence under high discharge ratio conditions ($Q_r > 1$) where the tributary flow discharge and sediment flux are dominant over the main channel. Under these conditions, Rhoads *et al.* (2009) reported that the tributary flow and bed load penetrate into the confluence wrapping around the downstream junction corner, creating a bar along the inner bank of the main channel. The tributary flow penetration confines the main channel flow to the outer bank, where it accelerates and erodes the bed. The bed sediment mixture was composed of a coarse sediment bar along the inner bank of the main channel, a fine sediment corridor along the crest of the bar, and the presence of fine sediment from the main channel at the lateral slope of the bar (Rhoads *et al.*, 2009) due to the curvature-induced helical flow, which sweeps the bed sediments from the outer bank to the lateral slope of the bar. This is in contrast with the results observed in this study, in which inputs of sediment from each channel remained segregated downstream of the confluence (cf. Figure 15). This difference may be attributed to the large bar formed in this study that, in spite of the presence of helical flow, only interacts with the lateral slope of the bar.

The similar bed morphology between this study (based on a discordant confluence with a low discharge ratio, $Q_r < 1$) and that of Rhoads *et al.* (2009) (based on a concordant confluence with a high discharge ratio, $Q_r > 1$), lies on the outward deflection of the main channel flow that leads to flow acceleration at the outer bank, where erosion occurs. In the concordant confluence (Rhoads *et al.*, 2009), the outward flow deflection is strongly influenced by the tributary inflow due to the dominant tributary discharge ($Q_r > 1$), whereas in this study with a discordant bed, the tributary inflow deflects the upper part of the main channel flow, and the lower part is deflected by the bank-attached bar.

Comparison with Leite Ribeiro *et al.*'s (2012a) results

To analyze the influence of the sediment supplied into the main channel, the results obtained in this study are compared with those obtained by Leite Ribeiro *et al.* (2012a), where sediment was supplied only to the tributary. Both studies were carried out in the same laboratory confluence, for the same discharge ratio ($Q_r = 0.11$) (cf. Table III), and supplying the same sediment mixture to the tributary.

To guarantee sediment transport capacity all along the main channel in this study, the total flow discharge (Q_{p-c}) was increased to 30 L/s, which contrasts with the 20 L/s adopted by Leite Ribeiro *et al.* (2012a). This increase in flow discharge leads to a reduction in the momentum ratio ($M_r = M_t/M_m$) from 0.22 to 0.16 (cf. Table III).

Table III compares the discharge and momentum values, computed for the equilibrium state, for the present study with those of Leite Ribeiro *et al.* (2012a). Only the kinetic component of momentum was considered, i.e. for the tributary $M_t = \rho Q_t U_t$ and for the main channel $M_m = \rho Q_m U_{mu}$, where U_{mu} and U_t are the upstream mean velocities for the main channel and the tributary, respectively (see Table II).

The larger discharges adopted in this study enhanced the sediment transport capacity in both channels, which may explain the difference in time required to reach equilibrium between this study (14 h) and that of Leite Ribeiro *et al.* (2012a) (24 h).

At equilibrium, the bed morphology obtained by both studies exhibited several common features such as the bank-attached bar downstream of the confluence, the avalanche slope at the tributary mouth and the discordance between the tributary and main channel beds (Figure 18).

Similarities were also observed in the hydrodynamic features. For instance, the presence of a hydraulic jump at the tributary mouth, due to the different flow regimes between tributary and main channel, was observed in both studies.

Differences between the study by Leite Ribeiro *et al.* (2012a) and the present study were observed mainly in the main channel bed morphology. Deposition prevailed in the former study (see Figure 18(a)), whereas both erosion and deposition co-existed in the present study (see Figure 18(b)). The most relevant morphological differences in the present study consisted of a deeper scour hole at the outer bank of the main channel and a narrower and higher bank-attached bar at the inner bank. Leite Ribeiro *et al.* (2012a) reported only slight erosion of the bed at the outer bank of the main channel (see Figure 18).

The enhanced erosion might be a consequence of the larger discharges adopted in this study than those adopted by Leite Ribeiro *et al.* (2012a), though the discharge ratio was kept identical (see Table III). These larger flow discharges, confined in the same channel width as Leite Ribeiro *et al.* (2012a), may have resulted in higher velocities and stronger acceleration in the confluence, causing bed erosion and width reduction of the bank-attached bar.

No armor effect was observed in the present study along the corridor of the sediment originating from the main channel, whose GSD is represented by S1 (Figure 15). This is in contrast with the bed armoring reported by Leite Ribeiro *et al.* (2012a) in the same region. The d_{50} value corresponding to sample S1 was 1.8 mm for Leite Ribeiro *et al.* (2012a) and 1.0 mm for the present study, whereas the d_{50} value for the initial main channel bed sediment was 0.8 mm in both studies. In the present study, both the larger discharge of the main channel and the sediment discharge supplied into the main channel contributed to maintaining the texture of the sediment mixture during the experiment. In contrast, because Leite Ribeiro *et al.* (2012a) did not supply sediment into the main channel, the finer particles of the initial bed were washed away during the experiment and the coarse particles remained at the bed, constituting an armor layer.

In this study, sediment supplied to the main channel during the experiment may have contributed to bed erosion. The

Table III. Discharge and momentum ratios adopted in this study and by Leite Ribeiro *et al.* (2012a)

	Q_t	Q_m	Q_{p-c}	Q_r	$M_t = \rho Q_t U_t$	$M_m = \rho Q_m U_{mu}$	$M_r = M_t/M_m$
Research	[L/s]	[L/s]	[L/s]	[-]	[N]	[N]	[-]
Present study	3.0	27.0	30.0	0.11	2.15	13.38	0.16
Leite Ribeiro (2012a)	2.0	18.0	20.0	0.11	1.33	5.94	0.22

Subscripts *t*, *m* and *p-c* correspond to tributary, main and post-confluence channel values, respectively. ρ is the water density ($\rho = 1000 \text{ kg/m}^3$).

Figure 18. Bed topography at equilibrium: (a) for Leite Ribeiro *et al.* (2012a) and (b) for this study. The topographies correspond to the discharge ratio of $Q_r = 0.11$. Bed-level contours are spaced by $\Delta Z = 0.01$ m.

sediment discharge of the main channel maintained the portion of finer particles in the bed sediment mixture fairly constant, and this fine bed material reduced the critical shear stress for sediment motion enhancing the mobility of the bed, including relatively coarse particles (Wilcock, 1998; Wilcock *et al.*, 2001), which promoted bed erosion.

Segregation was also observed by Leite Ribeiro *et al.* (2012a) in the bed sediment at equilibrium as the sediment from the tributary was deposited at the inner bank of the main channel, downstream of the confluence (cf. Figure 15). In addition, as observed in this study, a fine sediment corridor was identified along the crest of the bank-attached bar, whereas the coarser particles were conveyed through the lateral slope of the bar (cf. Figure 15).

Conclusions

The hydro-morphodynamic evolution of an experimental 90° discordant laboratory confluence with low momentum and discharge ratio conditions and with sediment supplied into both channels was studied herein. Interaction between flow dynamics and bed morphology was observed during the experiment through a simultaneous increase of the gradients of bed topography and water surface.

Once in equilibrium, the bed morphology presented typical features of discordant confluences, such as an avalanche face at the tributary mouth and a bank-attached bar along the inner bank of the post-confluence. In addition, a marked scour hole was observed at equilibrium, a finding that contrasts with previous work that noted the absence of marked scour holes in discordant confluences. The different erosion patterns are related to net deflection of flow toward the outer bank and the consequent acceleration.

The hydrodynamic features observed at equilibrium are consistent with those reported in previous investigations of discordant confluences. In particular, the upwelling flow at the downstream junction corner, which contributes to the presence of a zone of reduced velocities instead of a recirculation zone therein, was identified as characteristic of discordant confluences. Moreover, the hydraulic jump observed at the tributary mouth is characteristic of discordant confluences with narrow steep tributaries that provide abundant sediment load to the confluence.

At equilibrium, the spatial distribution of the bed sediments exhibited segregation between the sediments provided by the tributary and main channel. This segregation is in good

agreement with previous investigations that reported similar patterns for both discordant and concordant confluences.

The sediment discharge supplied to the main channel kept the portion of fine and coarse particles fairly constant throughout the experiment, avoiding bed armoring along the corridor followed by the sediments of the main channel. The lack of bed armoring may have facilitated scour of the bed of the main channel.

The present research, although inspired by real confluences, is based on laboratory experiments which have limitations on reproducing all aspects of reality. In the future, field investigation of high-mountain river confluences should be envisaged to compare with the present results.

Acknowledgements—This research was supported by the Portuguese national Funding agency for Science, Research and Technology (FCT) and the Laboratory of Hydraulic Construction (LCH) at EPFL in the framework of the Joint Doctoral Initiative IST-EPFL, and of the projects SFRH/BD/51453/2011, PTDC/ECM/118775/2010, and the LCH/EPFL. The paper was considerably improved thanks to the editors and reviewers' comments and suggestions.

References

- Ashmore P, Parker G. 1983. Confluence scour in coarse braided streams. *Water Resources Research* **19**(2): 392–402. DOI: 10.1029/WR019i002p00392
- Benda L, Andras K, Miller D, Bigelow P. 2004. Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. *Water Resources Research* **40**(5). DOI: 10.1029/2003WR002583
- Best JL. 1987. Flow dynamics at river channel confluences. Implications for sediment transport and bed morphology. *Recent Developments in Fluvial Sedimentology, Spec. Publ. SEPM Soc. Sediment Geology* **39**: 27–35. DOI: 10.2110/pec.87.39.0027
- Best JL. 1988. Sediment transport and bed morphology at river channel confluences. *Sedimentology* **35**(3): 481–498. DOI: 10.1111/j.1365-3091.1988.tb00999.x
- Best JL, Rhoads BL. 2008. Sediment transport, bed morphology and the sedimentology of river channel confluences. In *River Confluences, Tributaries and the Fluvial Network*, Rice SP, Roy AG, Rhoads BL (eds). John Wiley and Sons, Ltd: Chichester, UK; 45–72. DOI: 10.1002/9780470760383.ch4.
- Best JL, Roy AG. 1991. Mixing-layer distortion at the confluence of channels of different depth. *Nature* **350**(6317): 411–413. DOI: 10.1038/350411a0
- Biron PM, Roy AG, Best JL, Boyer CJ. 1993. Bed morphology and sedimentology at the confluence of unequal depth channels. *Geomorphology* **8**(2–3): 115–129. DOI: 10.1016/0169-555X(93)90032-W

- Biron PM, Best JL, Roy AG. 1996a. Effects of bed discordance on flow dynamics at open channel confluences. *Journal of Hydraulic Engineering*. DOI: 10.1061/(ASCE)0733-9429(1996)122:12(676)
- Biron PM, Roy AG, Best JL. 1996b. Turbulent flow structure at concordant and discordant open-channel confluences. *Experiments in Fluids*. DOI: 10.1007/BF00189046
- Biron PM, Richer A, Kirkbride AD, Roy AG, Han S. 2002. Spatial patterns of water surface topography at a river confluence. *Earth Surface Processes and Landforms* **27**(9): 913–928. DOI: 10.1002/esp.359
- Biron PM, Ramamurthy AS, Han S. 2004. Three-dimensional numerical modeling of mixing at river confluences. *Journal of Hydraulic Engineering* **130**(3): 243–253. DOI: 10.1061/(ASCE)0733-9429(2004)130:3(243)
- Boyer C, Roy AG, Best JL. 2006. Dynamics of a river channel confluence with discordant beds: Flow turbulence, bed load sediment transport, and bed morphology. *Journal of Geophysical Research, Earth Surface* **111**(F4): F04007. DOI: 10.1029/2005JF000458
- 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**(8): 1371–1396. DOI: 10.1002/(SICI)1099-1085(19980630)12:8<1371::AID-HYP620>3.0.CO;2-C
- Bradbrook KF, Lane SN, Richards KS, Biron PM, Roy AG. 2001. Role of bed discordance at asymmetrical river confluences. *Journal of Hydraulic Engineering*. DOI: 10.1061/(ASCE)0733-9429(2001)127:5(351)
- Chow VTE. 1959. *Open-Channel Hydraulics*. McGraw-Hill Book Company: New York.
- Fujita I, Komura S. 1989. Visualization of the flow at a confluence. In *Proceedings of the International Symposium on Refined Flow Modeling and Turbulence Measurements*, Tokyo, Japan; 517–524.
- Ghobadian R, Bajestan MS. 2007. Investigation of sediment patterns at river confluence. *Journal of Applied Sciences* **7**(10): 1372–1380. DOI: 10.3923/jas.2007.1372.1380
- Kennedy BA. 1984. On Playfair's law of accordant junctions. *Earth Surface Processes and Landforms* **9**(2): 153–173. DOI: 10.1002/esp.3290090207
- Leclair SF, Roy AG. 1997. Variability of bed morphology and sedimentary structures at a discordant river confluence during low flows. *Géographie Physique et Quaternaire* **51**(2): 125–139.
- Leite Ribeiro M. 2011. *Influence of Tributary Widening on Confluence Morphodynamics*. École polytechnique fédérale de Lausanne PhD Dissertation n° 4951: Lausanne, Switzerland.
- Leite Ribeiro M, Blanckaert K, Roy AG, Schleiss AJ. 2012a. Flow and sediment dynamics in channel confluences. *Journal of Geophysical Research* **117**(F1): F01035. DOI: 10.1029/2011JF002171
- Leite Ribeiro M, Blanckaert K, Roy AG, Schleiss AJ. 2012b. Hydromorphological implications of local tributary widening for river rehabilitation. *Water Resources Research* **48**(10): n/a–n/a. DOI: 10.1029/2011WR011296
- Leite Ribeiro M, Blanckaert K, Schleiss AJ. 2015. Local tributary widening for river rehabilitation. *Ecohydrology*. DOI: 10.1002/eco.1588
- Miller JP. 1958. High mountain streams; effects of geology of channel characteristics and bed material. *Memoir - New Mexico, Bureau of Mines and Mineral Resources*, 53. Retrieved from <http://search.proquest.com/docview/53085097?accountid=14244>
- Mosley MP. 1976. An experimental study of channel confluences. *Journal of Geology* **84**(5): 535–562. Retrieved from <http://www.jstor.org/stable/30066212>
- Parsons DR, Best JL, Lane SN, Orfeo O, Hardy RJ, Kostaschuk R. 2007. Form roughness and the absence of secondary flow in a large confluence-diffuence, Rio Paraná, Argentina. *Earth Surface Processes and Landforms* **32**(1): 155–162. DOI: 10.1002/esp.1457
- Rhoads BL. 2006. Scaling of confluence dynamics in river systems: some general considerations. In *Proceedings of the 4th IAHR Symposium on River, Coastal and Estuarine Morphodynamics (RCEM 2005, Urbana, Illinois, USA, 4-7 October 2005)*, Parker G, García M (eds). Taylor and Francis: London; 378–387. DOI: 10.1201/9781439833896
- Rhoads BL, Kenworthy ST. 1995. Flow structure at an asymmetrical stream confluence. *Geomorphology* **11**(4): 273–293. DOI: 10.1016/0169-555X(94)00069-4
- Rhoads BL, Kenworthy ST. 1998. Time-averaged flow structure in the central region of a stream confluence. *Earth Surface Processes and Landforms* **23**(2): 171–191. DOI: 10.1002/(SICI)1096-9837(199802)23:2<171::AID-ESP842>3.0.CO;2-T
- 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**(9): 2393–2410. DOI: 10.1029/2001WR000316
- Rhoads BL, Riley JD, Mayer DR. 2009. Response of bed morphology and bed material texture to hydrological conditions at an asymmetrical stream confluence. *Geomorphology* **109**(3–4): 161–173. DOI: 10.1016/j.geomorph.2009.02.029
- Smart GM. 1984. Sediment transport formula for steep channels. *Journal of Hydraulic Engineering* **110**(3): 267–276. DOI: 10.1061/(ASCE)0733-9429(1984)110:3(267)
- Weber LJ, Schumate ED, Mawer N. 2001. Experiments on flow at a 90° open-channel junction. *Journal of Hydraulic Engineering* **127**(5): 340–350. DOI: 10.1061/(ASCE)0733-9429(2001)127:5(340)
- Wilcock PR. 1998. Two-fraction model of initial sediment motion in gravel-bed rivers. *Science* **280**(5362): 410–412. DOI: 10.1126/science.280.5362.410
- Wilcock PR, Kenworthy ST, Crowe JC. 2001. Experimental study of the transport of mixed sand and gravel. *Water Resources Research* **37**(12): 3349–3358. DOI: 10.1029/2001WR000683