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Morphodynamic differences induced by different confluence angles in widen confluences

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ABSTRACT: River widening is commonly used as a solution for the rehabilitation of rivers with the main purposes of allowing the river to adjust to its natural dynamics and to improve riparian and in-stream habitat for flora and fauna, by increasing the heterogeneity in substrate, flow and morphology. Local widening may also be used for confluences rehabilitation as, for many of them, the heterogeneity and fragmentation of the river system were severely affected by previous human interventions. Local tributary widening amplifies the morphodynamic processes, enhancing the diversity in sediment substrate, flow velocities and flow depths. In addition, widening should neither affect aspects such as water level in the tributary nor in the main channel, which is an important consideration for flood safety. The aim of this paper is to analyze the differences in terms of bed morphology and flow dynamics induced by different confluence angles in widen channel confluences.

1 INTRODUCTION

During the last century, many river training works were carried out with the aim of satisfying societal needs, i.e. flood protection, human and industrial water supply or irrigation. During this process, many environmental aspects were neglected, causing several and important impacts on the fluvial ecosystems, mostly through important morphological changes. Nowadays, many tributaries are environmentally disconnected from the main river due to channelization works. To rehabilitate the original environment at river confluences, it is essential to deepen the knowledge of the hydromophodynamic processes at these key areas.

In this context, previous authors carried out physical and numerical experiments with the purpose of describing the different flow and morphological features observed in confluences. Best (1987) described the flow in a confluence by six main zones: flow deflection, flow stagnation, flow separation or recirculation zone, acceleration zone, shear layer and flow recovery zone. Biron et al. (1996) and Bradbrook et al. (2001) analyzed the effects of discordant bed on the flow dynamics in channel confluences.

Although the flow dynamic in confluences is well known, only few laboratory experiments were carried out under mobile bed conditions (Mosley, 1976; Best, 1988; Boyer et al., 2006; Best & Rhoads, 2008; Leite Ribeiro et al., 2012a; b), among which only Boyer et al. (2006) and Leite Ribeiro et al. (2012a; b) were based on discordant-bed confluences.

Leite Ribeiro et al. (2012b) studied the efficacy of local tributary widening as potential solution for confluence rehabilitation focused on discordant bed confluences, in which the tributary bed level differs from the main-channel bed level at the tributary mouth. This study was based on experiments under mobile bed conditions, carried out in a laboratory confluence where the tributary and main channel joined with a 90° angle, and where sediments were only supplied in the tributary. Leite Ribeiro et al. (2012) concluded that local tributary widening can enhance heterogeneity in sediment substrate, flow velocities and flow depths, improving the local habitat and the connectivity of the tributary to the river network without having adverse impact on flood safety.

Widening is a commonly used solution for river rehabilitation whose main purpose consists on allowing the river to recover its natural dynamics. Widening also increase the heterogeneity in substrate, flow and morphology and thus, it enhances the river ecosystem (Weber et al., 2009).

In the present study, the effects of the confluence angle on the bed morphology and flow dynamics is analyzed for discordant bed confluences with local tributary widening.

2 METHODS

2.1 *Experimental facilities*

Two sets of two tests were carried out in a laboratory confluence consisting on an 8.5 m long and 0.5 m wide rectangular straight glass flume corresponding to the main channel, and a 4.9 m long and 0.15 m wide rectangular PVC channel that corresponds to the tributary. Both channels connect with an angle of 90º (1st set) or 70º (2nd set). For each set of tests, two geometries were tested: one so called "reference configuration", which corresponds to the no-widen tributary, and the second one in which the tributary was widen at the downstream reach, called herein "widen configuration". The widening was 0.45 m wide and 0.60 m long as shown in Figure 1.

2.2 *Experimental set up*

The adopted discharge ratio ($Q_r = Q_t/Q_m$), defined as the ratio between the tributary discharge (Q_t) and the main channel discharge (Q_m) both considered upstream of the confluence, was the same for all the tests ($Q_r = 0.11$), which corresponds to the same adopted by Leite Ribeiro et al. (2012).

During the tests two sediment mixtures were used: 0–4 mm sand for the main channel and a mixture of 80% of sand (0–4 mm) and 20% of 4–8 mm gravel for the tributary. Figure 2 depicts the grain size distribution of the sediments for each channel.

Table 1 contains the grain density (ρ_s) and characteristic diameters of each mixture where d_m is the mean grain size, approached by d_{65}, and d_x is the grain size diameter for which x% of the sediments by weight are finer.

The sediment discharges for the tributary and main channel were defined by assuming as initial hypothesis that the longitudinal bed slope, and grain size distribution were in the range of those observed at the Upper-Rhone River confluences. Hence, the hypothetical bed slopes under equilibrium conditions were set to 1.0% for the tributary and between 0.3%–0.4% for the main channel. With these slopes, the defined discharge scenario, and assuming uniform flow in both channels, the sediment discharges for both channels were estimated using the sediment transport formula of Smart & Jaeggi (1983) and Smart (1984).

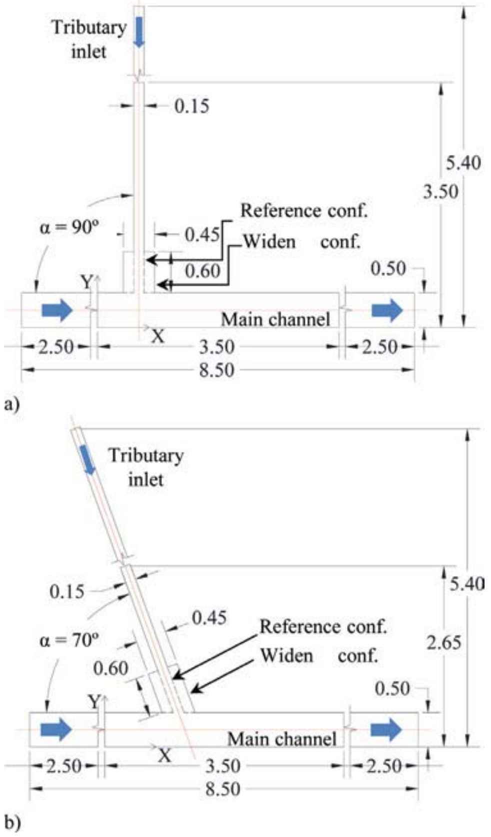

Figure 1. Plan view of the laboratory confluence with an angle of 90º (a) and with an angle of 70º (b).

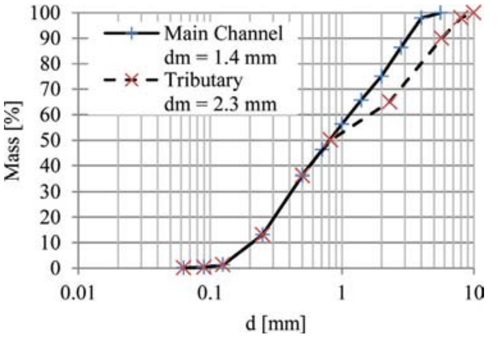

Figure 2. Grain size distribution for supplied sediment into tributary and main channel.

Table 1. Main characteristics of the supplied sediments.

Channel	ρ_s [kg/m³]	d_{30} [mm]	d_{50} [mm]	d_m [mm]	d_{90} [mm]
Tributary	2650	0.4	0.8	2.3	5.7
Main channel	2650	0.4	0.8	1.4	3.0

Table 2. Tests set up.

Test	α	Widen	Q_m [l/s]	Q_t [l/s]	Q_r [–]	Q_{sm} [kg/min]	Q_{st} [kg/min]
1	90°	No	27.0	3.0	0.11	0.30	0.50
2		Yes					
3	70°	No					
4		Yes					

$$Q_b = B_F \times \rho_s \times \frac{4}{s-1} \times R_s \times U \times S^{0.6} \times \left(S - \frac{d_m}{12.1 \times R_s} \right) + \left(\frac{d_{90}}{d_{30}} \right)^{0.2} \tag{1}$$

where Q_b is the sediment transport rate (bed load) in m³/s, B_F is the width of the flume in m, ρ_s is the sediment density (2650 kg/m³), s is the relative sediment density ($\rho_s/\rho = 2.65$), ρ is the water density ($\rho = 1000$ kg/m³) R_s is the hydraulic radio in m, U is the mean water velocity, S is the slope of the channel bed. Finally, the adopted sediment discharges were 0.3 kg/min for the main channel (Q_{sm}) and 0.5 kg/min for the tributary (Q_{st}).

Table 2 summarizes the adopted liquid and sediment discharges, the confluence angles and the geometries (widen or not) for each test.

2.3 *Experimental procedure*

To carry out the tests, the channel bed was prepared using the different sediment mixtures for each flume: sand for the main and the sand-gravel mixture for the tributary. At the same time, in order to accelerate the development of the discordant bed morphology, a step of around 0.03 m was imposed at the junction between the main channel and the tributary. Also, a slight slope (0.5%) was created in the tributary. This bed morphology did not affect to the final topography because the initial slope and the initial bed step were smaller than those reached in equilibrium.

Once the channel bed was prepared, the model was slowly filled up with water. Both bed topographies (tributary and main channel) were measured just before starting the test.

Water level and bed topography surveys were recorded after 1 and 7 hours of test's duration and when the equilibrium was reached. Topography was measured by means of a Mini-Echo-Sounder ± 1 mm accurate. For water level measurements, an ultrasonic limnimeter (± 1 mm accurate) was used.

Tests were run until reaching the equilibrium, i.e. when the ratio between outgoing and incoming sediment discharges was 90% or larger. To check the sediment transport rate at the downstream end, the outgoing sediments were weighted periodically. Additionally, equilibrium was also checked by means of topography evolution, considering equilibrium conditions when the topography variations were lower than 2%.

By comparing the initial bed surface to the surface recorded at equilibrium, scour and deposition areas were identified.

3 RESULTS AND DISCUSSION

3.1 *Widening effects for $\alpha = 90°$*

Comparing bed topographies at equilibrium, for the reference and for the widen configurations (Fig. 3a-b respectively), a wider and deeper erosion at the outer half of the main channel was observed in the widen configuration (Fig. 3b). Moreover, the deposition bar formed at the inner bank of the main channel, downstream of the confluence, was narrower and higher for the widen configuration as well (Fig. 3b-Fig. 4).

However, the water surface at the main channel did not present significant differences between reference and widen configurations (Fig. 4), which is in good agreement with the results of Leite Ribeiro et al., (2012b). Therefore, the widening did neither affect to the water level in the main channel nor in the tributary, which is within the interest of flood safety practices.

In the tributary, the bed level presented an elevation for the widen configuration at the downstream reach (Fig. 5). Also, the bed discordance and the bed tributary penetration into the main channel were enhanced in the case of widen configuration, in comparison to the reference configuration.

Along the tributary axis, the water level did not present important differences between both configurations (Fig. 5). Nevertheless, at the lateral banks of the widen reach, two stagnation zones were identified (Fig. 6), which confined the tributary flow to the central part of the widen reach.

This flow constriction caused by the bed elevation and by the presence of two stagnation zones at the lateral banks, led to an increase of the flow velocities and the tributary-momentum flux, besides a reduction of the junction angle with the main-channel flow (Leite Ribeiro et al., 2012b).

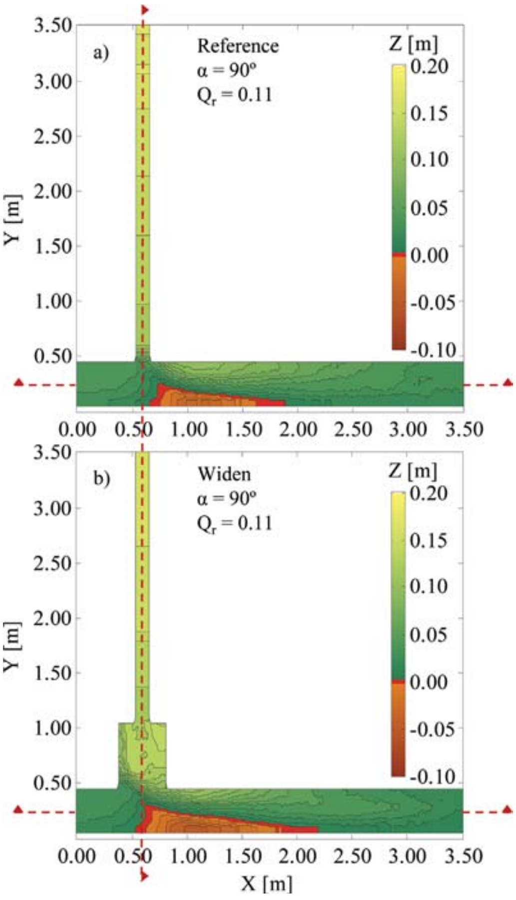

Figure 3. Bed topographies at equilibrium for $\alpha = 90°$ for reference configuration a), and widen configuration b). Dashed red lines indicate the position of the longitudinal profiles along the main channel axis (Y = 0.25 m), showed in Figure 4, and along the tributary axis (X = 0.60 m), showed in Figure 5.

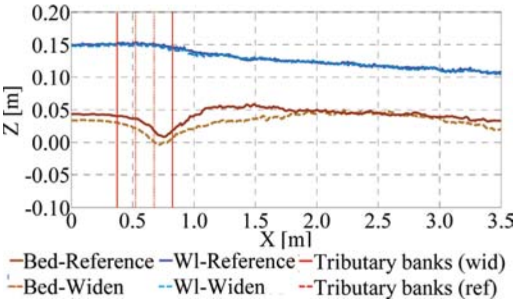

Figure 4. Bed surfaces and water levels (Wl) at equilibrium for the reference and the widen configurations along the main channel axis (Y = 0.25 m). See Figure 3 for positions.

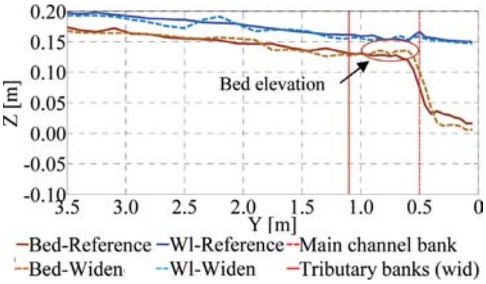

Figure 5. Bed surfaces and water levels (Wl) at equilibrium for the reference and the widen configurations along the tributary axis (X = 0.60 m). See Figure 3 for position.

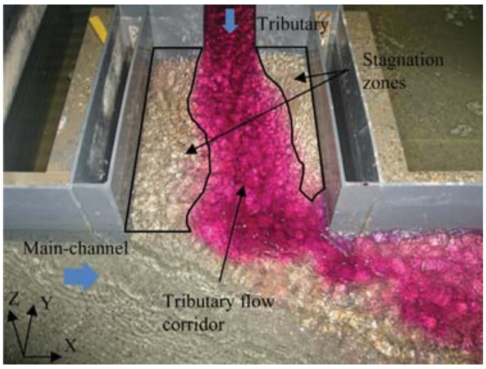

Figure 6. Downstream view of the widening with dye injection in the tributary.

The bed surface at the widen area is characterized by a high heterogeneity, where two zones of fine sediments were identified at the lateral banks, which correspond to the stagnation zones illustrated in Figure 6. In the tributary flow, the bed was composed by coarse sediment.

On the contrary, the bed substrate for reference configuration was exclusively characterized by an armor layer composed by the coarsest fraction of sediments (Fig. 7).

3.2 *Widening effects for $\alpha = 70°$*

For $\alpha = 70°$, the bed topography at equilibrium presented the same differences between the reference and the widen configurations as for $\alpha = 90°$. For the widen configuration, a narrower and higher deposition bar, besides a deeper and wider erosion were observed at the inner and at the outer bank of the main channel respectively (Fig. 8).

These different patterns between reference and widen configurations, observed either for $\alpha = 90°$ or $\alpha = 70°$ were in good agreement with the results reported by Leite Ribeiro et al. (2012b) in which higher deposition at the inner part and deeper erosion at the outer part of the main channel were observed as well. According to that study, that increase of the topographic gradient amplifies the topographic steering of the flow and the corresponding transverse fluxes of mass and momentum.

For $\alpha = 70°$, the water level observed in the main-channel at equilibrium, for the widen configuration, was lower than the observed for the reference configuration (Fig. 9).

In the tributary, the bed level at equilibrium did not present significant differences between both configurations upstream of the widen area (Y = 1.20 m) (Fig. 10). At this point, for the widen configuration, a step was observed in the bed level, which kept itself nearly horizontal until reaching the junction with the main channel, where it converged with the bed level of the reference configuration (Fig. 10).

As observed in the main channel, the tributary water level at equilibrium for the widen configuration was lower than the observed for the reference configuration (Fig. 10).

Figure 7. Tributary bed substrate in equilibrium for the reference configuration.

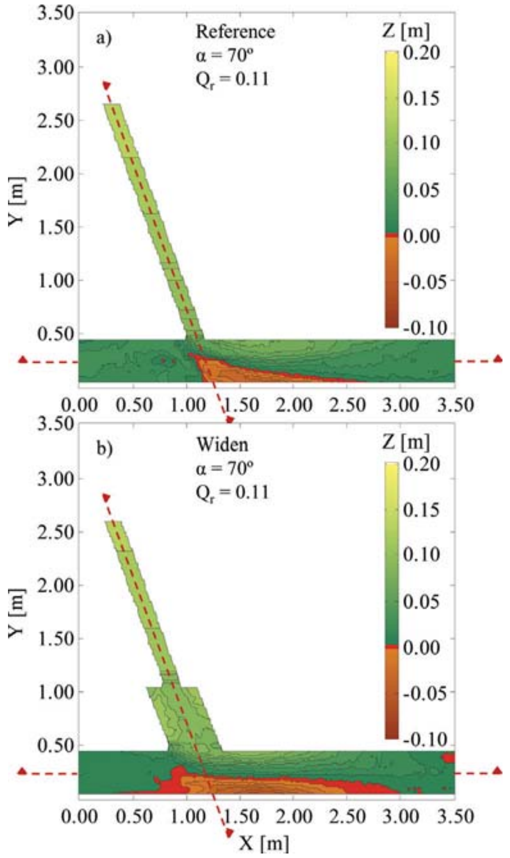

Figure 8. Bed topographies at equilibrium for $\alpha = 70°$ for reference configuration a), and widen configuration b). Dashed red lines indicate the position of the longitudinal profiles along the main channel axis (Y = 0.25 m), showed in Figure 9, and along the tributary axis, showed in Figure 10.

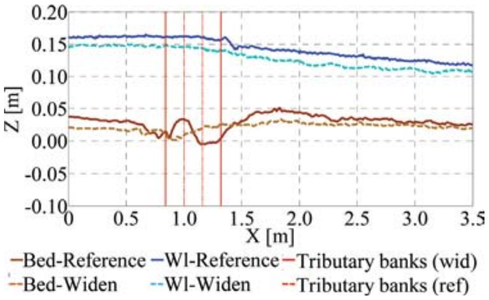

Figure 9. Bed surfaces and water levels (Wl) for the reference and the widen configurations along the main channel axis (Y = 0.25 m). See Figure 8 for positions.

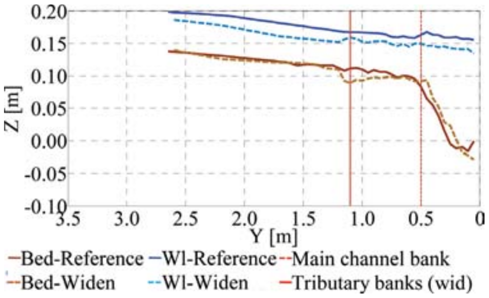

Figure 10. Bed surfaces and water levels (Wl) for the reference and the widen configurations along the tributary axis. See Figure 8 for position.

In the bed surface of the widen area, two zones with fine sediments were observed at the lateral banks. These zones were associated to the flow stagnation zones as shown for $\alpha = 90°$. Also, in the central part of the widen area, associated to the tributary flow corridor; the bed surface was composed by coarse sediments.

4 CONCLUSIONS

Independently of the confluence angle, local tributary widening creates zones with high diversity of flow velocities, water depth and bed substrate, associated to stagnation zones and to the tributary flow corridor.

In both widen configurations, for both angle configurations; the observed erosion at the outer half of the main channel was wider and deeper, whereas the deposition bar at the inner half of the main channel was higher and narrower in comparison to the observed for the reference configurations.

The measured water levels in the tributary and in the main channel were not affected by the widening for $\alpha = 90°$, whereas for $\alpha = 70°$, for the widen configuration, the water levels were lower.

Local widening configuration can be a potential solution for confluence rehabilitation since it creates an area with diversity of water depths, velocities and bed substrate without significant influence in the water surfaces of the tributary and main channel, an important fact for flood safety reasons.

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