EFFECT OF THE BED LOAD GRADATION ON THE MORPHODYNAMICS OF DISCORDANT CONFLUENCES

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ABSTRACT

Within the fluvial network, river confluences are particular areas characterized by complex hydrodynamic, morphodynamic and sedimentary processes. These processes have been observed to be governed by parameters such as the discharge ratio, the junction angle, the sediment rates and the bed material. This study analyzes the influence of the sediment gradation on the hydro-morphodynamics of open channel confluences, characterized by a bed discordance between the tributary and main channel. For that purpose, experiments are conducted at two different laboratory confluences in which only the gradation of the supplied sediment mixtures is different. This paper presents the results of two of these experiments with a discharge ratio between the tributary and main channel of $Q_r = Q_t/Q_m = 0.15$. In one experiment, non-uniform sediment mixtures with a mean diameter of $d_{50} = 0.82$ mm are supplied to the main channel and tributary. These mixtures are representative of the sediments found in mountain river confluences such as those of the Upper-Rhone River. In the other experiment, a uniform sediment mixture with the same mean diameter ($d_{50} = 0.82$ mm) is supplied both to the tributary and main channel. The latter mixture is rather representative of the bed material found in low-land confluences. At equilibrium conditions, i.e. when the outgoing sediment rate is nearly equal to the incoming, bed and water surface topographies are recorded. These measurements show that with non-uniform sediments, the bed morphology at equilibrium presents a high topographic gradient, with a developed bar and scour hole in the main channel, a marked bed discordance and a steep bed-slope in the tributary. In contrast, with uniform sediments, the bed morphology presents attenuated features compared to those observed with non-uniform sediments. Also, with uniform sediments bedforms are observed throughout the flumes, whereas the non-uniform mixtures favor the bed armor.

Keywords: Confluences; sediment gradation; bed discordance; morphodynamics; armored bed.

1 INTRODUCTION

The hydrodynamic, morphodynamic and sedimentary processes involved in river confluences are controlled by a broad range of factors such as planform geometries, discharge ratios, bed material and sediment rates (Best, 1987; Best, 1988; Bristow et al., 1993; Best and Rhoads, 2008; Rhoads et al., 2009). Many studies focused on the influence of the confluent angles and discharge ratios on the confluence dynamics (Best, 1987; Best, 1988; Bristow et al., 1993; Rhoads et al., 2009; Leite Ribeiro et al., 2012; Guillén-Ludeña et al., 2015; Guillén-Ludeña et al., 2016; Schindfessel et al., 2015). However,few studies if any, analyzed the role of the gradation of the bed material on the flow dynamics and bed morphology of open-channel confluences. This study represents thus a novelty in the analysis of the dynamics of confluences, as it focuses on the influence of the sediment gradation on the hydrodynamics and morphodynamics of open-channel confluences. The gradation of a sediment mixture is defined in this study by means of the gradation coefficient *σ* defined as:

$$\sigma=\frac{1}{2}\left(\frac{d_{84}}{d_{50}}+\frac{d_{50}}{d_{16}}\right) \qquad [1]$$

where d_{84}, d_{50}, d_{16} are the particle sizes coarser than the 84%, 50% and 16% by weight of the sediment mixture, respectively. A high value of σ indicates a non-uniform sediment mixture and, on the opposite, a low value of σ denotes a uniform sediment mixture.

This study presents the results of two laboratory experiments in which different sediment mixtures are continuously supplied to the tributary and main channel. These results show that with non-uniform mixtures, bed topography and flow dynamics evolve to high gradients in order to gain enough transport capacity to convey the large amount of sediment sizes that compose the non-uniform mixtures. In contrast, with uniform mixtures, the flow dynamics and bed morphology present attenuated gradients, since the fine particles which form the uniform mixtures are more easily transported.

2 METHODOLOGY

2.1 Experimental facilities

The experiments were conducted in two experimental facilities, one located at EPFL in Switzerland and other located at IST in Portugal. The facility at EPFL consisted of an 8.0 m long and 0.5 m wide rectangular straight main channel, and a 4.9 m long and 0.15 m wide rectangular straight tributary that joined the main channel at an angle of 70º. The facility at IST consisted of a 12.0 m long and 0.5 m wide rectangular straight main channel, and a 5.9 long and 0.15 m wide rectangular straight tributary which joined the main channel at an angle of 70º. Figure 1 shows the schematic plan view of the two laboratory confluences. The results presented in this study are referred to the reference axis *X, Y* and *Z* indicated in Figure 1.

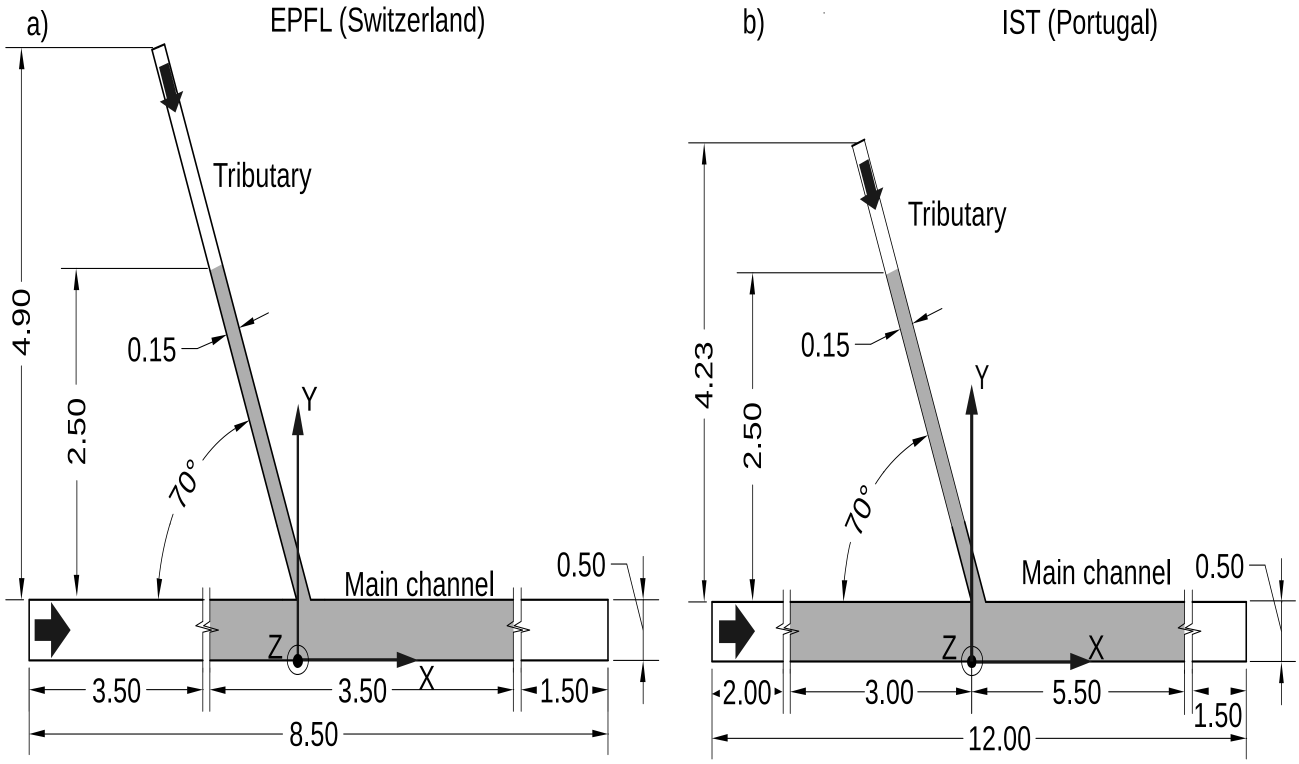

Figure 1. Sketch of the laboratory confluences. The shadow regions represent the measurement domain.

2.2 Experimental parameters

Both experiments were performed with a discharge ratio of Q_r = 0.15, which is representative of confluences in which the main channel provides the dominant flow discharge, compared to that provided by the tributary. The discharge ratio is defined as:

$$Q_r = \frac{Q_t}{Q_m} \qquad [2]$$

where Q_t is the flow discharge of the tributary upstream of the confluence and Q_m denotes the flow discharge of the main channel upstream of the confluence.

The sediment mixtures were different for each experiment. For the experiment performed at EPFL, a poorly-sorted sand-gravel mixture with d_{50} = 0.82 mm and σ = 3.15 was supplied to the tributary; and another poorly-sorted sand-gravel mixture with d_{50} = 0.82 mm and σ = 4.50 was supplied to the main channel. For the experiment performed at IST, a uniform sand with d_{50} = 0.80 mm and σ = 1.35 was supplied to both, the tributary and main channel. Figure 2 shows the grain size distribution (GSD) of the supplied sediment mixtures.

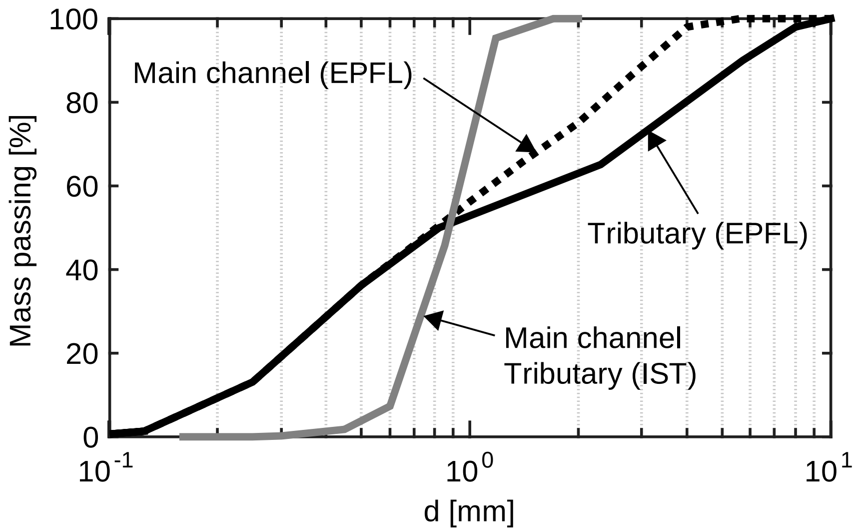

Figure 2. Grain size distribution of the supplied sediment mixtures

The sediment mixtures were continuously supplied during the experiment at rates of 0.5 kg/min for the tributary and 0.3 kg/min for the main channel. These rates were estimated by assuming that the bed slope and grain size distributions were in the range of those observed in the Upper-Rhone river confluences (Guillén-Ludeña, 2015), where the tributaries provide the dominant sediment load to the confluences. With these sediment rates and the adopted flow discharges, the downstream flow depth h_d was calculated by assuming uniform flow at the downstream end of the main channel. The values of h_d, the associated flow velocity (U_d), and the width of the main channel (B) were used to normalize the different magnitudes.

2.3 Experimental procedure and measurements

At the beginning of each experiment, the bed of each flume was prepared with the same sediment mixture that was subsequently supplied to the flume. In the main channel, the initial bed was nearly horizontal. In the tributary, a small bed discordance of ~0.03 m at the tributary mouth, and a bed slope of ~ 0.5% were imposed in order to accelerate the bed evolution. The initial bed morphology was observed to not affect the final morphology, since the bed discordance and bed slope at equilibrium were higher than those imposed initially.

The experiments were run until reaching equilibrium, i.e. when the outgoing sediment rate was nearly equal to the incoming, and the bed topography reached a steady state. To assess whether equilibrium was reached, the outgoing sediments captured in a sediment trap at the downstream end of the main channel were weighed periodically. Additionally, the evolution of the bed topography was monitored by means of periodical topography surveys.

Once equilibrium was reached, water surface and bed topography were recorded in the tributary and main channel. The bed topography was measured with a Mini Echo Sounder with ± 1 mm accuracy. The water surface was measured with an ultrasonic limnimeter with ± 1 mm accuracy. For the experiment performed at EPFL, with non-uniform sediments, the measurements consisted in 9 longitudinal profiles laterally spaced by 0.05 m along the main channel, and in 1 profile along the axis of the tributary. For the experiment performed at IST, with uniform sediments, the measurements consisted in 22 longitudinal profiles laterally spaced by 0.02 m along the main channel, and in 1 profile along the axis of the tributary. The spatial resolution was of 0.01 m for all the measurements.

3 RESULTS

3.1 Hydro-morphodynamics of the main channel

With non-uniform sediments, the bed morphology in the main channel at equilibrium was characterized by: i) a bank-attached bar along the inner bank downstream of the confluence, ii) a scour hole that extended from the tributary mouth to the outer bank, iii) a bed raise at the inner bank, upstream of the confluence, and iv) penetration of the tributary-mouth bar into the main channel.

In this experiment, the water surface at equilibrium presented: i) a horizontal profile upstream of the confluence associated with a back-water curve, ii) a drop at the downstream junction corner indicating the presence of a low pressure zone, and iii) a steep slope downstream of the confluence associated with higher flow velocities. These features are depicted in Figure 3, which shows, for the experiment performed with non-uniform sediments, the bed topography at equilibrium as well as two longitudinal profiles of the bed and water surface elevations, along the inner and outer bank of the main channel.

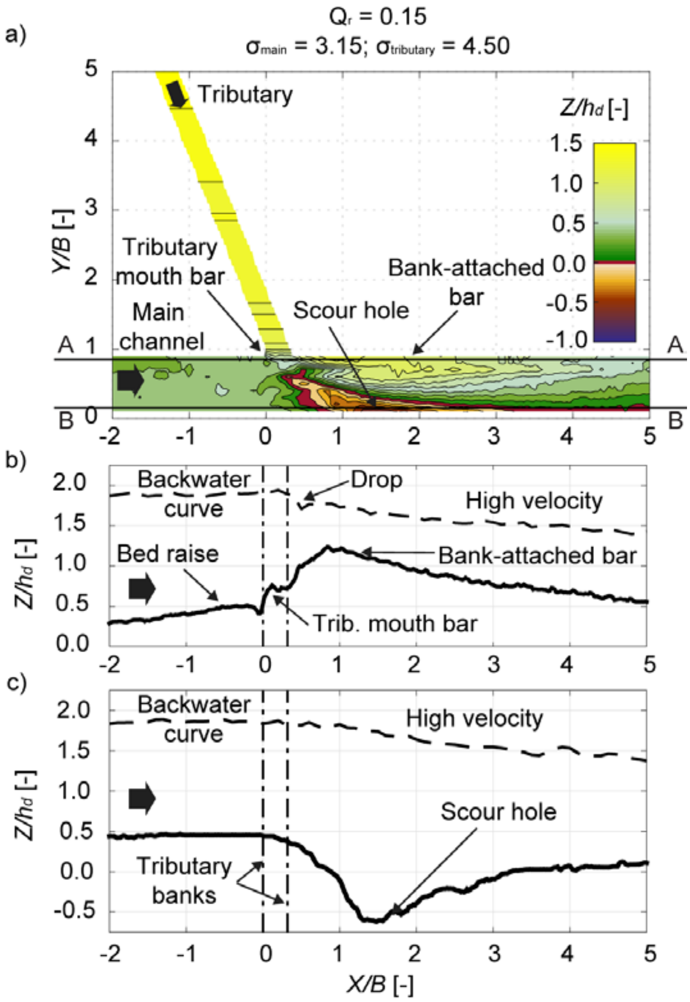

Figure 3. Bed topography and water surface at equilibrium with non-uniform sediments. a) Plan view of the bed topography at equilibrium for the tributary and main channel. b) Bed elevation and water surface elevation along the inner bank of the main channel (Section A-A indicated in Figure 3a). c) Bed elevation and water surface elevation along the outer bank of the main channel (Section B-B indicated in Figure 3a).

Figure 4 shows, for the experiment performed with uniform sediments, the bed topography at equilibrium and two longitudinal profiles of the bed and water surface elevations, along the inner and outer bank of the main channel. In this experiment, the bed morphology of the main channel at equilibrium presented similar features as those observed with non-uniform sediments, i.e. a bank-attached bar and a scour hole. Besides these features, the bed morphology obtained with uniform sediments included dune-like bedforms throughout the main channel.

The bedforms observed in the main channel upstream of the confluence presented an average wave length of $\lambda \sim 3\ h_d$ and a height of about $\Delta \sim 0.1\text{-}0.3\ h_d$. Downstream of the confluence, the length and height of the bedforms were $\lambda \sim 10\text{-}12.5\ h_d$ and $\Delta \sim 0.5\ h_d$, respectively. No tributary penetration into the main channel was observed with uniform sediments. The water surface at equilibrium presented attenuated features, compared to those observed with non-uniform sediments. These features are: i) a steeper slope of the water surface downstream of the confluence, indicating higher velocities; and ii) the water surface drop at the downstream junction corner associated with a low-pressure zone.

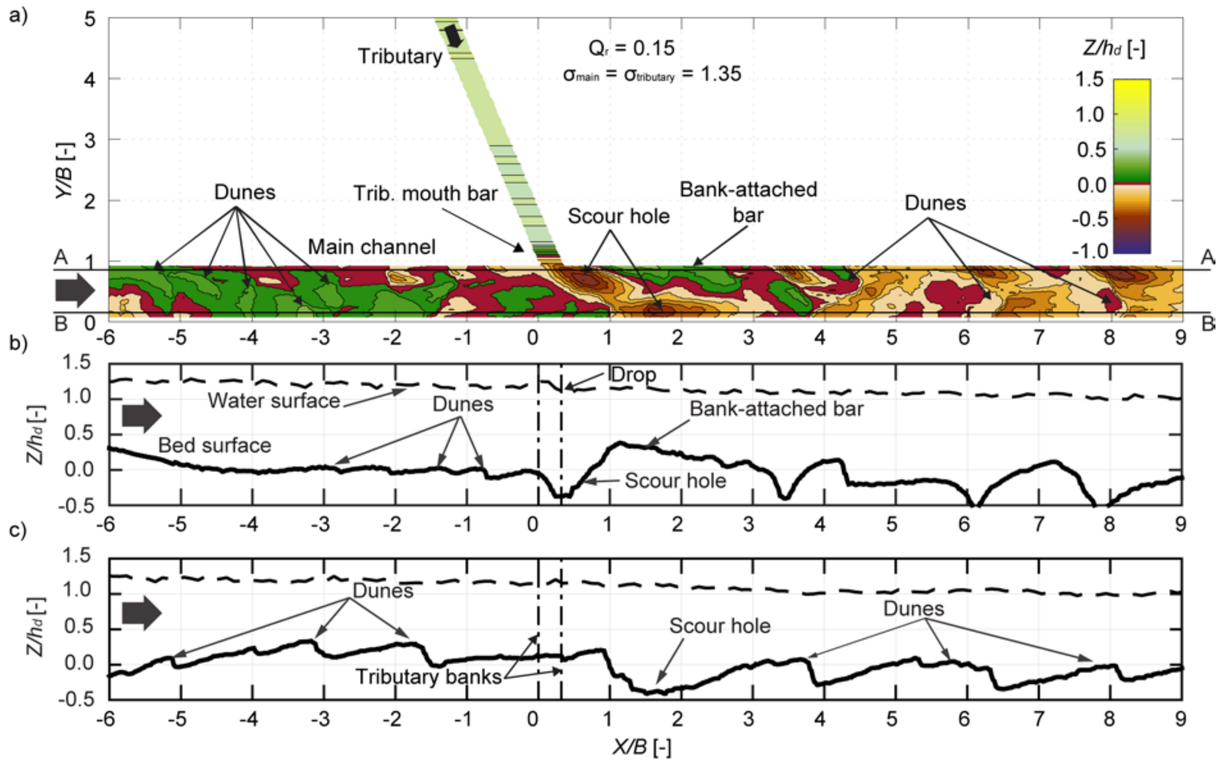

Figure 4. Bed topography and water surface at equilibrium with uniform sediments. a) Plan view of the bed topography at equilibrium for the tributary and main channel. b) Bed elevation and water surface elevation along the inner bank of the main channel (Section A-A indicated in Figure 4a). c) Bed elevation and water surface elevation along the outer bank of the main channel (Section B-B indicated in Figure 4a).

The flow regime of the main channel was classified based on the mean values of flow depth (*h*), mean velocity (*U*), and Froude number (*Fr*). In addition, the van Rijn's (1984b) method was used upstream and downstream of the confluence to classify the bedforms of the main channel. According to this method, the bed material and the sediment transport capacity are characterized by D_* and *T*, respectively. Both are defined as:

$$D_*=d_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \quad [3]$$

$$T=\frac{(u_*)^2-(u_{*,cr})^2}{(u_{*,cr})^2} \quad [4]$$

In this study, the mean diameter d_m was adopted to characterize the bed material instead of the median diameter d_{50}. The reason of this modification is that the supplied sediment mixtures have the same d_{50} values (d_{50} = 0.82 mm, see Figure 2), which do not reflect the differences between them. Therefore, in equation [3], d_{50} is substituted by the mean diameter d_m, *s* denotes the specific density, *g* is the gravity acceleration, and ν is the kinematic viscosity coefficient. In equation [4], u_* denotes the bed-shear velocity, and $u_{*,cr}$ is the critical bed-shear velocity (Shields, 1936). u_* and $u_{*,cr}$ were obtained as follows:

$$u_*=U\left(g^{0.5}/C'\right) \quad [5]$$

$$u_{*,cr}=\sqrt{\tau_{cr}(s-1)d_m} \quad [6]$$

where *C'* is the Chézy roughness coefficient and τ_{cr} denotes the critical shear stress. These were obtained according to van Rijn (1984a):

$$C'=18\ \log\left(12R_h/3d_{90}\right) \quad [7]$$

$$\tau_{cr}=0.013\ (D_*)^{0.29} \text{for} \quad 20\leq D_*\leq 150 \quad [8]$$

where R_h denotes the hydraulic radius and d_{90} is the particle size coarser than 90% by weight of the bed material.

For the experiment performed with non-uniform sediments, the bed material of the main channel upstream of the confluence was characterized by the GSD of the sediment mixture supplied to the main channel (d_m = 1.4 mm and d_{90} = 3.0 mm). The bed material of the tributary and that of the main channel downstream of the confluence were characterized by the GSD of the sediment mixture supplied to the tributary (d_m = 2.3 mm and d_{90} = 5.7 mm). In the case of the experiment performed with uniform sediments, the bed material of both flumes was approached by the GSD of the sediment mixture supplied to them (d_m = 0.82 mm and d_{90} = 1.40 mm)

Table 1 shows the normalized mean values of flow depth (h/h_d) and flow velocity (U/U_d) for the main channel upstream and downstream of the confluence. Also, the Froude number (Fr) and the dimensionless parameters of van Rijn(1984b) (D_* and T) are shown in Table 1. Sub-indexes *up* and *dw* refer to upstream and downstream of the confluence, respectively.

Table 1. Non-dimensional mean values of the hydraulic variables of the main channel at equilibrium.

Sediment mixture	Q_r	Upstream (X/B < 0)					Downstream (X/B > 0)				
		h_{up}/h_d	U_{up}/U_d	Fr_{up}	D_{*up}	T_{up}	h_{dw}/h_d	U_{dw}/U_d	Fr_{dw}	D_{*dw}	T_{dw}
	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Non-uniform	0.15	1.45	0.60	0.42	35	0.82	1.04	0.96	0.80	58	2.71
Uniform		1.05	0.83	0.55	22	2.19	1.04	0.97	0.57	22	3.33

Both experiments presented subcritical flow regime (Fr <1) upstream and downstream of the main channel at equilibrium. Also, for both experiments, the flow velocity increased from upstream to downstream of the confluence, which resulted in an increase of the sediment transport capacity ($T_{dw}>T_{up}$). The differences in flow depth, flow velocity, Froude number, and sediment transport capacity between upstream and downstream of the confluence were more pronounced for the experiment performed with non-uniform sediments (Table 1).

The dune-like bedforms observed in the main channel at equilibrium in the experiment performed with uniform sediments, as well as the absence of bedforms reported for the experiment performed with non-uniform sediments, are in agreement with the observations made by van Rijn(1984b) for the pairs of values $\{D_*,T\}$, corresponding to each experiment. In addition, the increase of the length and height of the bedforms of the main channel, observed from upstream to downstream of the confluence is consistent with the increase of the sediment transport capacity, reported above. This increase may be attributed to the augmented shear stress associated with the higher velocities registered downstream of the confluence, compared to those registered upstream.

3.2 Hydro-morphodynamics of the tributary

Figure 5 visualizes, for both experiments, the elevation of the bed and water surface of the tributary at equilibrium. Figure 6 depicts the tributary-mouth bar at equilibrium of each experiment. The bed morphology of the experiment performed with non-uniform sediment was characterized by a steep and nearly constant slope where Y/B> 1.5, a marked bed discordance with the main channel, a significant penetration of the tributary mouth bar into the main channel, and armored bed along the tributary (Figures 5a and 6a). In the case of the experiment performed with uniform sediments, the bed morphology presented a mild and nearly constant slope where Y/B> 1.5, a marked bed discordance with the main channel, a little penetration of the tributary-mouth bar into the main channel, and dune-like bedforms where 3 >Y/B> 1.5 (Figure 5b and 6b). The wave length of these bedforms was of λ~ 3.2-3.6h and the height increased from $\Delta \sim 0.12h$ to $\Delta \sim 0.20h$ as approaching the confluence. h is the mean flow depth of the tributary where Y/B> 1.5.

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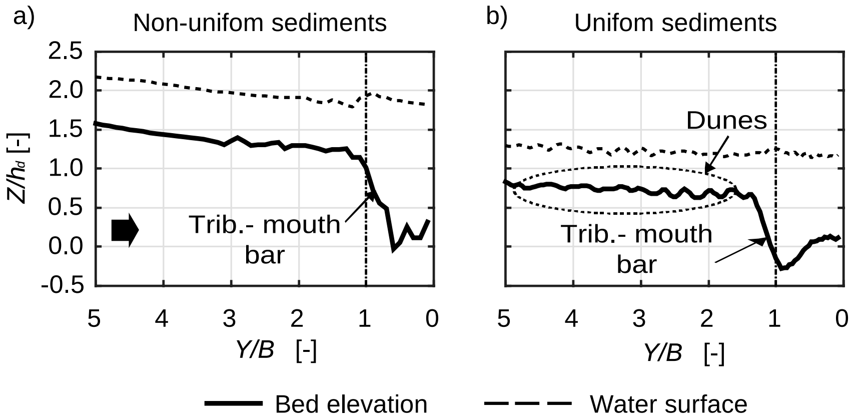

Figure 5. Longitudinal profiles of the bed elevation and water surface measured at equilibrium along the axis of the tributary. a) Non-uniform sediments, b) Uniform sediments.

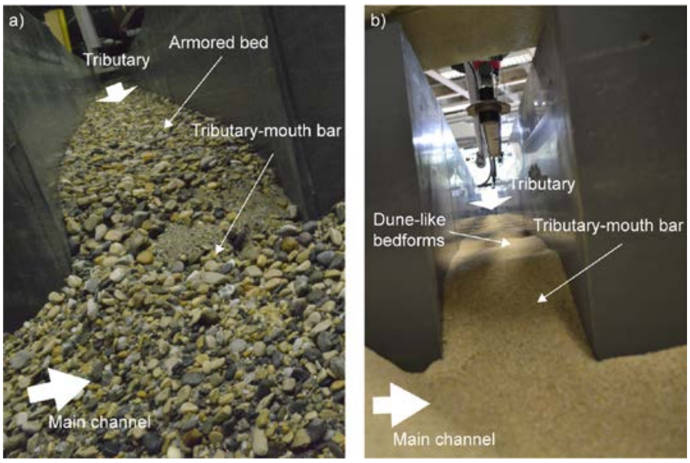

Figure 6. Views of the tributary mouth at equilibrium corresponding to: a) Non-uniform sediments, and b) uniform sediments.

Table 2 contains the values of the non-dimensional mean values of the flow depth (h/h_d), flow velocity (U/U_d), Froude number (Fr), and the particle and transport stage parameters of van Rijn(1984b) (D_* and T), corresponding to the upstream reach of the tributary (Y/B >1.5) at equilibrium. These values revealed that the flow regime of the tributary at equlibrium was subcritial (Fr< 1) for both experiments. Also, the armored bed observed for non-uniform sediments, and the bedforms observed for uniform sediments are in agreement with the observations made by van Rijn(1984b) for the pair of values {D_*, T} obtained for each experiment.

Table 2. Non-dimensional values of the hydraulic variables of the tributary at equilibrium where Y/B> 1.5.

Sediment mixture	Q_r [-]	h/h_d [-]	U/U_d [-]	Fr [-]	D_* [-]	T [-]
Non-uniform	0.15	0.63	0.69	0.74	58	1.97
Uniform		0.50	0.86	0.74	22	4.01

4 DISCUSSION

The bed morphology at equilibrium presented common features in both experiments. These features are typically observed in river confluences (Best, 1987; Best, 1988; Biron et al., 1993; Bristow et al., 1993; Best and Rhoads, 2008), and consist of: i) a bank-attached bar at the inner bank of the main channel, ii) a scour hole which extends from the tributary mouth to the outer bank, iii) and a marked bed discordance between the tributary and main channel. Such features are influenced by the gradation (σ) of the sediment mixtures supplied to the flumes during the experiments.

The bank-attached bar formed with non-uniform sediments (high σ) is considerably larger than that formed with uniform sand (low σ) (Figures 3 and 4). With non-uniform sediments, the coarser particles provided by the tributary to the confluence could not be conveyed downstream. They consequently tend to deposit at the downstream junction corner, building the bar. During the experiments, the size of the bar increases, which reduces the effective flow section and accelerates the flow until the necessary conditions to transport the bedload imposed from upstream are met. In contrast, the finer sediments supplied to the confluence for the experiment performed with uniform sand, are conveyed more easily by the resultant flow, yielding smaller bars.

In the experiment performed with non-uniform sediments, the scour hole is mostly concentrated at the outer bank, whereas in the experiment performed with uniform sediments the scour hole extends from the tributary mouth to the outer bank (Figures 3 and 4). The comparatively deeper scour holes at the tributary mouth observed with uniform sediments (Figure 4) can be justified as the fine particles are transported more easily than the coarse ones, promoting more erosion. The deeper erosion observed at the outer bank of the main channel with non-uniform sediments (Figure 3), compared with the results obtained with uniform sediments (Figure 4), may be attributed to a stronger flow concentration and acceleration at that location. This major concentration and acceleration of the flow is caused by the larger bank-attached bar formed with non-uniform sediments. In contrast, the smaller bars formed with uniform sediments lead to less flow deflection, resulting in lesser erosion at the outer bank.

In the tributary and with non-uniform sediments, the bed morphology at equilibrium presented steeper bed slopes upstream of the confluence and further penetration of the tributary-mouth bar in the main channel, with respect to the results obtained with uniform sediments (Figure 5). To convey the wide range of particle sizes supplied to the tributary in the experiment performed with non-uniform sediments, the bed adopted a steep slope increasing the available shear stress. In contrast, the bed evolves toward comparatively flatter slopes in the experiment performed with uniform sand, since the sediment load is composed of finer particles. These fine particles are easily eroded by the turbulence associated with the flow junction and thus, the tributary bed does not penetrate into the main channel as far as it does with the coarser sediments of the non-uniform mixtures. The bed discordance is related to the different sediment rates transported by each flume (Leite Ribeiro et al., 2012; Guillén-Ludeña et al., 2015; Guillén-Ludeña et al., 2016). The similar bed discordance observed for the low and intermediate discharge ratios in both experiments may be attributed to the fact that the sediment rates are the same. In the case of uniform sediments, the turbulence associated to the flow junction erodes the fine bed increasing the discordance, whereas for the experiment performed with non-uniform sediments, the flow resulting from the junction is not able to erode the bed at the tributary mouth because it is composed of coarse particles.

The morphodynamics differences observed between both set of experiments may be qualitatively explained through the Lane's (1955) balance:

$$Q \times J \sim Q_s \times d \quad [9]$$

where Q and J denote the flow discharge and bed slope, and Q_s and d denote the rate and characteristic grain size of the sediment supplied from upstream. Lane (1955) stated that the river regime requires a balance between the sediment supply and the transport capacity. The idea is based on that if any of the variables is altered, at least any one other will change to maintain the regime. In this study, the sediment rates (Q_s) and the flow discharges (Q) were fixed for the experiments run with the same discharge ratio, and the characteristic grain diameter of the supplied sediments (d) was coarser for the non-uniform sediments than for the uniform. This implies that the variable which must compensate the variation in *d* is the bed slope (*J*). In this line, the coarser sediments supplied with the non-uniform mixtures lead to an increase of the bed slope, which in turn is reflected in a steeper slope of the water surface (Figure 3).

In the experiment performed with non-uniform sediments, the morphodynamics of the confluence seem to be governed by the imposed sediment loads. In this experiment, the bed morphology evolves as to enhance the sediment transport capacity of the flow and thus conveys the coarser sediments provided by the tributary. The development of the bank-attached bar, the scour hole, and the steep bed slope of the tributary are evidences of this morphological evolution. In the experiments performed with uniform sediments, the dunes observed in both flumes at equilibrium reveal a relative excess of transport capacity (Dey, 2014), which lead to attenuated morphological features that are masked by the bedforms. The differences in bed morphology are reflected in the water surface. With non-uniform sediments, the water surface exhibits an abrupt change of slope from upstream to downstream of the confluence (Figure 3), revealing a high velocity gradient. With uniform sediments, only minor changes are observed in the slope of the water surface (Figure 4), indicating a smoother flow acceleration.

In the experiment performed with non-uniform sediments, the high gradation coefficient of the mixture supplied to the tributary results in an armored bed which inhibits the formation of bedforms (Chiew, 1991). On the contrary, in the experiment performed with uniform sediments, the low gradation of the supplied sediment mixture leads to the formation of bedforms in the tributary and main channel. These bedforms are dunes, agreeing with the bedform predicted by van Rijn (1984) and Yalin (1992), though the length of these dunes differs from what is proposed by them.

5 CONCLUSIONS

The effects of the sediment gradation coefficient (σ) on the hydro-morphodynamics of open-channel confluences are analyzed and discussed in this study.

With non-uniform sediments (high σ), the confluence morphodynamics evolve until the sediment transport capacity, necessary to transport the wide range of particle sizes, is attained. This evolution results in a bed morphology characterized by a high topographic gradient with a large bank-attached bar, a deep scour hole at the outer bank of the main channel, and a steep and armored tributary bed that notably penetrates into the main channel. Also, the high value of σ promotes bed armoring, which inhibits the formation of bedforms.

The lack of coarse particles in the uniform sediment mixture (low σ) facilitates the transport of the imposed sediment load. This results in a bed morphology with an attenuated bank-attached bar and scour hole, a flatter bed slope in the tributary and a slight penetration of the tributary-mouth bar into the main channel. Also, the migrating dunes observed in both channels mask the typical morphological features of the confluence.

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