# Morphodynamic differences induced by a widening of the tributary mouth in a river confluence

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ABSTRACT: River widening has progressively been studied as a structural solution in the context of river rehabilitation works in order to improve riparian and in-stream habitat for fauna and flora by allowing the river to adjust to its natural dynamics which consist in the increasing diversity of flow, morphology and sediment substrate. Specifically, investigation has shown that local tributary widening amplifies the diversity in sediment substrate, flow velocities as well as flow depths which contribute to an intensification of the morphodynamic processes. Thus, this paper aims the analysis of the differences induced by an uniform sediment substrate in a widen tributary in a river confluence in which sediment were discharged in both confluent channels.

## 1 Introduction

River training works have been carried out, since the beginning of the industrial era, with the aim of appeasing societal needs such as conquering land from the river to agriculture, flood protection, irrigation and navigation. During these processes, fluvial ecosystems and river's natural dynamics were strongly affected causing several impacts, as most interventions did not foresee or underestimated such impacts, particularly through morphological changes that often led to an impoverishment of biological conditions. Such deterioration was characterized by the lack of structural diversity such as riffles, pools, backwaters, gravel banks or islands. In this context, river confluences, nodes of river networks and thus having a central role over fauna circulation, bed morphology and hydrodynamics as well as sediment transport, were affected by the changes mentioned above. Therefore, the current river intervention philosophy aims the merger between flood protection and the increase of biological values.

In this context, preceding authors performed physical experiments as well as field experiments with the intention of characterizing flow and morphological features in river confluences. Best (1987) proposed a flow model in confluences defined by five zones: i) flow deflection, ii) flow stagnation, iii) flow separation or flow recirculation, iv) acceleration and v) flow recovery. He later presented the respective model for sediment transport and bed morphology (Best, 1988). Biron *et al.* (1996) analyzed the effects in flow dynamics of discordant bed in channel confluences (in which the tributary bed level differs from the main channel bed level at the tributary mouth), which is, according to Kennedy (1984), a more common feature in river confluences. Albeit the valuable information on morphological and flow dynamics provided by laboratory and field experiments over the last 30 years, few were the ones that were performed under mobile bed conditions (Mosley, 1976; Best, 1988; Best & Rhoads, 2008). In order to fill this gap, Boyer *et al.* (2006), Leite Ribeiro *et al.* (2012a, b) and Guillén-Ludeña *et al.* (2015) analyzed the effects of discordant bed confluences on flow, morphodynamics and sediment transport.

Leite Ribeiro *et al.* (2012a, b) studied the effectiveness of local tributary widening on discordant bed confluences as a potential solution of confluence rehabilitation on discordant bed confluences. His experiments were made under mobile bed conditions, carried in a laboratory confluence where the tributary and the main channel joined at a 90º angle, the bed was constituted of poorly-sorted sediments (gradation coefficient of 4.15) and sediments were only supplied to the tributary. Guillén-Ludeña *et al.* (2015) expanded Leite Ribeiro's research by studying the effects of confluence angles (90º and 70º) and sediment feeding in both channels using the same sediment bed material, the same discharge ratio but different discharge values. Both authors concluded that local tributary widening is supposed to enhance heterogeneity in flow depths and velocities as well as sediment substrates, developing the local habitat. According to Weber *et al.* (2009), widening is a common solution for river rehabilitation whose main purpose consists on allowing the river to recover its natural dynamics.

The present study expands the scope of previous authors works by analyzing the effects of a tributary widening in a bed mobile laboratory confluence characterized by a junction angle of 70º and an uniform sand (gradation coefficient of 1,36) as sediment substrate, to be fed in both channels.

# 2 Methodology

## 2.1 Experimental facilities

Two tests were carried out in a laboratory confluence consisting in a 9.6 m long and 1.00 m wide rectangular straight concrete flume corresponding to the main channel, and a 4,0 m long and 0.15 m wide rectangular PVC channel corresponding to the tributary. Both channels connect with an angle of 70º. For both tests, two geometries were used: the so called "reference configuration", which corresponded to the non-widen tributary configuration whereas the second one in which the tributary presented a widening at its downstream reach was called herein "widen configuration". The widening was 0.45 m wide and 0.60 m long as shown in Figure 1.

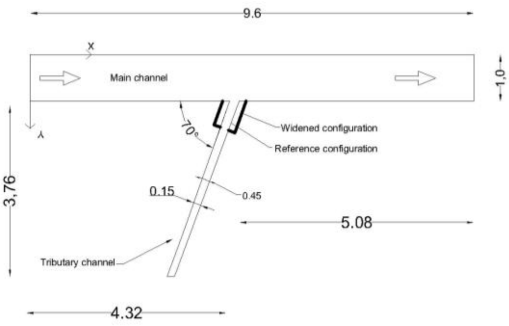


Figure 1: Plan view of the 70º laboratory confluence [m]

## 2.2 Experimental set up

The adopted discharge ratio ($Q_r = Q_t/Q_m$) in the present study, which is the ratio between the tributary discharge ($Q_r$) and the main channel discharge ($Q_m$) both considered upstream of the confluence, was 0.11 corresponding to the discharges adopted by Leite Ribeiro *et al.*(2012) and Guillén-Ludeña *et al.* (2015). The tributary discharge was 5.6 $l/s$ and the main channel discharge was 48.8 $l/s$. The solid discharge in the tributary was 0.5 $kg/min$, the same as used by Guillén-Ludeña *et al* .(2015), whereas, in the main channel, the sediment discharge was 0.6 $kg/min$. Such value for the main channel sediment discharge corresponds to twice the value of Guillén-Ludeña *et al.* (2015)'s, which was 0.3 $kg/min$, as their main channel width was 0.5 $m$.

As mentioned before, the sediment substrate in the present study was constituted by an uniform sand with a gradation coefficient of 1.36 for both tributary and main channel. Figure 2 depicts the grain size distribution of the sand.

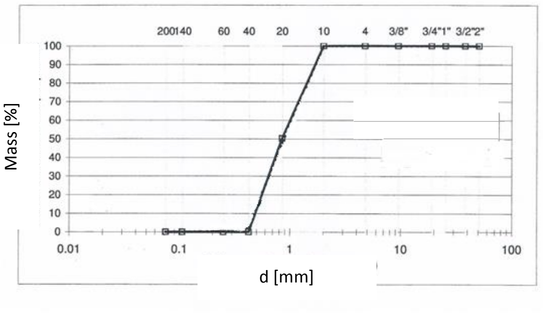


Figure 2: Grain size distribution for supplied sediment into tributary and main channel.

The grain density $(\rho_s)$ and characteristic diameters of the sand mixture, $(d_x)$, where $d_x$ is the grain size diameter for which x% of the sediments by weight are higher, are presented in Table 1.

Table 1. Main characteristics of the supplied sediments

| Channel | $\rho_s$ | $d_{30}$ | $d_{50}$ | $d_m$ | $d_{90}$ | $\sigma$ |
|---|---|---|---|---|---|---|
| | [kg/ m$^3$] | [mm] | [mm] | [mm] | [mm] | [-] |
| Tributary/Main | 2610 | 0.65 | 0.86 | 1.02 | 1.07 | 1.36 |

### 2.3 Experimental procedure

To carry out the experiments, sand was placed in both channels. A small step of around $0.03\,m$ was imposed at the junction between the tributary and the main channel, in order to fasten the development of the discordance between the main channel bed and the tributary bed. Furthermore, a slight slope of around 1% was imposed in the tributary channel and a 0.4% slope was set in the main channel. According to Guillén-Ludeña *et al.* (2015) such slopes do not affect the final topography since they are smaller than those reached in equilibrium. Once these slopes were set, the channels were slowly filled up with water (a discharge of around 10-15 l/s) and then both bed topographies were measured before the starting of the test.

Bed topography and water level measurements were recorded after 1, 4, 7 hours and when the equilibrium was reached (attained for 12 h) for the reference configuration test and 1, 7, 10 and 12 h, when equilibrium was reached, in the case of the widen configuration test. Water level measurements were performed with ultrasonic limnimeters $(\pm\, 1mm\, accurate)$ while the bed topography was measured with a Mini-Echo Sounder $(\pm\, 1\, mm\, accurate)$, which needed to be submerged, requiring the raise of the water level and therefore the interruption of the test.

Equilibrium was assumed to be reached when the sediment discharge ratio between the incoming and outgoing sediment discharge was larger than 85%. In order to control the sediment transport rate, the outgoing sediments were weighted periodically.

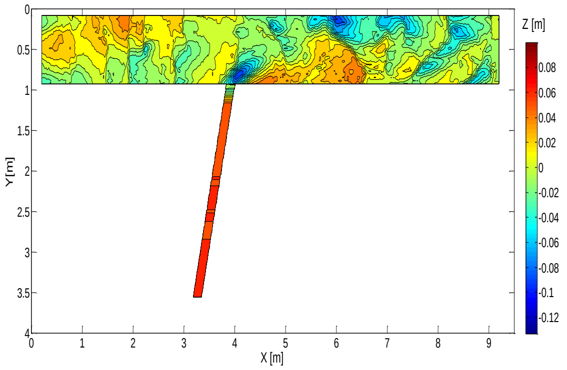
## 3. Results and discussion

### 3.1 Reference configuration test

The reference configuration test provided valuable information to be compared with Leite Ribeiro (2012)'s and Guillén-Ludeña *et al.* (2015)'s studies.

In this experiment, several topographic features detected by Leite Ribeiro (2012) were also identified. They include a step in the tributary mouth, the presence of a deposition bar at the inner bank of the main channel, downstream of the confluence, and the existence of a scour dominated zone at the outer bank of the post-confluence channel (cf. Figure 3). However, the present results presented few differences to Leite Ribeiro's (2012) results, being more in line the results recorded by Guillén-Ludeña *et al.* (2015).

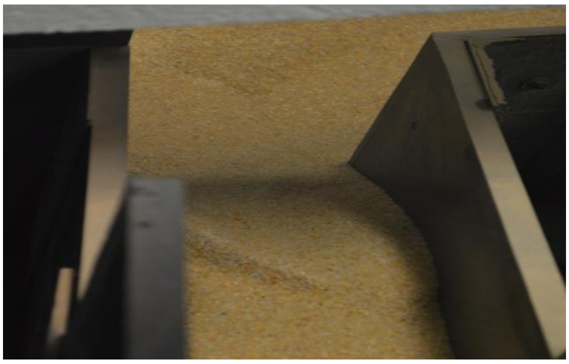
Figure 3: Bed topography at equilibrium for the reference configuration test



A well marked scour hole occurred in the tributary mouth ($Z = -0.071\,m$). This hole was deeper than the one recorded by Guillén-Ludeña (2015). A well marked scour path near the outer bank of the main channel was observed. None of these features were identified by Leite Ribeiro (2012). The explanation proposed by Guillén-Ludeña *et al.* (2015) to these differences is based in the fact that the liquid discharge in the tributary channel was higher, leading to a flow constriction in the same width that originated higher velocities and bigger accelerations causing more erosion and provoking a higher discordance between bed levels at the tributary mouth and in the outer bank. Furthermore, the discordance between the tributary bed level and the main channel bed level was 0,02 m higher than the ones recorded by the mentioned authors. According to Guillén-Ludeña *et al.* (2015), the higher sediment discharge in the tributary channel induces a raise in the bed level discordance. Notwithstanding, in the present experiment, the sediment discharge in the tributary was the same as used in Guillén-Ludeña *et al.* (2015)'s study but the bed level discordance was higher. It is important, though, to refer that the liquid discharge in the present experiment was 5.6 $l/s$, contrasting with the 3 $l/s$ used in Guillén-Ludeña *et al.* (2015)'s experiments. That difference is conjectured to be the reason for the observation of a higher discordance. Hence, bed level discordance between confluent channels depends not only on solid discharge but on liquid discharge as well. Moreover, a crest/edge, crossing the width of the tributary channel, preceded the steep slope at the tributary mouth, which is a characteristic only observed in the present study (Figure 2).

The origin of this crest (cf. Figure 4) is believed to accrue from a secondary near bed vortex characterized by a horizontal axis, in the direction of the main channel, with an upwelling component that protrudes in the tributary that tends to difficult the sediment transport from the tributary to the main channel. In that situation, sediment accumulate originating that crest.

Figure 4: Image of the crest in the tributaty channel near the mouth



Additionally, the crest provides a potential energy raise that allows the sediment particles to progress towards downstream. The water surface presented similarities with Guillén-Ludeña *et al.* (2015)'s results. At the tributary mouth, the water surface presented an abrupt increase (cf. Figure 5), related to the tributary inflow that preceded a decrease in its surface level ($X \approx 4\,m$). In turn, this decrease preceded an increase of the water surface (cf. Figure 4), most probably, reflecting the influence of the upwelling flow. The aforementioned decrease of the water surface is believed to be consequence of a zone of lower pressures, situated at the downstream corner of the confluence. Those pressures accrue from a loss of energy induced by the abrupt separation of the water from the inner walls of the main channel once the flow reaches the downstream corner of the confluence.

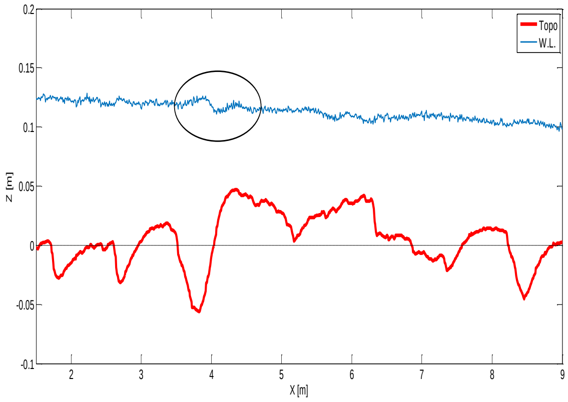
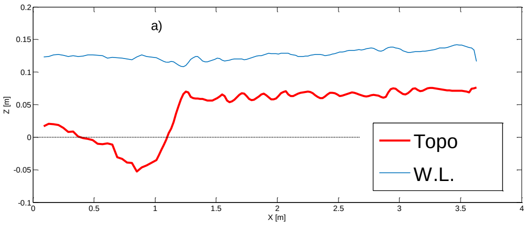


Figure 5: Bed surface (red)[1] and water level (blue) along the inner bank axis (Y = 0,93 m).

Hydrodynamic characteristics such as the flow separation zone were detected in the experiments that sustain the present report. Furthermore, an oblique stationary wave was registered throughout the experiment at the mouth of the tributary channel, indicating the jet effect from the tributary flow in the main flow. This oblique wave might have been an incipient form of hydraulic jump. This assertion is based in the fact that the crest in the tributary channel might have forced a local critical or supercritical flow since the Froude number in the tributary channel, varied from 0.72 to 0.93 thus revealing the unsteady character of the flow. That unsteady and transitory regime induced different morphologies throughout the experiment. Bed waves with marked sinusoidal profile, characteristic feature from anti-dunes were recorded (cf. Figure 6a) as well as was recorded almost horizontal bed, a transitory regime characteristic (cf. Figure 6b).



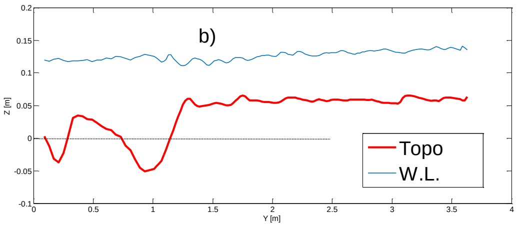


Figure 6: a) Bed surfaces and water levels at equilibrium for the reference configuration along the tributary axis with a) antidunes and b) horizontal bed

At last, it is important to highlight the fact that in this experiment, no armouring effect was recorded in channels morphologies. The grain size of the sediments being almost uniform, no grain size segregation could be registered as it had been in Leite Ribeiro *et al.* (2012a, b) and Guillén-Ludeña *et al.* (2015)'s experiments.

### 3.2 Widened configuration test

The widened configuration test presented morphological characteristics identical to those of the reference configuration test but it also induced morphological changes in both tributary and main channels.

The comparison between bed topographies at equilibrium, for the reference and widen configurations, revealed, in one hand, a raise of bed topography in both channels in the widen configuration (Figure 6) and, in the other hand, it revealed a shallower scour hole at the tributary mouth and in the outer bank of the post-confluence channel (Figure 6).

Moreover, a narrower, longer and slightly higher deposition bar was observed at the inner bank of the post confluence channel for the widen configuration (Figure 7 and Figure 8) as well as a deeper bed tributary penetration into the main channel (Figure 7), confirming Leite Ribeiro *et al.* (2012)'s and Guillén-Ludeña *et al.* (2015)'s results.

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[1] "Topo" stands for Topography and "W.L." stands for Water Level

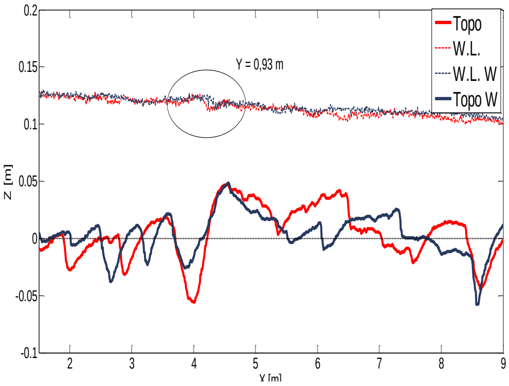

Figure 7: Bed surface and water levels for the reference (Topo and W.L.) and widen configurations (Topo W. and W.L. W).

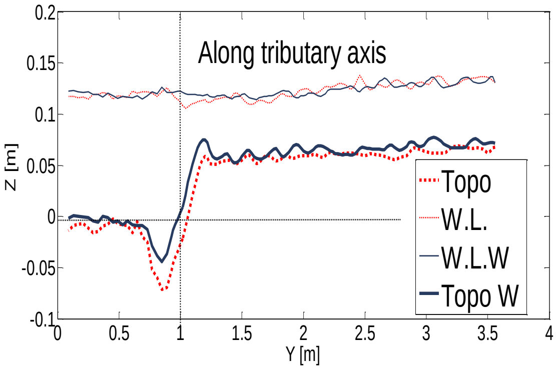

Figure 8: Bed surface and water levels at equilibrium for the reference and the widen configurations along the tributary axis[2]

Notwithstanding, the bed discordance between confluent bed channels is smaller $(\Delta z = 0{,}12\, m)$ than the one registered in the reference configuration $(\Delta z = 0{,}13\, m)$ which contradicts the aforementioned author's results.

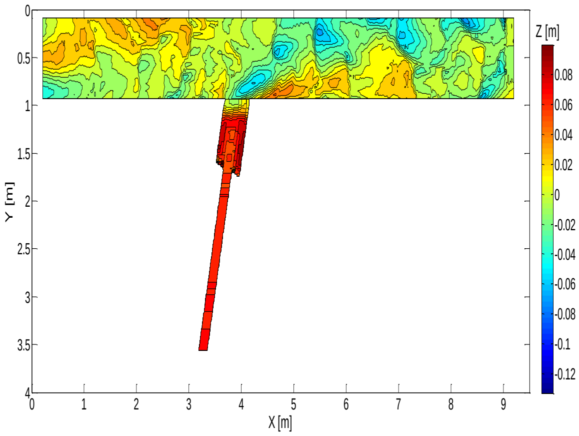

Figure 9: Bed topography at equilibrium for the widened configuration test

Besides, the widening reach presents different morphologies which are formed by two ditches at the upstream corners of the widening (zones 1 and 2 in Figure 9), two banks (zones 3 and 4 in Figure 9) near the lateral widening walls and a central corridor (zone 5 in Figure 9), where the widening thalweg is found. Such corridor presents a deviation towards downstream direction in the widening reach (Figure 9) reflecting the influence of the main channel flow that protrudes in the widening, forcing the mentioned deviation. Therefore, the solid and liquid discharge presented a higher X-axis velocity component that allowed an easier deposition immediately downstream of the confluence corner and the lower momentum along the Y-axis.

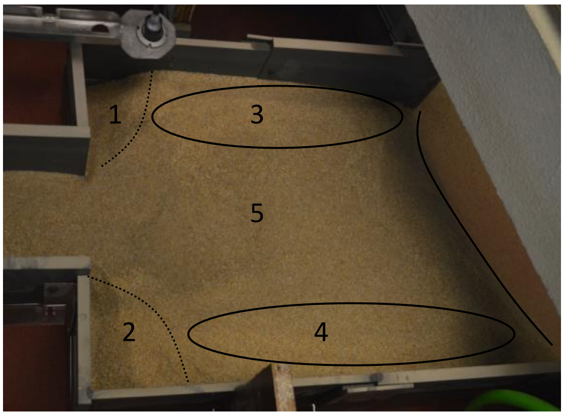

Figure 10: Lateral view of the widening reach of the tributary channel with different topographic zones

Concomitantly to the raise of the deposition bar, as said before, the widening induces scour hole depth reduction in the tributary mouth and in the outer bank of the post-confluence channel. Such reduction of scour hole depths contradicts the results presented by Leite Ribeiro (2012) and Guillén-Ludeña *et al.* (2015). Therefore it seems that the tributary flow loses its erosive power. This loss is conjectured to be the consequence of a lower intensity from the vortexes and mixing layer turbulence that accrue from a smoother entrance of the tributary flow "jet" in the main flow. Additionally, the tributary flow in the central corridor is wider than the one in the reference configuration, though being constrained by flow stagnation zones near the

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[2] "Topo W" and "W.L.W" stand for Topography Widening and Water Level Widening respectively

lateral walls of the widening reach, contributing to a smaller momentum that led to less vorticity than in the reference configuration. Thus, penetrating less in the main channel, the tributary flow jet is less outwards directed contributing therefore to less important erosion in the outer bank as well as in the tributary mouth. Finally, since the main channel in the present experiment has twice the width of Leite Ribeiro *et al.* (2012a, b) and Guillén-Ludeña *et al.* (2015)'s main channel, the tributary flow jet had much more influence than the one in the present study.

The topographic zones in the widening reach engendered different flow heights to which corresponded different flow velocities. No velocity measurements were made in the experiments that sustain the present study. However, the equilibrium topography suggests that, in face of a level near the downstream lateral wall of the widening reach (Figure 9), flow velocities are higher. In this situation, the flow has more sediment transport capacity, thus conveying more easily sediment to the inner bank of the main channel, immediately downstream of the confluence. Besides, the black line in Figure 9, at the tributary mouth, shows that the avalanche face, near the lateral downstream wall of the widening reach, protrudes further in the main channel when compared with the avalanche face in the lateral upstream wall of the widening reach. This feature reveals the important deviation of sediment towards downstream, strengthening the hypothesis suggesting that the tributary sediments are mainly transferred to the inner bank of the post-confluence channel, forming the deposition bar.

The ditches present at the widening reach are a consequence of the local hydrodynamics. As the flow reaches the widening, an abrupt separation from the transverse walls occurs and the flow is directed towards downstream without touching the upstream walls of the widening reach. The sediment path in the widening reach coincides, approximately, with the flow path shown in Figure 10, put into evidence by the dye injected in the upstream reach of the tributary channel.

Figure 11: Lateral view of the widening reach with dye injection in the tributary.

In these terms, few are the sediment particles that are deposited in the upstream corners of the widening reach, therefore generating the aforementioned ditches. Besides, visual observations evidenced the presence of water recirculation zones in those areas that could generate vertical vortices hindering the deposition of sediment.

The stationary water wave at the tributary mouth, observed in the reference configuration test, was also observed in the widen configuration test. Nevertheless, such wave was less marked than in the reference configuration test (cf. circle in Figure 6), occurring further towards downstream $(X \approx 4{,}34\ m)$.

As observed in Figure 8, there are no dry zones in the upstream corners of the widening reach, contrary to the observations by Leite Ribeiro *et al.* (2012). Such results are in line with the ones recorded by Guillén-Ludeña *et al.* (2015) who suggested that the submersion of those areas is due to the higher water discharge in the tributary channel.

## 4. Conclusions

The main purpose of the present work was to study the differences induced by the use of uniform sand as sediment substrate in the confluence channels. Many morphological hydrodynamic features recorded by previous authors were observed. Such features presented although slight differences such as the absence of the armouring effect in bed morphology.

Albeit some differences and contrary results accruing from the use of a wider channel, higher liquid and sediment discharges and different sediment substrate, this study revealed that a tributary widening in its final reach creates zones characterized by high diversity of water depths, flow velocities and bed substrate associated to flow stagnation zones and a central tributary flow corridor.

The widen configuration led to a narrower and higher deposition bar at the inner bank of the main channel, downstream of the confluence, and wider but shallower hole path in which recorded scour holes presented shallower depths when compared to those of Leite Ribeiro *et al.* (2012) and Guillén-Ludeña *et al.* (2015)'s. The explanation herein suggested consists in one hand on the fact that the effects of the tributary flow jet are more pronounced in narrower channels which is the case in the aforementioned authors experiments. In the other hand, the less outwards skewed tributary flow jet deviates towards downstream direction, closer to the inner bank of the post-confluence channel. This situation allows a "smoother entrance of the tributary flow jet" in the main channel, inducing less turbulence in the mixing layer associated with the weaken contact between confluent flows, leading to a loss of the tributary flow erosive power.

Hence, a higher heterogeneity in bed morphology, sediment transport paths and flow velocities are observed in the widening reach as well as in the main channel. Therefore, such widening is expected to develop adequate conditions for the settlement of diverse aquatic and riparian species, which need these habitats to complete their life cycle. Furthermore, widening reaches can shelter fish and other aquatic species during flood events besides presenting shallow slow-flowing areas offering suitable spawning and rearing conditions for rheophilic fish (Weber, 2009).

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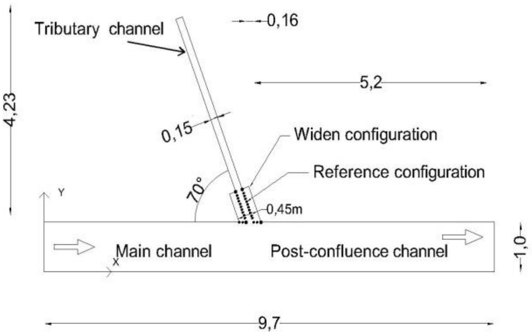
Tributary channel
0,16
5,2
4,23
0,15
Widen configuration
Reference configuration
70°
Y
0,45m
Main channel
Post-confluence channel
X
1,0
9,7