Influence of tributary widening on morphology and hydraulic variability in confluence zones

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Abstract: *In the aim of assessing the potential of tributary widening with respect to river rehabilitation in fluvial systems, attention is focused on the effects of tributary widening on the morphodynamic processes of confluence zones. Systematic tests were performed in a confluence flume where the confluent channels are connected with an angle of 90° and the main channel is 0.50 m wide. Three different widening of the tributary are compared to a reference configuration with a constant tributary width of 0.15 m for different discharge scenarios. All experiments were performed with mobile bed conditions and poorly sorted sediments supplied in the tributary channel and run until equilibrium conditions. Water levels, morphology and sediment size distribution were measured. Local widening of the tributary is shown to increase the variability of flow depth, flow velocity and particle size distribution, which enhances the ecological value of confluence zones without reducing the conveyance capacity of a given network.*

Keywords: *channel confluences, experimental investigation, morphodynamics, river rehabilitation.*

1. INTRODUCTION

In alpine regions of Europe, river training works were typically responsible for the transformation of wide and braided rivers into straight channels exhibiting monotonous linear profiles (Gurnell et al., 2009). Currently, only about 10% of the most important rivers of the entire European Alpine region are still in a "near-natural" condition (Rohde et al., 2005).

From the end of the 20th century, "river rehabilitation" has been a concept heavily used by environmental professionals. The purpose of rehabilitation is to recover the vital space required for the rivers which were degraded by human interventions and to link the sustainable use of rivers and wetlands with human well-being. In river systems, the vital space ensures the fluvial dynamics and the interface favourable to the river's fauna and flora. It is necessary to maintain the quantity and quality of the water in the natural water system in order to safeguard its role in the ecosystem over time (Havinga et al., 2005). Thus, river rehabilitation can be considered as complex processes in which fluvial dynamics, environment and flood protection play an important role. Additionally, no adverse impacts on flood safety resulting from rehabilitation projects can be tolerated.

Piedmont confluences such as found in alpine environments are typically characterized by steep gravel-bed streams carrying large sediment loads, which often connect asymmetrically at large angles with the main river at the valley bottom. A good understanding of the flow patterns, the sediment transport as well as the bed morphology is essential to successfully design river rehabilitation project of confluence zones.

Recently, Leite Ribeiro et al. (2009) investigated the influence of the discharge ratio ($Qr=Q_t/Q_m$) and the momentum flux ratio ($Mr=\rho Q_tU_t/Q_mU_m$) on the morphology of small asymmetric confluences by means of systematic experiments performed in a 90° confluence flume. The experimental conditions are representative of piedmont confluences such as found in the Upper Rhone River, in Switzerland. Results confirm that the morphology of the confluence zone is highly responsive to changes in *Mr*. With the increase of *Mr*, the following morphological behaviours can be highlighted: 1) the discordance between the tributary and main channel decreases; 2) the penetration of the tributary into the main channel decreases and 3) the deposition at the separation zone decreases. Leite Ribeiro et al. (2010) study the potential of a small local tributary widening on the increase of the ecological potential of confluence zones for three different discharge scenarios. Experiments were performed in the same experimental set-up described by Leite Ribeiro et al. (2009).

The present paper extends the analyses performed by Leite Ribeiro et al. (2010) to different widening dimensions. The aim is to understand how robust/stable is the resulting morphology with respect to changes in the geometric configuration of the tributary widening and to analyse the ecological potential of a local tributary widening in confluence zones.

2. DESIGN OF THE EXPERIMENTS

In order to design the experimental set-up and the conditions for the research project, a detailed analysis of the Upper Rhone River basin (Switzerland) and its twenty main confluences between Brig and Lake Geneva was conducted. This basin was chosen because of its representativeness of regulated piedmont river systems. Furthermore, rehabilitation projects are planned in this basin and their design suffers from a lack of knowledge about the morphodynamic processes involving the confluences zones. The main hydraulic and geometrical characteristics of the Upper Rhone confluences used for designing the experimental set-up and the experimental conditions are summarized in Table 1.

Table 1: Hydraulic and geometric characteristics of the main confluences of the Upper Rhone

	Angle [°]	*B_t/B_m*	*$B_m/B_{p\text{-}c}$*	*Tributary bed slope*	*Qr_Q2*	*Fr_{tQ2}*	*Mr_Q2*
Average	62	0.22	1.02	1.1%	0.10	0.83	0.11
Max	90	0.54	1.27	4.0%	0.32	1.29	0.45
Min	30	0.07	0.71	0.0%	0.01	0.03	0.01

Qr_Q2= *Discharge ratio between the tributary (Qt) and main channel (Qm) during a 2-year return period flood event*

Fr_{tQ2} = *Tributary Froude Number during a 2-year return period flood event*

Mr_Q2= *Momentum flux ratio between the tributary and main channel during a 2-year return period flood event*

The Upper Rhone confluences are usually characterized small steep tributaries (average tributary slope of 1.1%). During channel-forming events (Q_2), the discharge and momentum flux ratios relatively low (0.01<*Qr*<0.32 and 0.01<*Mr*<0.45 respectively). From the analyses of the existing literature (Figure 1), it is possible to see that the couples *Mr versus Qr* characterizing the Upper Rhone confluences are considerably lower and out of the range those already investigated in river confluence studies (Best, 1988; Biron et al., 1993; Rhoads & Kenworthy, 1995; Leclair & Roy, 1997; Rhoads & Kenworthy, 1998; Biron et al., 2002; Boyer et al., 2006).

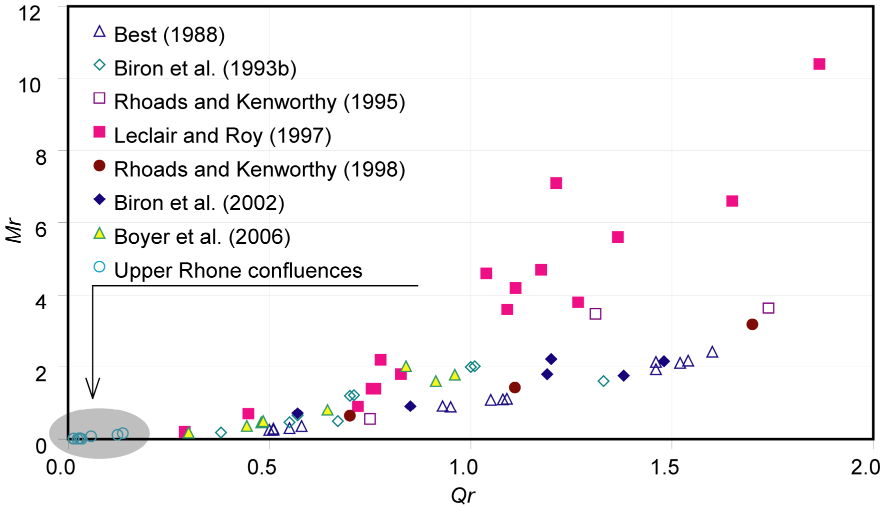

Figure 1: Momentum flux ratios (*Mr*) versus the discharge ratios (*Qr*) studied in literature and those characterizing the Upper Rhone confluences. With exception of Best (1988), who investigated laboratory confluence, all the other works considered field measurements.

3. EXPERIMENTAL SET-UP

Laboratory tests were performed in a confluence flume (Figure 2) where the main channel is 8.5 m long and 0.50 m wide. A tributary channel, 4.9 m long and 0.15 m wide is connected with an angle of 90°, 3.60 m downstream of the inlet of the main channel. More details about the experimental set-up can be found in Leite Ribeiro (2011).

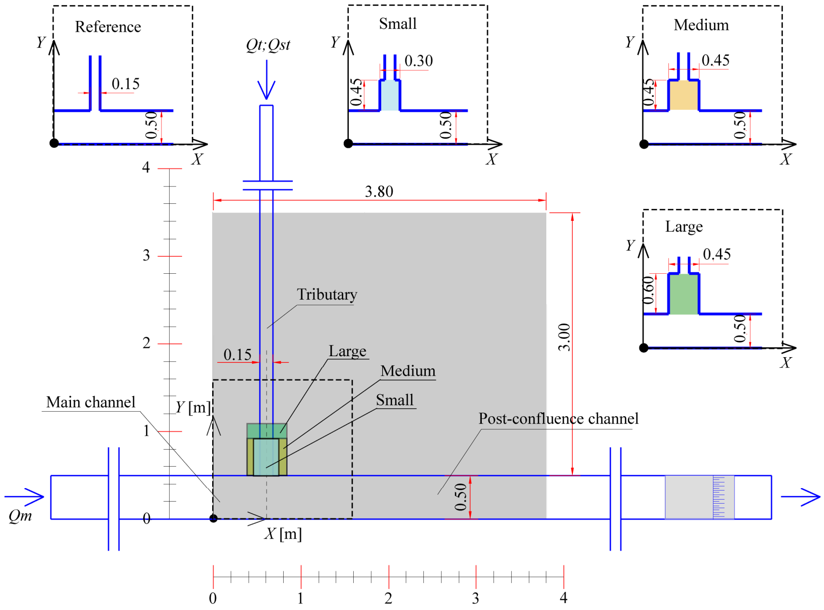

Figure 2: Experimental set-up and geometric configurations of the confluence zone

Three water discharge scenarios were chosen in the range of the discharge ratios *Qt/Qm* presented in Table 1: a "low discharge scenario", where Q_t=2 l/s and Q_m=18 l/s (Q_t/Q_m=0.11), an "intermediate discharge scenario" with Q_t=2.6 l/s and Q_m=17.4 l/s (Q_t/Q_m=0.15) and a "high discharge scenario" where Q_t=3.7 l/s and Q_m=16.3 l/s (Q_t/Q_m=0.23).

Four geometric configurations of the confluence zone (Figure 2) including the reference case (no widening) and three local tributary widenings are analysed. For the "Small" configuration, the tributary width has been symmetrically doubled (B_w = 0.30 m) over a length (L_w) of 0.45 m while the "Medium" configuration considers a tributary three times wider (Bw = 0.45 m) within the same length (L_w = 0.45 m). The "Large" configuration is composed by a tributary also three times wider (B_w = 0.45 m) over a length L_w = 0.60 m.

For all experiments, the bed of the flume was covered with the poorly sorted sediment mixture. At the beginning of the experiment, the bed of the main and post-confluence channels was flat and the longitudinal slope of the tributary at its mouth was approximately 0.5%. An adjustable tailgate at the end of the post-confluence channel controlled the flow depth within the entire flume. The water level at the end of the channel was kept constant at 0.07 m. For the experiments, poorly-sorted sediments (d_{50} = 0.82 mm, d_{90} = 5.7 mm) were adopted. Sediments were only introduced in the tributary in a constant rate of Qs_t=0.30 kg min^{-1}.

The evolution of the water levels (automatic ultrasonic limnimeters) and the bed topography (Mini EcoSounder) are recorded during the tests. All the results discussed in this paper concerns the equilibrium state of each experiment.

4. MORPHODYNAMICS OF CONFLUENCE ZONES

The equilibrium bed morphologies of the confluence zones (0<X<2 m and 0<Y<1.2 m) are shown in Figure 3. The equilibrium morphologies of the different tests confirms the morphological description of the confluence zones presented by (Leite Ribeiro *et al.*, 2009) and discussed in section 1. However, no important differences could be highlighted in the main, post-confluence and tributary channels due to the different widening dimensions for each same discharge scenario.

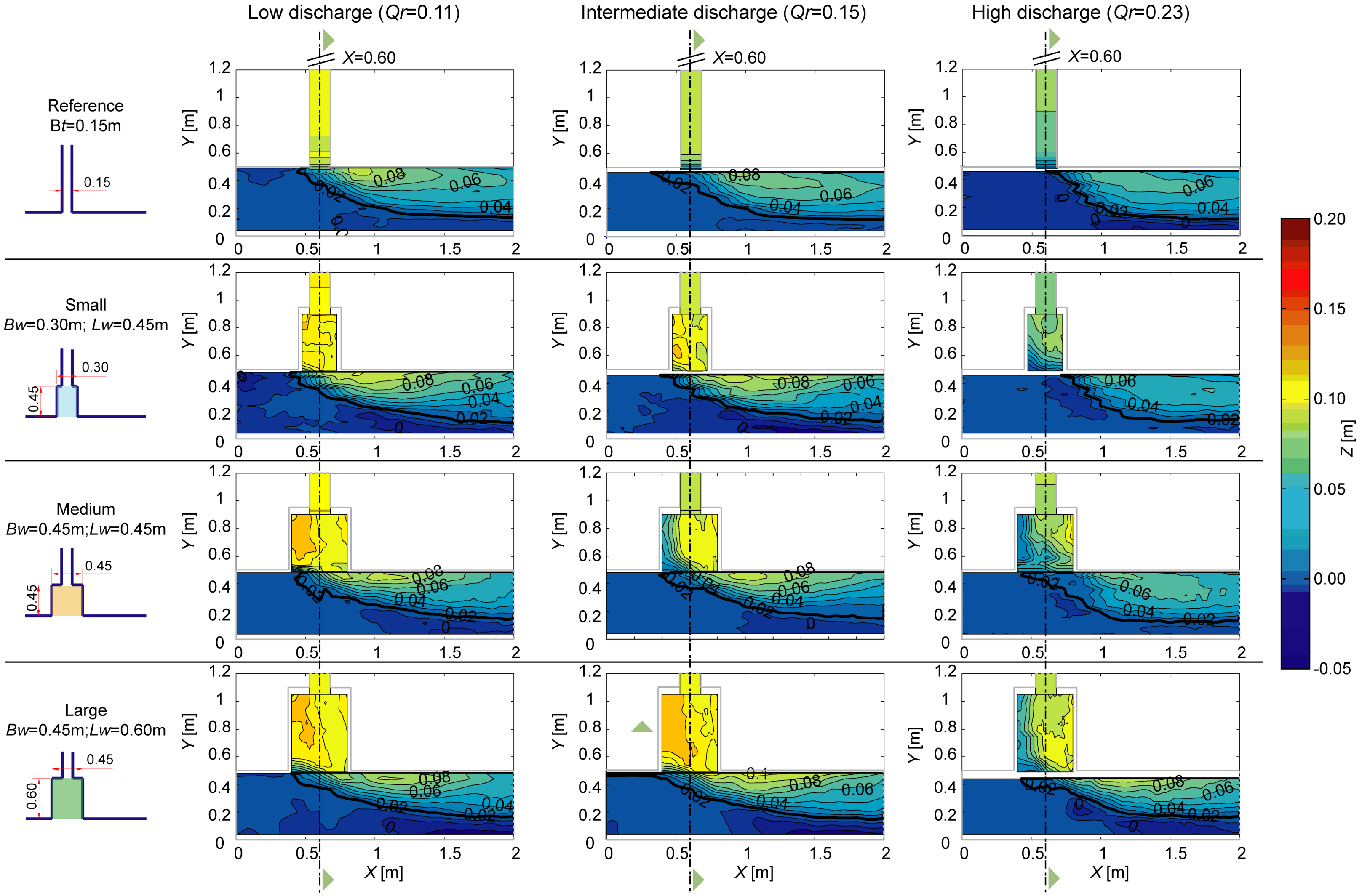

Figure 3: Equilibrium bathymetry of the main, post-confluence and part of the tributary channels for the three discharge scenarios and the reference and widened configurations. Contour lines denote the bed elevation, *Z* [m]. The limit of the sediment bar corresponds to the main channel bed elevation (elevation *Z*=0.02 m) and is marked by thick black line.

The interaction between flow dynamics and sediment transport in the widened zones creates complex three-dimensional bed morphologies, without modifying the water levels with respect to the reference configuration. Grain sorting and aggradation are the two dominant morphological processes responsible for the development of equilibrium beds.

Different morphodynamic responses are associated with the different widening dimensions and the hydraulic conditions. Figure 4 shows the surface flow behaviour in the widened zone of the nine tests performed with the widening configurations. The flow limits indicated are based on the observation of the surface flow using colour dye. Three important flow features can be distinguished in the enlarged zones. (i) The main flow corridors (*mfc*) recognized by the presence of the colour dye in the flow. It is usually oriented towards the inner bank of the widened zone. (ii) The dry zones (*dz*), where the sediment deposition of quite fine material generally attains the flow surface. (iii) The flow stagnation zones (*fsz*), where the flow depths are relatively high and some recirculation is observed.

The main tributary flow detaches from the confining lateral walls and expands laterally as it enters the widened zone. Due to the relatively short length of the widened zone (L_w), the tributary flow appears to be influenced by the main channel flow well upstream from the tributary mouth. Consequently, the global lateral expansion of the tributary flow does not occur symmetrically on both sides. For the present experiments, flow reattachment only occurs at the inner bank of the tributary.

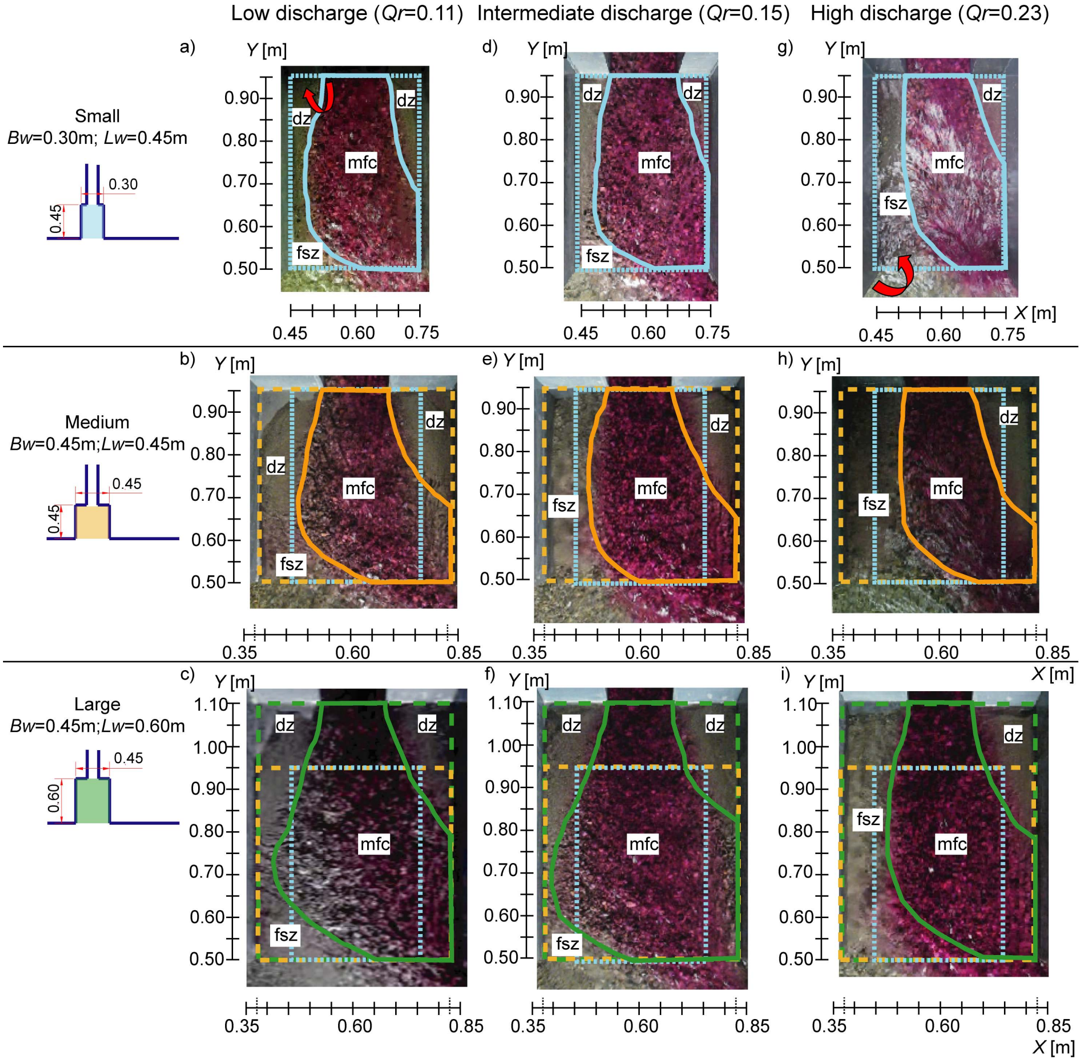

Figure 4: Flow visualization of the widened zones for the runs using colour dye. "*dz*" denotes the dry zones, "*mfc*" the tributary main flow corridors and "*fsz*" the flow stagnation zones.

The difference between the dry zones and the flow stagnation zones is remarkable. On the one hand, the flow detachment at the entrance of the widened zone creates flow recirculation zones at both upstream corners of the enlarged areas that are mainly supplied by the tributary flow. In the case where fine sediments carried by the tributary are transported into these zones, it tends to settle, filling up this part of the channel and forming the dry zones (Figure 4a). On the other hand, visual observations show that the flow stagnation zones are supplied by the main flow (Figure 4g). Therefore, no fine sediments reach these zones and consequently there is no deposition.

For the low discharge ratio scenarios (Figure 4a,b,c), the morphologies on the enlarged zones are quite similar, characterized by a complete filling up of the widened area. The formation of both the upstream dry zones occurs for all tests. The inner dry zones are confined while the outer dry zones extend along borders of the main flow corridors.

The intermediate discharge scenarios (Figure 4d,e,f) show the most important difference between the widened configurations. The small (Figure 4d) and large (Figure 4e) geometries are characterized by the presence of two dry zones, similar to those encountered for all geometries of the low discharge scenario. The morphodynamic behaviour observed for the medium widening (Figure 4e) is marked by the presence of a flow stagnation zone on the outer bank of the widening and a confined dry zone on the inner bank. The outer bank is not completely filled by the sediments.

The presence of flow stagnation zones (*fsz*) at the outer bank of the widening for the high discharge scenarios is the most important characteristic of these tests. As explained above, there is no sedimentation in these zones. Therefore, the final bathymetry of the enlarged zones is characterized by a lateral slope towards the outer bank (Figure 3).

Although there are small differences in the absolute bed and water elevations in the tributary channel upstream of the widened zone, the overall bed and water slopes do not change between the runs performed under the same discharge conditions for the different geometries. These important results indicate that the local widening of the tributary does not affect the upstream hydraulic and morphological behaviour of the tributary channel.

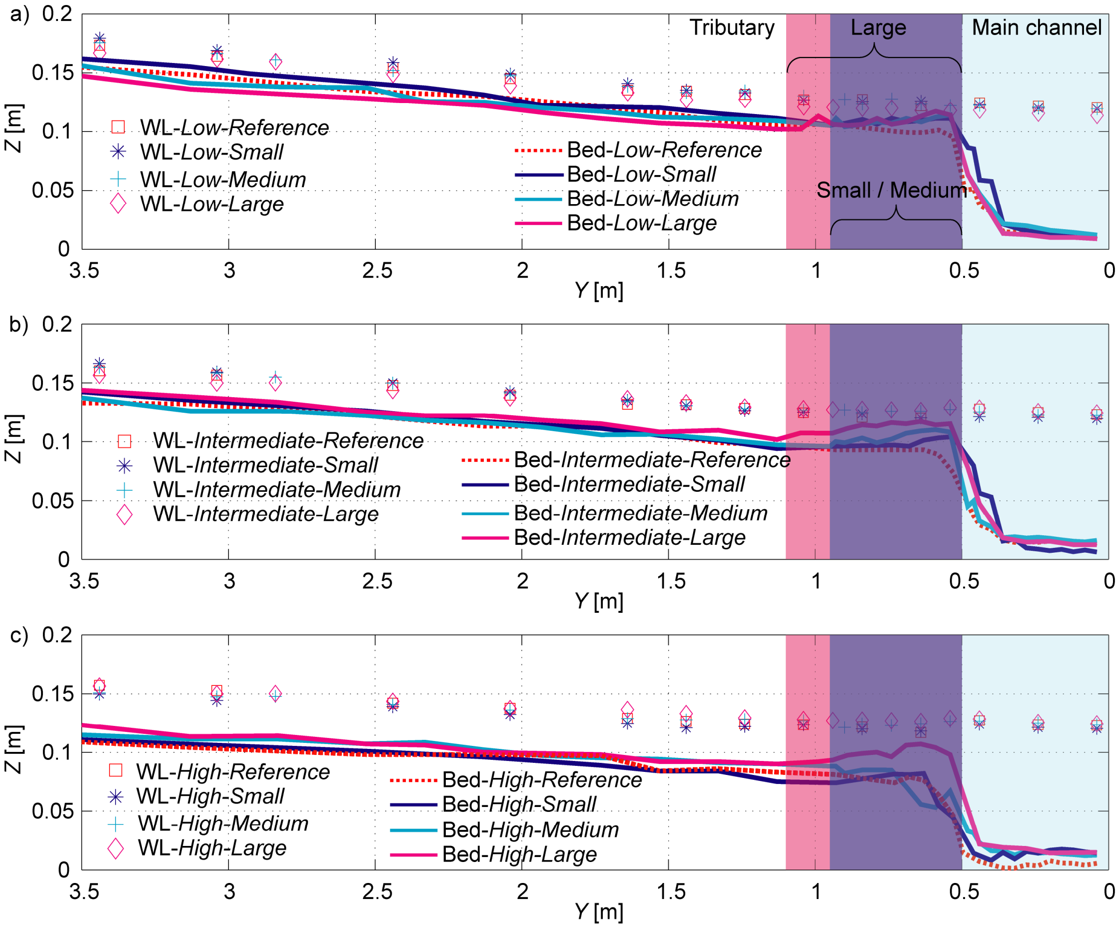

Figure 5: Longitudinal profiles along the tributary axis (*X*=0.60 m) showing the water level and bed elevations for the different geometric configuration for a) Low discharge ratios (*Qr*=0.11), b) Intermediate discharge ratios (*Qr*=0.15) and c) High discharge ratios (*Qr*=0.23).

5. APPLICATION FOR RIVER REHABILITATION

As discussed in previous sections, local tributary widenings are responsible for the development of regions characterized by a combination of flow corridors with dry and flow stagnation zones. The presence of such as zones is extremely important for the habitat suitability (Rohde et al., 2005; Weber et al., 2009). Dry zones are request for example for the development of the riparian zones that are commonly associated to the habitat of micro invertebrates whereas flow stagnation zone can become refuge areas during flood events.

In fluvial systems, flow depths characteristics strongly influence the quality of habitat for aquatic biota (Schweizer et al., 2007). As illustrated in Figure 6, the relatively low variability of the flow depths of the channelized tributaries (reference cases) measured in the tributary main corridors (Figure 4) increases considerably with the local widening. The increase in the variability of flow depths, associated to the different dry and flow stagnation zones and the important heterogeneity of the bed granulometry can generate local hotspots for biodiversity in confluence zones.

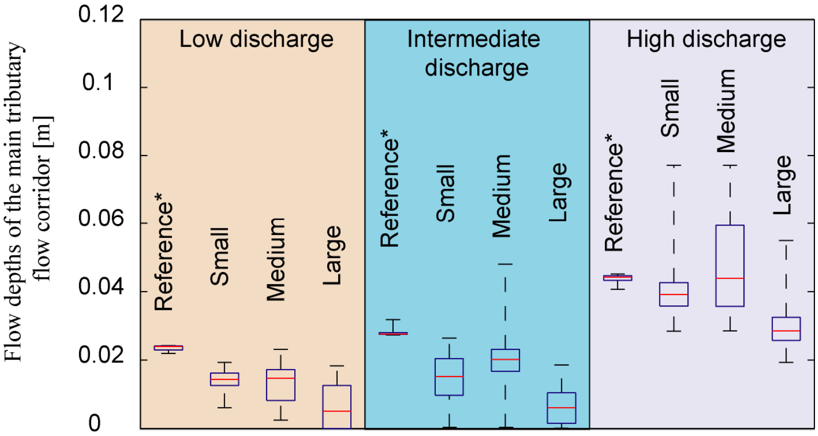

Figure 6: Boxplots of the flow depths in the widening zone showing the median values (mid-lines), 25th and 75th percentiles (box) and the maximum and minimum values (extreme limits). Reference, Small, Medium and Large correspond to the configurations presented in Figure 2.

Rive confluences are the nodes of fluvial systems and one of its most important ecological function is to guarantee its lateral connectivity (Rice et al., 2008). Rehabilitation projects in non-confluence zones can fail if the lateral connectivity of regulated confluence zones is not recovered. For that reason, even small interventions in confluence zones can get important benefits in terms of the increase of the ecological potential in fluvial networks. Furthermore, no adverse impacts associated to the local tributary widening could be observed. This is extremely important because water level's raise can by catastrophic for the flood safety, putting in risk confluence rehabilitation projects.

6. CONCLUSIONS

Systematic experimental tests were carried out in the perspective of a research project related to the rehabilitation of piedmont confluences such as those found in alpine environments. Experimental conditions were based on the major confluences of the Upper Rhone River, in Switzerland.

The behaviour of three local tributary widenings for three discharge scenarios has been investigated. It has been shown that these relative small interventions can increase the variability of water depths, flow velocities and bed material substrate in confluence zones. These hydraulic and morphological conditions are potentially important for recovering diverse natural riparian ecosystems, and restoring the fluvial systems that were degraded by river training works. Results of this research demonstrate the complexity of the morphodynamics responses to a given widening configuration. It depends on the discharge scenarios and on the widening dimensions. For all cases, some parts of the widened space are not used by the flow in equilibrium conditions. These areas are either completely filled by fine sediments or occupied by stagnating flows.

The different tributary widening configurations tested in this research did not cause major consequences for the morphodynamics neither in the tributary channel upstream of the widening nor in the post-confluence channels for a given discharge scenario. It is important to notice that in the experiments, the solid discharge introduced in the tributary corresponds exactly to its transport capacity (equilibrium conditions) and the above statements only concerns this situation. In these conditions, local tributary widening can increase the lateral connectivity of fluvial systems without reducing the conveyance capacity of a given network.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Best, J. L. (1988). *Sediment transport and bed morphology at river channel confluences*. Sedimentology, 35(3), pp.481-498.

Biron, P., Roy, A. G., Best, J. L. and Boyer, C. J. (1993). *Bed morphology and sedimentology at the confluence of unequal depth channels*. Geomorphology, 8(2-3), pp.115-129.

Biron, P. M., Richer, A., Kirkbride, A. D., Roy, A. G. and Han, S. (2002). *Spatial patterns of water surface topography at a river confluence*. Earth Surface Processes and Landforms, 27(9), pp.913-928.

Boyer, C., Roy, A. G. and Best, J. L. (2006). *Dynamics of a river channel confluence with discordant beds: Flow turbulence, bed load sediment transport, and bed morphology*. Journal of Geophysical Research, 111(F04007), pp.1-22.

Gurnell, A., Surian, N. and Zanoni, L. (2009). *Multi-thread river channels: A perspective on changing European alpine river systems*. Aquatic Sciences, 71(3), pp.253-265.

Havinga, H., Jagers, H. R. A. and Sloff, C. J., 2005. Knowledge requirements for sustainable fairway management. River, Coastal and Estuarine Morphodynamics, 1173-1182.

Leclair, S. and Roy, A. G. (1997). *Variabilité de la morphologie et des structures sédimentaires du lit d’un confluent de cours d’eau discordant en periode d’étiage*. Géographie physique et Quaternaire, 51, pp.125–139.

Leite Ribeiro, M. 2011. *Influence of Tributary Widening on Confluence Morphodynamics*. Laboratory of Hydraulic Constructions (LCH). Lausanne, Ecole Polytechnique Fédérale de Lausanne. PhD n° 4951.

Leite Ribeiro, M., Blanckaert, K., Boillat, J. L. and Schleiss, A. J., 2009. Influence of the momentum flux ratio on confluence morphology. 3rd IAHR Congress "Water Engineering for a Sustainable Environment", Vancouver, Canada.

Leite Ribeiro, M., Boillat, J.-L., Schleiss, A. J. and Blanckaert, K., 2010. Experimental study on a widening tributary channel and its influence on the confluence morphology. River Flow 2010, Braunschweig, Germany, 961-968 Bundesanstalt für Wasserbau (BAW), Karlsruhe, Germany.

Rhoads, B. L. and Kenworthy, S. T. (1995). *Flow structure at an asymmetrical stream confluence*. Geomorphology, 11(4), pp.273-293.

Rhoads, B. L. and Kenworthy, S. T. (1998). *Time-averaged flow structure in the central region of a stream confluence*. Earth Surface Processes and Landforms, 23(2), pp.171-191.

Rice, S. P., Kiffney, P., Greene, C. and Pess, G. R., 2008. *The Ecological Importance of Tributaries and Confluences*. River Confluences, Tributaries and the Fluvial Network, John Wiley & Sons, Ltd,

Rohde, S., Schutz, M., Kienast, F. and Englmaier, P. (2005). *River widening: An approach to restoring riparian habitats and plant species*. River Research and Applications, 21(10), pp.1075-1094.

Schweizer, S., Borsuk, M. E., Jowett, I. and Reichert, P. (2007). *Predicting joint frequency distributions of depth and velocity for instream habitat assessment*. River Research and Applications, 23(3), pp.287-302.

Weber, C., Schager, E. and Peter, A. (2009). Habitat diversity and fish assemblage structure in local river widenings: A case study on a Swiss River. River Research and Applications, 25(6), pp.687-701.