

# Experimental study on a widening tributary channel and its influence on the confluence morphology

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**ABSTRACT:** This paper investigates the morphologic impacts of the widening of tributaries in confluence zones by means of systematic hydraulic tests performed in a confluent laboratory flume. The confluent channels are connected with an angle of  $90^\circ$  and the main channel is 0.50 m wide. The tributary is 0.15 m wide in the reference configuration and enlarged to 0.30 m over a length of 0.45 m in the widened configuration. Experiments are carried out under mobile bed conditions. Sediments with a wide grain size distribution are fed in the tributary and all tests are run until equilibrium conditions. The influence of the local tributary widening is highly dependent on the momentum flux ratio between the upstream flows. The widened zone is characterized by a higher variability of the flow depth, the flow velocities and the particle size distribution, showing that tributary widening can improve the ecological value of confluence zones.

*Keywords: River confluence, River restoration, Laboratory experiments, Morphodynamics, Alpine rivers*

## 1 INTRODUCTION

During the past few centuries, river training works have been applied in many industrialized countries to improve flood protection of cultivated and urban land. Most river regulations underestimate or do not foresee ecological impacts (Havinga et al. 2005), resulting in a considerable reduction of the natural dynamic processes and the biological diversity. From the end of the 20th century, attempts are made to identify long-term effects of river regulations in order to alleviate adverse impacts (Armitage, 2006). Therefore, river restoration has become a concept widely employed by environmental professionals (Nakamura et al., 2006; Reichert et al., 2007). One of the most common solutions for fluvial restoration is the “river widening”, which allows the channel movement within a spatially limited area and increases the amount of in-stream habitat heterogeneity (Rohde et al, 2009).

In fluvial networks, confluences favour a high variability in flow, sediment load, sediment size and water quality (Rice et al. 2001), which is a requisite for a sound fluvial ecology. Moreover, confluences are key elements that have to ensure the lateral and longitudinal connectivity in river networks. The geomorphological changes at con-

fluences zones can be dramatic especially during important flood events (Sloam et al, 2001). Consequently, a good understanding of the interaction between the flow patterns, the sediment transport and the bed morphology development is necessary to successfully accomplish river rehabilitation projects at confluences. Surprisingly, the application of “river widening schemes” to confluence zones has not yet been investigated.

The complex three-dimensional hydrodynamics in confluences have been extensively studied by e.g. Best (1985), Bradbrook et al. (1998), Weber et al. (2001), Biron et al. (2004). Best (1985) suggests a descriptive model of flow dynamics at confluences, as shown in Figure 1. He distinguishes six different zones, characterized by flow deflection, flow stagnation, flow separation, maximum flow velocity, shear layers and flow recovery, respectively.

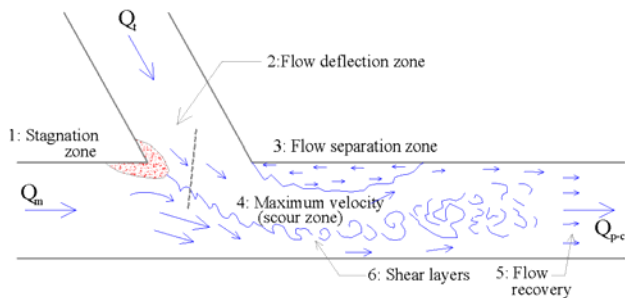


Figure 1 Descriptive model of flow dynamics at channel confluence (Biron et al., 1996 based on Best, 1985)

Studies on the bed morphology in fluvial confluences are scarce and those attempting to quantify the nature of sediment transport within the junction are about nonexistent. Roy and Bergeron (1990) attribute this lack of laboratory studies on flow and sediment transport at confluences to the difficulty in implementing adequate experimental procedures.

Mosley (1976) performed a laboratory study on the evolution and morphology of channel confluences considering symmetrical and asymmetrical planforms. In his study, the post-confluence channel has been cut in erodible material and was free to adjust the experimental solicitations. Ashmore and Parker (1983) extended Mosley's analyses to self formed confluences by means of experimental tests in two wide channels and field investigations. Best (1986) is among the first investigators to present a detailed description of the bed morphology, based on experimental tests in small channels (0.15 m wide) connected asymmetrically. In his conceptual description, bed morphology of confluences is basically characterized by three distinct elements, as illustrated in Figure 2:

- Avalanche faces, which form at the mouth of each channel forming a confluence;
- Bed scour that occurs in the region into which the avalanche faces dip
- A separation zone bar, which forms in the post-confluence channel.

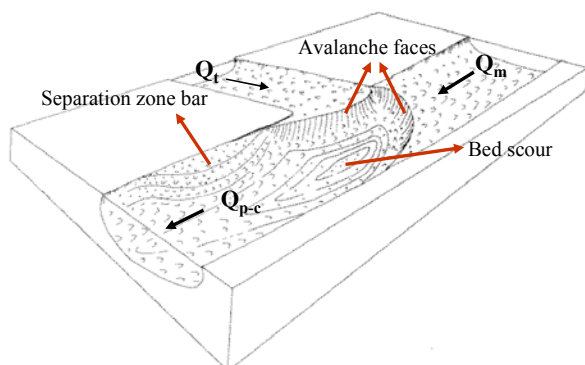


Figure 2 Schematic bed morphology of an asymmetric confluence with bed concordance proposed by Best (1986).

The objective of the present paper is to gain insight in the morphologic features of a confluence (section 3.1) and to investigate and quantify the

influence of the widening of a tributary on the morphology in the confluence zone (section 3.2). This purpose is achieved by means of systematic experimental laboratory tests. Results and differences between both configurations are discussed in section (4).

## 2 EXPERIMENTAL INVESTIGATION

### 2.1 Laboratory facilities and procedures

The choice of the experimental configuration, and especially of the geometry, the sediment parameters and the flow and sediment discharges, is based on the analyses of the main confluences of the Upper Rhone River, upstream of Lake Geneva in Switzerland. One example of these confluences (Rhone and Avançon River) is shown in Figure 3.

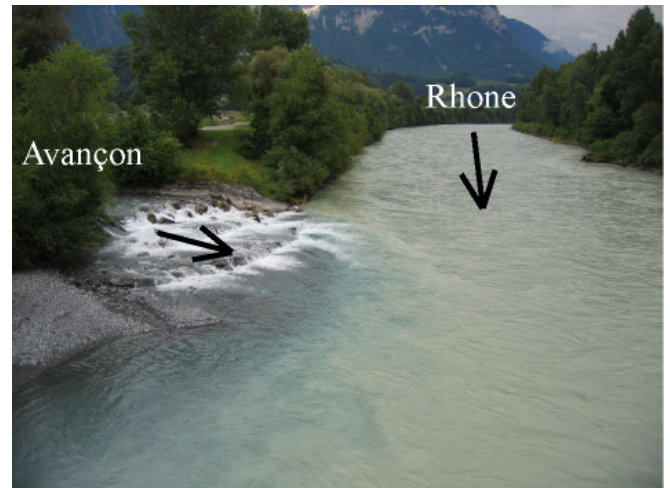


Figure 3 Confluence of the Avançon and Rhone Rivers in Switzerland

Laboratory tests are performed in a confluence flume (Figure 4) where the main channel is 8.5 m long and 0.50 m wide. An adjustable tailgate at the end of the post-confluence channel is used to control the flow depth in the flume. A tributary channel, 4.9 m long and 0.15 m wide is connected with an angle of  $90^\circ$ , 3.60 m downstream of the inlet of the main channel.

The movable bed is initially flat in the entire flume and consists of a sediment mixture characterized by  $d_{50} = 0.82$  mm and  $d_{90} = 5.7$  mm with a gradation coefficient  $\sigma = 4.15$ . A constant solid discharge of the same sediment mixture is supplied by a conveyor belt at the tributary inlet only. The sediment feeding rate is identical in all tests at 0.30 kg/min. At the end of the post-confluence channel, a sediment trap is installed to remove the sediments. All tests are run until equilibrium, which is defined by a steady level of the bed topography and water profile. The evolution of the water levels (automatic ultrasonic limnimeters) and the bed topography (Mini EchoSunder) are

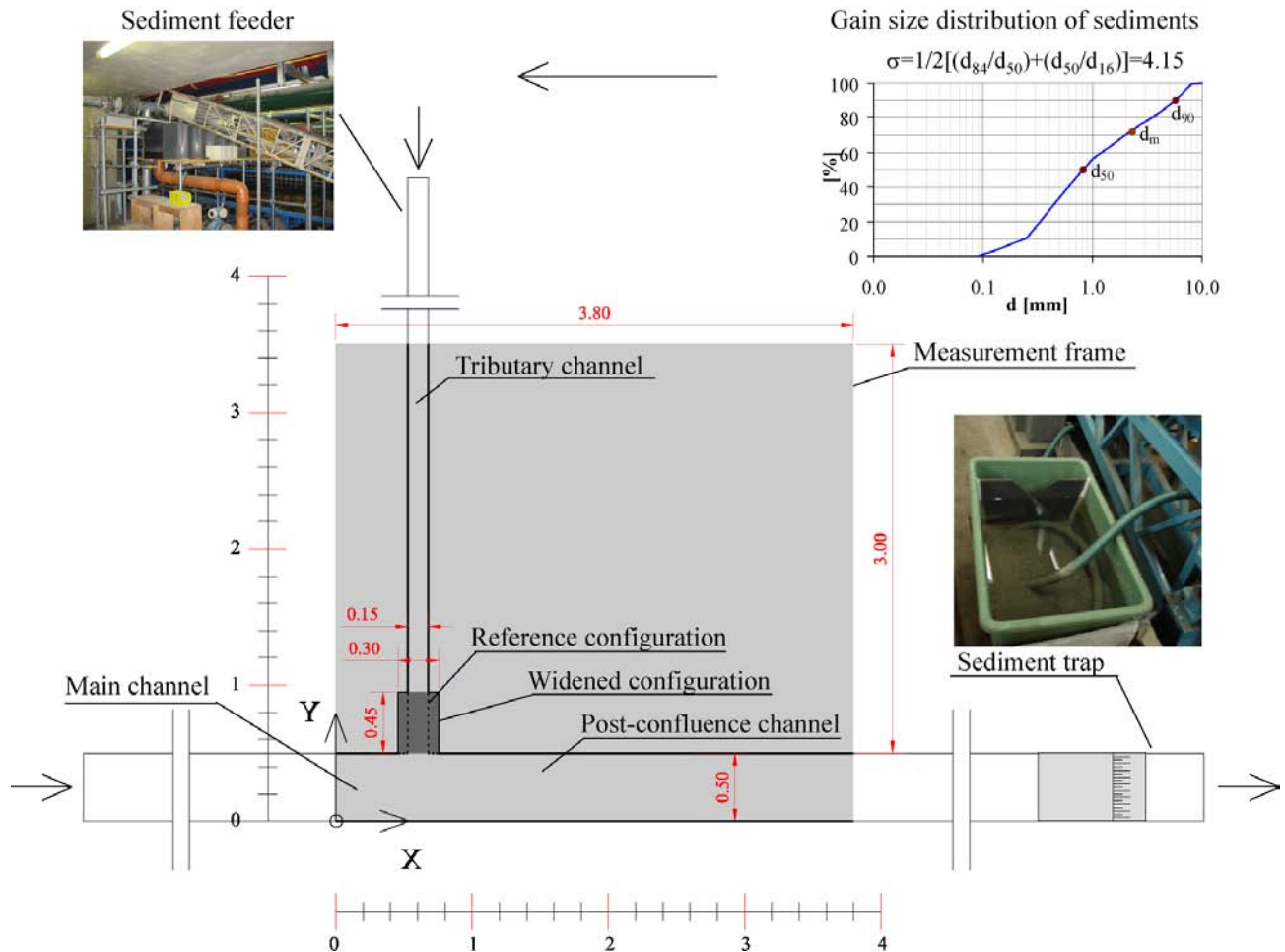


Figure 4 Experimental setup and characteristics of the sediment mixture

recorded during the tests. The instrumentation is installed on a movable frame that covers part of the experimental set-up (3.80 m in the main and post-confluence channels and 3.00 m in the tributary). All results are presented in the [X,Y] reference system shown in Figure 4. Flow visualization using a colour dye is used to identify the interactions between flow and bed morphology.

In this paper, two different geometric configurations are considered: a so-called “reference” configuration with a constant tributary width of 0.15 m, and a so-called “widened” configuration where the tributary is enlarged to 0.30 m in over a length of 0.45 m.

## 2.2 Hydraulic conditions

For both geometric configurations, three different discharge scenarios ( $q_t/q_m=0.25, 0.50$  and  $0.75$ ) are considered. The notation  $q$  represents the unit discharges in terms of channel width, e.g, the total discharge  $Q$  ( $m^3/s$ ) divided by the channel width  $b$  (m) and the subscripts  $t$  and  $m$  refer to the tributary respectively main channels. All discharge scenarios share the same total discharge of 20 l/s in the post-confluence channel.

As suggested by Rhoads and Kenworthy (1995), the bed morphology of small confluences

is highly responsive to changes in momentum flux ratio, defined as  $Mr = \rho Q U_t / \rho Q U_m$ , where  $\rho$  is the water density ( $kg/m^3$ ) and  $U$  the mean velocity (m/s). For the tests performed in the reference configuration, the values of  $Mr$  are 0.12 for the run  $Q_m 18.6\_Q_t 1.4$ , 0.29 for the run  $Q_m 17.4\_Q_t 2.6$  and 0.43 for the run  $Q_m 16.3\_Q_t 3.7$ . Such values are representative for alpine confluences, as they are in the range of the momentum flux ratios between the main tributaries and the Upper Rhone River (Switzerland), when considering the two and five years return period floods.

In the widened configuration, average values of the momentum flux at the tributary are difficult to evaluate. Due to the high variability of the bed elevations, specific discharges and flow velocities are extremely variable within the tributary width. However, the momentum flux ratio for the widened configuration for a given discharge scenario is lower than those for the reference configuration as the tributary width is increased.

The main hydraulic characteristics of the tests performed in the reference and widened configurations are presented in Table 1. At the equilibrium state the flow is subcritical in the main and post-confluence channels for all experiments. At the tributary, the runs  $Q_m 18.6\_Q_t 1.4$  and  $Q_m 17.4\_Q_t 2.6$  are characterized by a supercritical

flow. This leads to a change of flow regime by means of weak undulated hydraulic jump at the confluence. In the scenario  $Q_m16.3\_Q_t3.7$ , the Froude Number of the tributary is about 0.82. The mean bed equilibrium slopes reached at the tributary channel for the tests with the reference configuration are around 2.5%, 1.4% and 1.25% respectively for the runs  $Q_m18.6\_Q_t1.4$ ,  $Q_m17.4\_Q_t2.6$  and  $Q_m16.3\_Q_t3.7$ .

When the tributary is widened, the same average

bed slopes are found in the reach upstream of the enlarged zone.

At the beginning of each test, flow recirculation is observed in the separation zone, following the model proposed by Best (1985). However, the flow recirculation leads to the deposition of fine sediments and at the end of the all tests, the separation zone bar is characterized by a straight flow.

Table 1 Hydraulic characteristics of the experimental runs for the reference configuration

Run	Discharge (l/s)		$q_t/q_m$	Froude Number $Fr=U/(gh)^{0.5}$			Mean tributary bed slope	$Mr = \rho Q U_t / \rho Q U_m$	
	Main ( $Q_m$ )	Tributary ( $Q_t$ )		main	tributary	post-confluence		Reference configuration	Widened configuration
$Q_m18.6\_Q_t1.4$	18.6	1.4	0.25	0.32	1.34	0.69	2.50%	0.12	< 0.12
$Q_m17.4\_Q_t2.6$	17.4	2.6	0.50	0.32	1.20	0.69	1.40%	0.29	< 0.29
$Q_m16.3\_Q_t3.7$	16.3	3.7	0.75	0.26	0.82	0.69	1.25%	0.43	< 0.43

### 3 RESULTS

#### 3.1 Reference configuration

Figure 5 illustrates the final bed configuration in the main channel for the three runs. Avalanche faces are created along the deposition zone and are formed by a uniform armour layer, composed by coarse material. As no solid discharge is provided in the main channel upstream of the confluence, where the transport capacity is almost zero, only fine materials are washed. A relative fine armour layer is formed. This phenomenon is also

reproduced at the tributary but as the transport capacity is higher, the superficial bed layer is formed by coarser materials.

With the increase of  $Mr$ , the following morphological behaviours can be highlighted: 1) the bed discordance between the tributary and main channel decreases. Bed discordance means the difference between the bed elevations at the tributary mouth and the main channel; 2) the penetration of the tributary into the main channel decreases and 3) the deposition in the separation zone decreases.

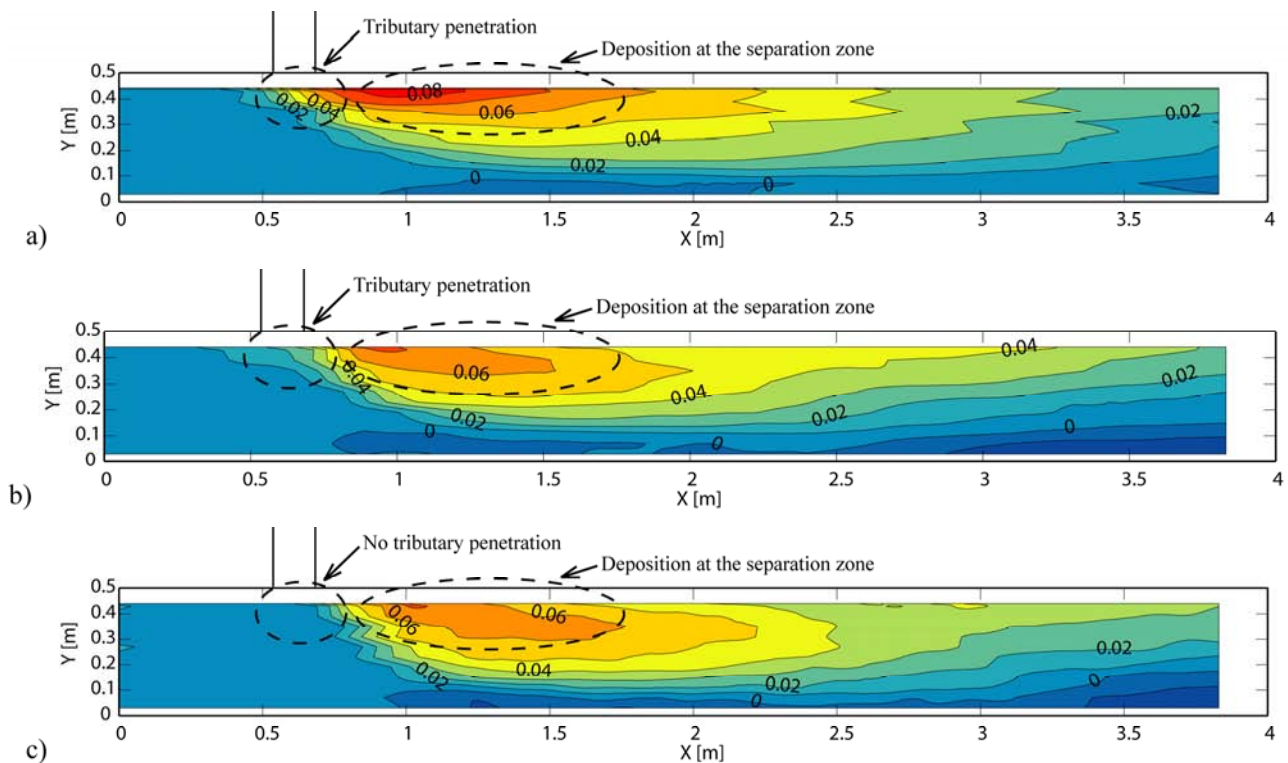


Figure 5 Bed morphology in the main channel for the tests a)  $Q_m18.6\_Q_t1.4$ , b)  $Q_m17.4\_Q_t2.6$  and c)  $Q_m16.3\_Q_t3.7$ . The bed elevations of the tributary are not shown here.

Significant grain sorting occurs at the confluence zone, but no differences related to the momentum flux ratio could be highlighted at the different points.

All the results concerning the tests performed in the reference configuration are discussed in detail by Leite Ribeiro et al. (2009).

### 3.2 Widened configuration

The local widening of the tributary in the confluence zone causes significant differences in the bed morphology, which depend on the discharge scenario. For the run  $Q_m18.6_{Q_t1.4}$  (Figure 6a left), the widened zone is completely filled and there is a small lateral bed inclination along the  $X$  axis. In

the downstream corner of the confluence, small depression occurs and the bed elevations of the tributary and the main channel are almost the same. The run  $Q_m17.4_{Q_t2.6}$  (Figure 6b left) follows the same behaviour, but with higher lateral inclination and depression on the downstream corner of the confluence.

The bed morphology in the run  $Q_m16.3_{Q_t3.7}$  is different from the other two runs, as illustrated in Figure 6c (left). The upstream part into the widened zone of the tributary is not completely filled. The lateral bed inclination along the  $X$  axis is reversed.

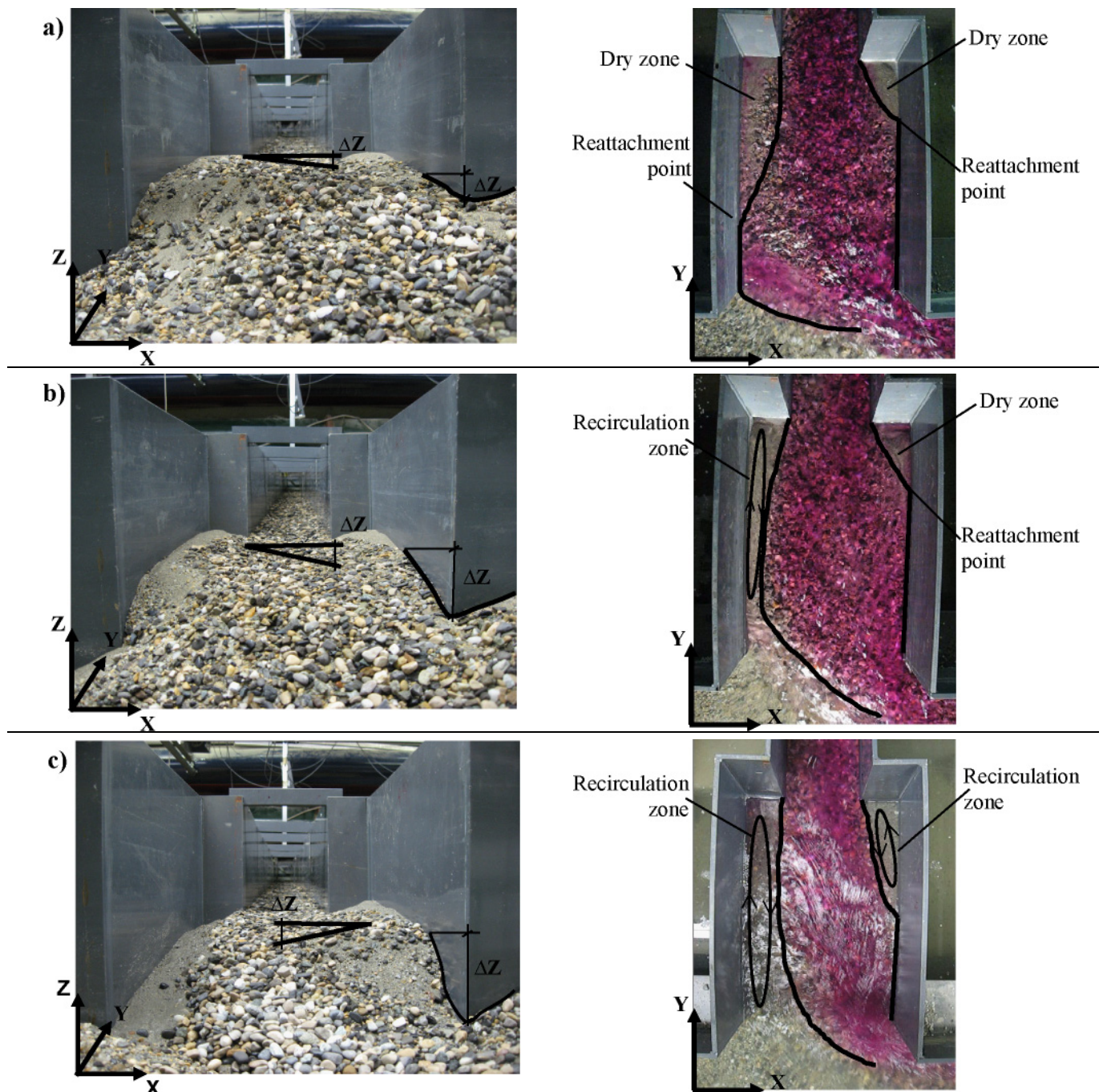


Figure 6 Pictures from downstream of the tributary (left) and upper view of the widened zone (right) for the runs a)  $Q_m18.6_{Q_t1.4}$ , b)  $Q_m17.4_{Q_t2.0}$  and c)  $Q_m16.3_{Q_t3.7}$

As for the tests performed in the reference configuration, significant grain sorting can be observed in the different zones of the confluence flume depending on discharge scenario. Except for the widened area, these variations cannot be linked to the variations of the momentum flux ratio.

Flow visualisations show that for the investigated discharge conditions, the widened tributary zone is not crossed by a symmetrical flow. The flow is detached from the tributary walls at the entrance of the widened region. For the run  $Q_m18.6\_Q_t1.4$  (Figure 6a right), two asymmetrical dry zones formed by fine materials appear at the start of the widened zone. For this run, the flow reattaches to the lateral walls inside the enlarged area.

For the run  $Q_m17.4\_Q_t2.6$  (Figure 6b right), only the downstream dry zone can be observed. The flow reattaches after a small distance in the widened area. The entrance of the enlarged region is characterized by a horizontal circulation zone.

No dry zones are present in the widened area for the run  $Q_m16.3\_Q_t3.7$  (Figure 6c right). The tributary flow is slightly deviated towards downstream and reattaches almost at the middle of the widened area. The horizontal circulation zones observed in this run are more intense than in the previous runs.

The analyses done for the reference configuration can be applied in the widened case. For the run  $Q_m18.6\_Q_t1.4$  (the lowest value of  $Mr$ ), the tributary penetrates in the confluence zone, forming avalanche faces constituted by coarse material. The bed discordance between the tributary and the main channel as well as the deposition at the separation zone is the highest, compared to the other runs. With the increase of the tributary discharge and decrease of the main channel discharge (increase of  $Mr$ ), the tributary penetration, the bed discordance and deposition at the separation zone decreases. For the run  $Q_m16.3\_Q_t3.7$ , the tributary does not get into the main channel as can be seen in the Figure 6c (left).

#### 4 DISCUSSION

Different from the morphological models proposed in previous works (Best, 1986; Boyer et al, 2006), scour is absent in the confluence zone at the equilibrium state for the studied cases. However, at the beginning of all tests, small ero-

sion occurs at the meeting of the upstream flows, along the shear layers. The scour zones are naturally filled by coarse materials during the tests. The lack of a scour hole can be then explained by the size of the coarse materials constituting the mixture. The shear stresses resulted from the flow at the confluence zone is not large enough to transport those particles and therefore, it fills the erosion zones.

The particle motion in the post-confluence channel for all tests occurs in the left bank (along the  $X$  axis). Fine materials are transported near wall while coarser particles move near the centre of the channel. These observations are in agreement with those made by Roy and Bergeron (1990) in a river confluence with coarse bed. However, in the present case, the sediment transport occurs in the most elevated part of the channel and does not transit by the deepest part (inexistent scour hole), as described by the Roy and Bergeron (1990).

Figure 7 illustrates the differences of the bed elevation at the main and post-confluence channels between the reference and widened configuration for the three different runs. For the discharge scenarios  $Q_m18.6\_Q_t1.4$  and  $Q_m16.3\_Q_t3.7$ , widening the tributary does not influence significantly the bed morphology at the post-confluence channel, as shown in the Figure 7a and in the Figure 7c. However, the penetration of the tributary on the post-confluence channel increases when the tributary is widened for the discharge scenario  $Q_m17.4\_Q_t2.6$  (Figure 7b).

A probably explanation is that the reduction of the momentum flux of the tributary due to its widening is more important for this scenario than for the others. It means that even if the tributary has more “space” to flow, the main flux remains concentrated for the scenarios  $Q_m18.6\_Q_t1.4$  and  $Q_m16.3\_Q_t3.7$ .

Widened zones are related to significant grain sorting as well as an important variability of flow velocities and water depths. These characteristics are essential for the re-establishment of the fluvial ecosystems. It indicates that tributary widening in the confluence zone provides a potential for confluence rehabilitation projects.

Nevertheless, it is important to note that tributary widening are small-scale interventions that are necessary, but not sufficient, for recovering the river system to its condition prior to degradation. The success of the restoration projects needs intervention in a catchment scale.

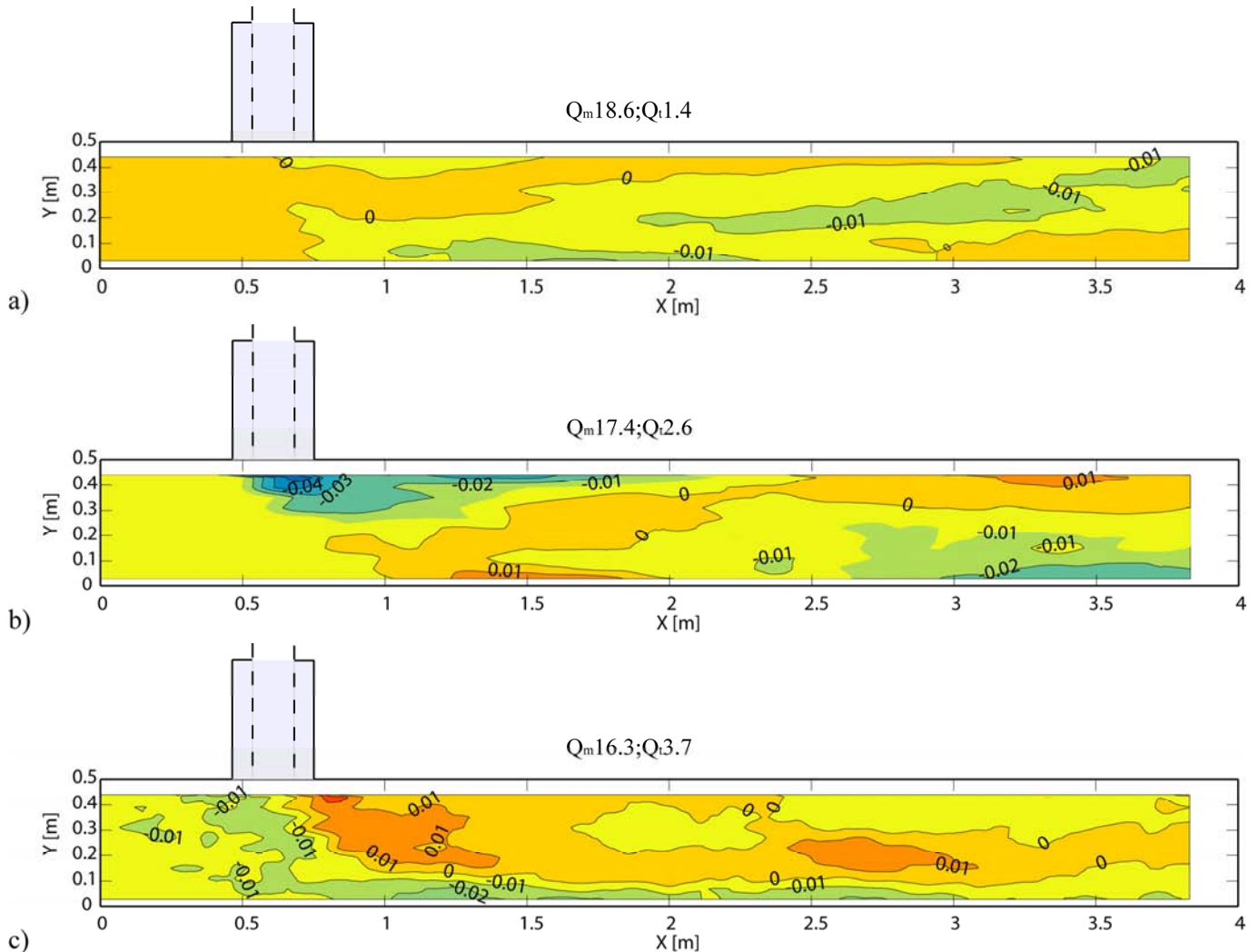


Figure 7 Bed elevation differences between the reference and the widened configurations at the main and post-confluence channels for the runs a)  $Q_m18.6\_Q_t1.4$ , b)  $Q_m17.4\_Q_t2.6$  and c)  $Q_m16.3\_Q_t3.7$ . The gray area represents the widened zone and the dashed lines represent the tributary channel for the reference configuration

## 5 CONCLUSIONS

Laboratory experiments on the influence of tributary widening on the morphology, under experimental conditions that are representative for the Upper Rhone River, in Switzerland were carried out.

Changes in momentum flux ratio between the tributary and the main channel lead to different morphologic responses. For a given momentum flux ratio, tributary widening considerably modifies the morphology in the vicinity of the confluence but only causes minor differences downstream of the junction. The flow depth and the morphology show a markedly increased variability, which enhance the ecological value of the confluence.

Further experimental tests with different tributary widening configurations are required in order to correlate optimum channel geometries with discharge scenarios.

## ACKNOWLEDGEMENT

The research is supported by the Swiss Federal Office of Environment in the framework of the project "Integrated management of river systems". K. Blanckaert was partially funded by the Chinese Academy of Sciences fellowship for young international scientists under grant 2009-YA1-2.

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