Effect of different inlet flow conditions on turbulence in a straight compound open channel

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Abstract: *Under uniform flow conditions, compound channel flows are characterised by an horizontal mixing layer developing at the junction between the flows in the main channel (deeper and faster) and in the floodplain (shallower and slower), e.g. Shiono & Knight (1991). Maintaining the total discharge corresponding to the uniform flow and imposing a disequilibrium in the upstream discharge distribution generates a non-uniform flow where lateral mass exchange occurs between channels along the flume. Two cases are distinguished: an excess and a deficit in the inlet floodplain discharge. The over- and under-feeding of the floodplain reduces and increases, respectively, the difference in velocity between both channels at the inlet, compared to uniform flow conditions. This paper investigates the effect of the magnitude of the upstream disequilibrium on the turbulent shear layer. The influence of lateral mass exchange on three-dimensional velocity field and on Reynolds stresses is assessed.*

Keywords: *Compound channel, shear flow, mixing layer, turbulence, mass transfer, advection*

1. INTRODUCTION

This paper investigates the turbulent characteristics of non-uniform flows in straight compound open channels. The interaction between advection and turbulent exchange within free-surface shear flows is analyzed. Mass exchanges in this prismatic geometry are created by an imbalance in the upstream discharge distribution between the floodplain and the main channel (compared with the distribution under uniform flow conditions for the same total discharge). These disequilibrium give rise to mass exchange from the floodplain(s) towards the main channel along the flume.

Flows in straight compound channels with a disequilibrium in the upstream discharge distribution were experimentally studied by Proust (2005), Bousmar *et al*. (2005) and Proust *et al.* (2010), mostly focusing on the mean flow parameters (sub-section discharges, mean velocity field). Relying on measurements of mean velocity field and boundary shear stress, Fernandes *et al.* (2010) evaluated the effect of inlet flow conditions on the apparent shear stress coefficient at the interface between the main channel and the floodplain (but without turbulence measurements). The turbulent characteristics of a developing flow in straight compound channel are investigated in Stocchino & Brocchini (2010), but in the particular case of a flume with horizontal bottom, *i.e.* with streamwise variation in flow depth. They analyzed the generation and evolution of the macro-vortices with vertical axis under "quasi-uniform flow conditions".

This paper presents new experiments of developing flows in straight compound geometry, characterized by a mass exchange due to either an overfeeding or an under-feeding of the floodplain. Given a total discharge Q, an excess in the floodplain discharge Q_f (compared to the floodplain discharge under uniform flow conditions) induces a mass transfer from the floodplain towards the main channel. An opposite transfer is observed with a deficit in the upstream floodplain discharge Q_f. This study aims at clarifying the link between turbulent shear stresses and mass transfer in simple compound geometries. Comparing numerical simulations with experimental data, Proust *et al.* (2009) showed that turbulent exchanges are predominant in the momentum flux in straight geometry, only when mass transfer tends to zero. Mass transfer and turbulence were found to be dependent, but only relying on measurements of mean flow parameters. In the present study, the analysis is complemented by measuring the turbulent characteristics of such flows to address the following issue: in what extent the turbulence can be reduced or enhanced by the mass exchanges between the main channel and the floodplain?

2. EXPERIMENTAL SET-UP

2.1. Flume and measuring devices

Experiments were performed in the compound channel flume of the Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA), Lyon, France. The flume geometry is presented in Figure 1. The useful length L is 8 m, the total width B is 1.2 m, and the floodplain width B_f is 0.8 m. The cross-section is asymmetrical, with a vertical bank at the interface between the main channel and the floodplain. The bank full depth h_b is equal to 5.15 cm. The bottom is made of PVC and its slope S_0 is equal to 1.8 mm/m. The upstream inlet reservoir is separated into two tanks (as shown in Figure 1), one for the floodplain and the other one for the main channel. Each tank is fed by one independent pump and the discharge in each channel is controlled by one independent flow-meter and one discharge regulator (PID controller). At the downstream boundary, two independent tailgates, one for each sub-section, are used for a better control of the water surface.

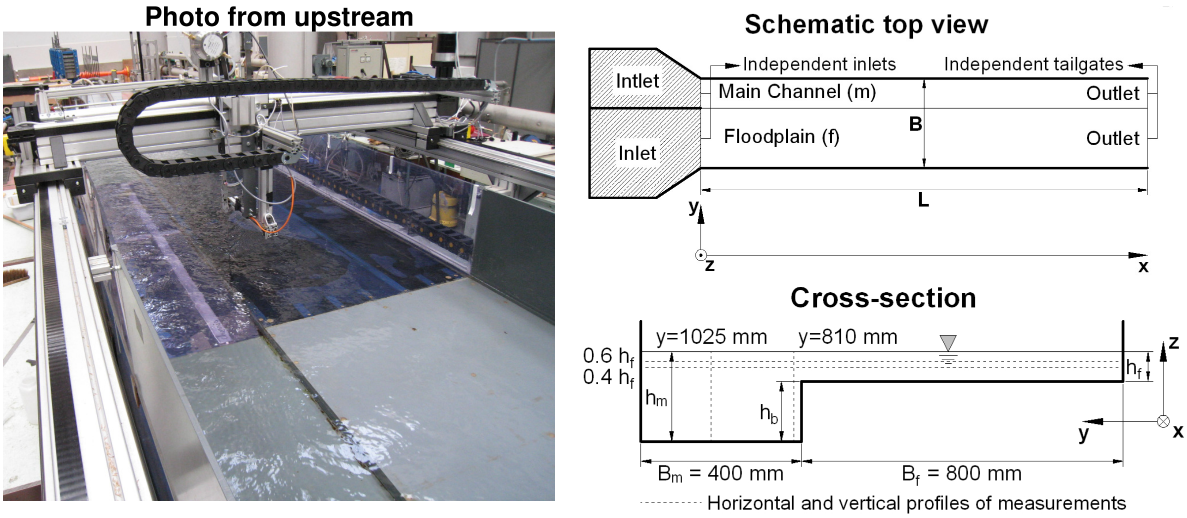

Figure 1 Compound channel flume at LMFA (scheme is not to scale)

Water levels were measured with an ultrasonic probe (accuracy: ± 0.3 mm). Velocity was measured with a Vectrino+ Micro-ADV 2D/3D side looking probe (Nortek). The acquisition time is 90 s for each measurement, with a sampling frequency of 100 Hz. The sampling volume is a 7 mm -long and 6 mm –diameter cylinder. To improve the signal quality, hollow glass spheres (10 µm) or polyamide seeding particles (20 µm) were added into the water. The measuring devices were fixed to an automatic displacement (see photo in Figure 1). The longitudinal slope of the railways is equal to the slope of the flume bottom. The cross-sections at x = 2.5 m, x = 4.5 m and x = 6.5 m were investigated. The mesh used for the measurements of the water levels consisted in 23 points across each cross-section. For ADV measurements four profiles were surveyed (see Figure 1), two of them were horizontal and located at elevation Z = $0.4h_f$ and $0.6h_f$ from the floodplain bottom. The other two profiles were vertical and were located at y = 810 mm and y = 1025 mm.

2.2. Flow conditions

The 15 flow cases investigated in this paper are presented in Table 2. Three reference flows are considered. Their total discharges are Q = 17.3 L/s, 24.7 L/s and 36.3 L/s, corresponding to relative flow depths h^* = 0.2, 0.3 and 0.4, respectively. These reference flows are analyzed in detail in Peltier (2011). Although these flows present no significant variation in flow depth and sub-section discharges in the streamwise direction, they cannot be rigorously considered as "uniform flow" throughout the flume length. A slight streamwise evolution in depth-averaged velocity and boundary shear stress is observed along with the development of the 3D velocity and turbulent field (notably in the first 3 meters of the flow).

Therefore, each of these quasi-uniform flows is considered as a reference flow, from which the upstream discharge distribution across the channel will be modified to generate mass exchange. As previously said, two cases are distinguished: an excess and a deficit in the inlet floodplain discharge. The over- and under-feeding of the floodplain reduces and increases, respectively, the difference in velocity between both channels at the inlet (downstream station x = 0 m), compared to reference flow conditions. Four types of disequilibrium in the upstream floodplain flow are studied: a relative variation of -19%, + 19%, +38% and +53% in the floodplain discharge compared to Q_f under reference flow conditions, but maintaining constant the total discharge Q.

Table 2 Flow conditions

Variation in upstream floodplain flow [(1)] (%)	Total discharge Q (L/s)	Floodplain discharge Q_f (L/s)	Main channel discharge Q_m (L/s)	Relative depth h^* [(2)] (-)
-19		1.93	15.36	
0 (reference flow)		2.38	14.91	
+19	17.3	2.83	14.46	0.2
+38		3.28	14.00	
+53		3.64	13.65	
-19		5.08	19.61	
0 (reference flow)		6.27	18.42	
+19	24.7	7.46	17.23	0.3
+38		8.65	16.04	
+53		9.59	15.10	
-19		11.42	24.87	
0 (reference flow)		14.1	22.2	
+19	36.3	16.78	19.52	0.4
+38		19.46	16.84	
+53		21.57	14.73	

(1) Percentage of variation in upstream floodplain discharge relative to reference flow conditions.
(2) For the reference flow only, approximated value for the flow cases with upstream disequilibrium.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Water level

The lateral distribution of water level Z is presented in Figure 2 for the smaller discharge Q = 17.3 L/s. The issue addressed in this part is: given a total discharge Q and a station x, what is the variation in water level when the lateral distribution of streamwise velocity is varied at the upstream boundary?

As shown in Figure 2, the water level in the cross-section increases from flow case "–19%" to flow case "+53%" for a fixed total discharge Q = 17.3 L/s and at a given station x. This is particularly marked in the upstream part of the flume at x = 2.5 m. A similar behavior was observed for the other discharges (23.7 L/s and 36.3 L/s). Besides, given a station x, the absolute difference in water level between the two extreme flow cases ("–19%" and "+53%") increases with the total discharge Q. In each cross-section, reducing the difference in velocity between the main channel and the floodplain leads to an increase in water depth for a fixed total discharge.

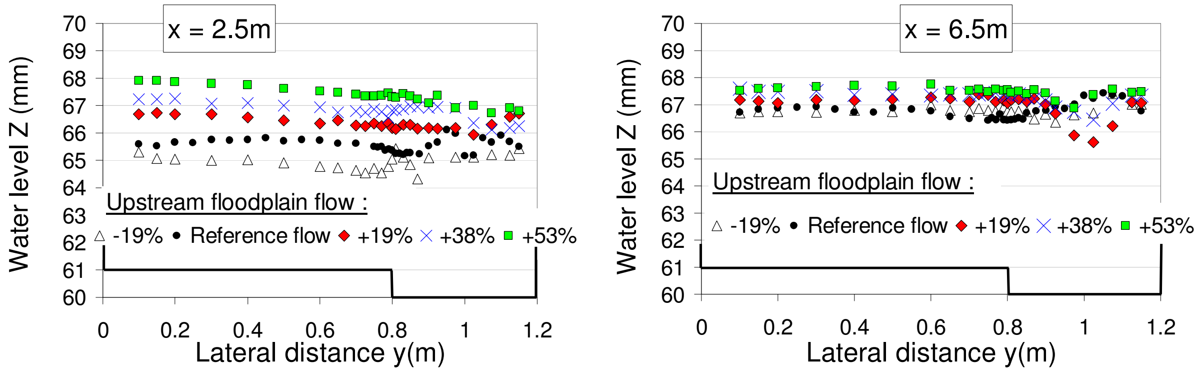

Figure 2 Water level *Z* measured from the bottom of the main channel. Discharge *Q* = 17.3 L/s. The flow conditions given in the legend are summarized in Table 2

3.2. Lateral profiles of streamwise velocity and Reynolds stress

The lateral variation in mean streamwise velocity *u* and Reynolds stress $\tau_{xy} = -\rho \overline{u'v'}$ is presented in Figure 3 for the 15 flow cases presented in Table 2. Measurements were carried out at downstream station *x* = 4.5 m, along an horizontal profile taken at an elevation equal to 60% ($Z = 0.6h_f$) of the floodplain flow depth (see Figure 1).

Given an upstream disequilibrium, the lateral profiles of the streamwise velocity show that the flow is increasingly destabilized relatively to the reference flow, when the total discharge rises from 17.3 L/s to 36.3 L/s. Near the interface between the main channel and the floodplain, the local lateral gradient of streamwise velocity *du/dy* is always positive for discharge *Q* = 17.3 L/s and 24.7 L/s. For the higher total discharge, *du/dy* is either positive or negative when the floodplain is overfed (flow cases +19%, +38%, +53%). For the 3 previous flow cases, negative values of shear stress are observed when *du/dy* is also negative, indicating a strong link between local mean velocity field and turbulence.

When increasing the floodplain overfeeding (from +19% to +53%), the lateral spreading of the shear layer decreases on the floodplain side for all total discharges. Nevertheless, the maximum values of τ_{xy} are observed near the interface for all flow cases.

To go further in the investigation of the position and the value of the maximum shear stress, a zoom of the shear layer is presented in Figure 4, for discharge *Q* = 24.7 L/s at two different elevations: $Z = 0.6h_f$ and $Z = 0.4h_f$ (see Figure 1). The shear stress peak decreases and is increasingly shifted towards the main channel, when rising the overfeeding of floodplain from +19% to +53%. This indicates a strong link between the upstream velocity distribution and the turbulence development at 4.5 m downstream. Comparing the two elevations $0.6h_f$ and $0.4h_f$, the shape and the magnitude are similar. This suggests that the link between mass transfer and turbulence is present in most of the flow depth ($Z \geq 0.4h_f$). Contrary to the floodplain, the lateral spreading of the shear layer in the main channel is rather constant, indicating that the primary flow in the main channel “blocks” the lateral spreading of the mixing layer.

Analyzing the spanwise velocity *v* enables a further investigation into the mass transfer coming from upstream. Figure 5 presents both the lateral variation in the spanwise velocity *v* and a zoom on the shear layer for the higher discharge. The lateral distribution of *v*-component evidences that mass transfer is still occurring at station *x* = 4.5 m. The effect of the upstream disequilibrium is more pronounced in the floodplain. Comparing the lateral distribution of spanwise velocity with the Reynolds stresses, it can be concluded that the magnitude of the former influences the shape of the latter.

From Figure 3 to Figure 5, we can conclude that: a) for a given total discharge, an increase in mass transfer induces a decrease in turbulent shear stress; and b) when rising the total discharge *Q* (*i.e.* the mean relative depth), the effect of mass transfer on turbulent shear layer is increasingly significant. For the smaller discharge, the lateral mass transfer is not strong enough to shift the peak of shear stress and to modify the classical shape of the shear layer.

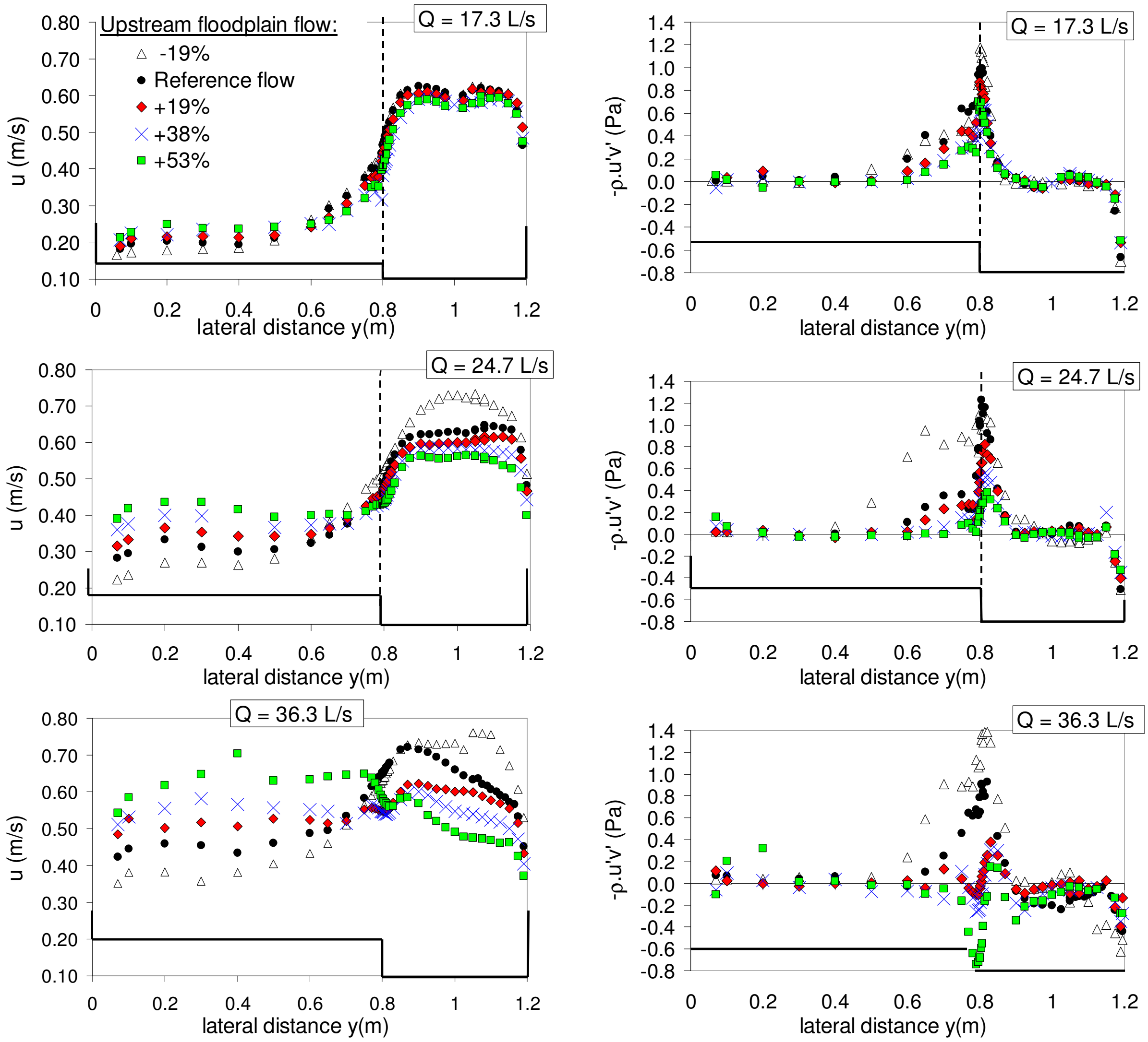

Figure 3 Mean streamwise velocities u and Reynolds stress τ_{xy} vs. lateral distance. Horizontal profile at elevation $Z = 0.6h_f$. Downstream station $x = 4.5$ m

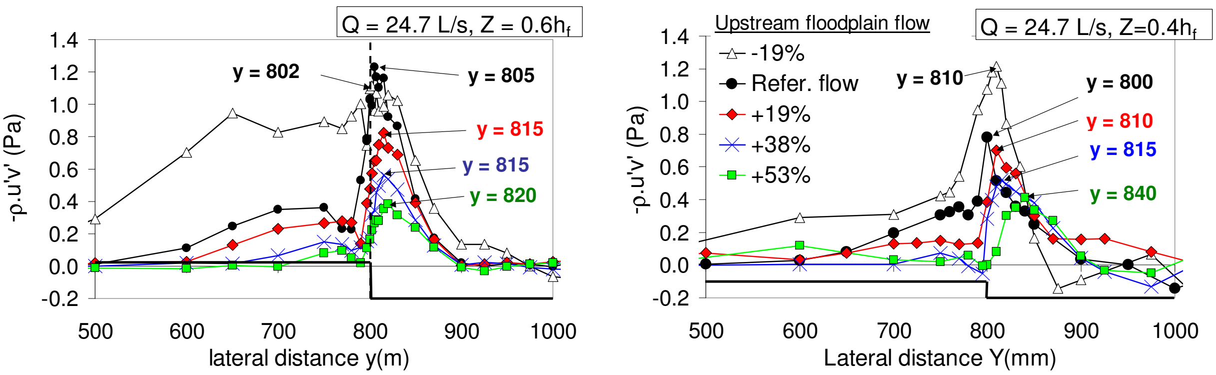

Figure 4 Position of the peak values of Reynolds stress τ_{xy} for discharge $Q = 24.7$ L/s, at two different elevations: $Z = 0.6h_f$ and $0.4h_f$

Considering the under-feeding of the floodplain (-19%), the opposite phenomena is observed: the deficit in upstream floodplain flow enhances the turbulence exchange. The lateral spreading of the shear layer over the floodplain and the magnitude of the shear stress are higher compared to the reference flow cases. No clear tendency was found in the shift of the shear stress peak.

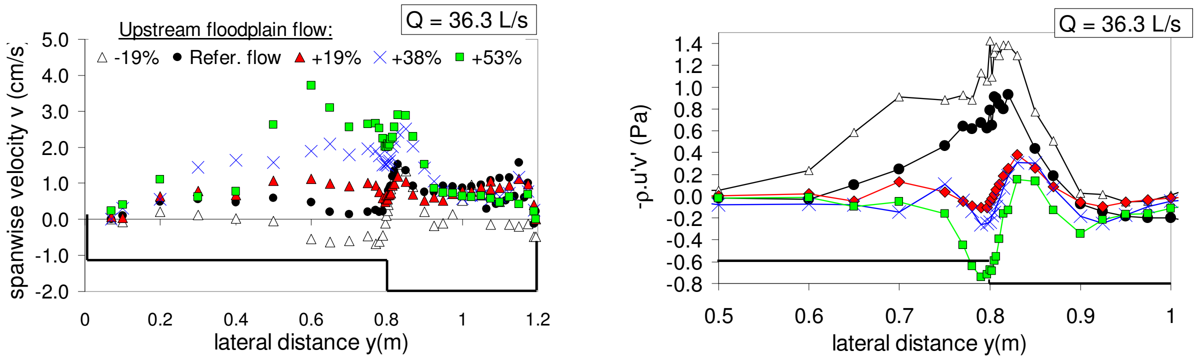

Figure 5 Spanwise velocity *v* and Reynolds stress τ_{xy} at elevation 0.6h_f for discharge *Q* = 36.3 L/s and downstream station *x* = 4.5 m

3.3. Vertical profiles of streamwise velocity and Reynolds stresses

Vertical profiles of both streamwise velocity *u* and Reynolds stresses τ_{xy} and τ_{xz} were carried out for each flow condition at two lateral positions in the main channel (see Figure 1): 1 cm far from the interface with the floodplain (*y* = 810 mm) and near the centre of the main channel (*y* = 1025 mm).

Figure 6 presents the streamwise velocities *u*(*z*). Given a total discharge, the velocity decreases when increasing the upstream floodplain flow at both *y* lateral positions. Near the interface (Figure 6a), the velocity profile has a "S-shape" for the higher discharge *Q* = 36.3 L/s for both reference flow and non-uniform flows. Just above the bankfull level, a local minimum in the velocity is observed. A similar "S-shape" was obtained for the medium discharge, *Q* = 24.7 L/s (not shown here).

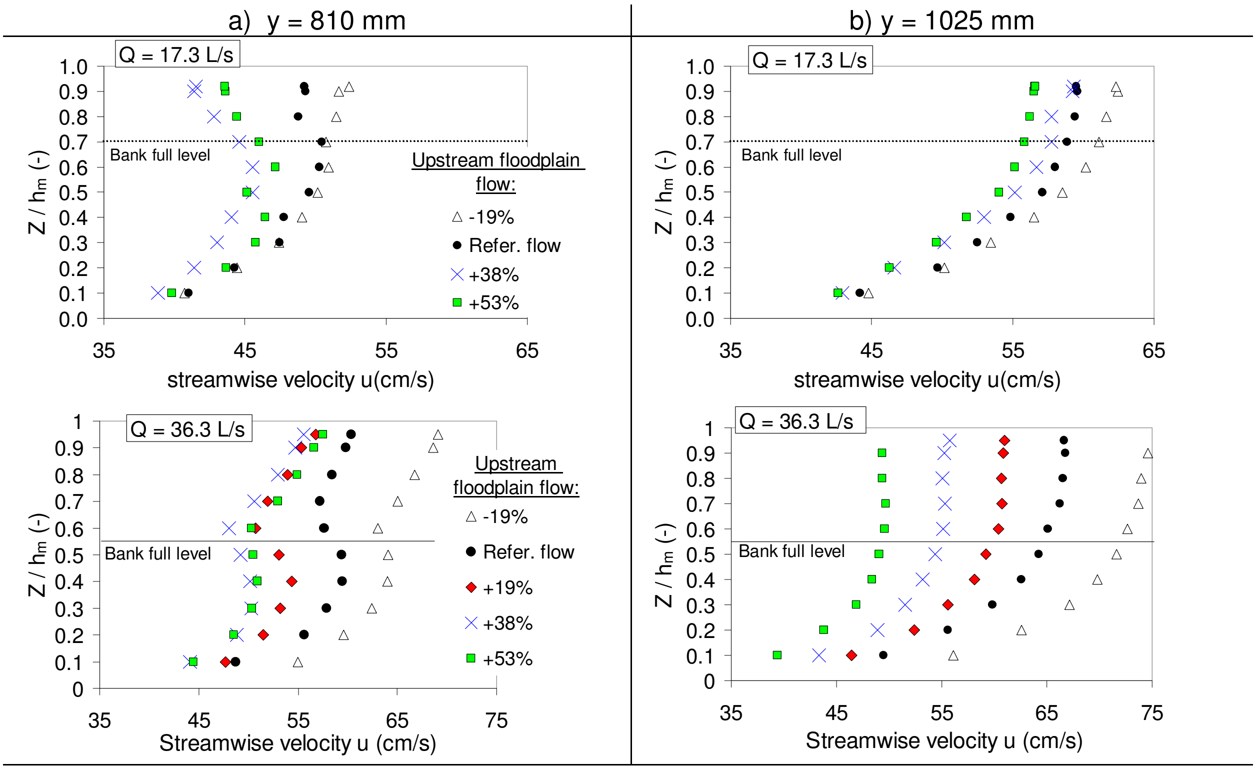

Figure 6 Vertical profiles of streamwise velocity *u* at two lateral positions in the main channel: a) *y* = 810 mm and b) *y* = 1025 mm. Downstream station *x* = 4.5 m

For the lower discharge, the water depth is too small to get a complete "S-shape" above the bankfull level. Near the centre of the main channel (Figure 6b), the shape is closer to a log-profile whatever the total discharge and the flow case, as the floodplain flow has less influence at this location. Comparing the flow cases, we observe both decelerated and accelerated velocity profiles for overfeeding and underfeeding of the floodplain, respectively.

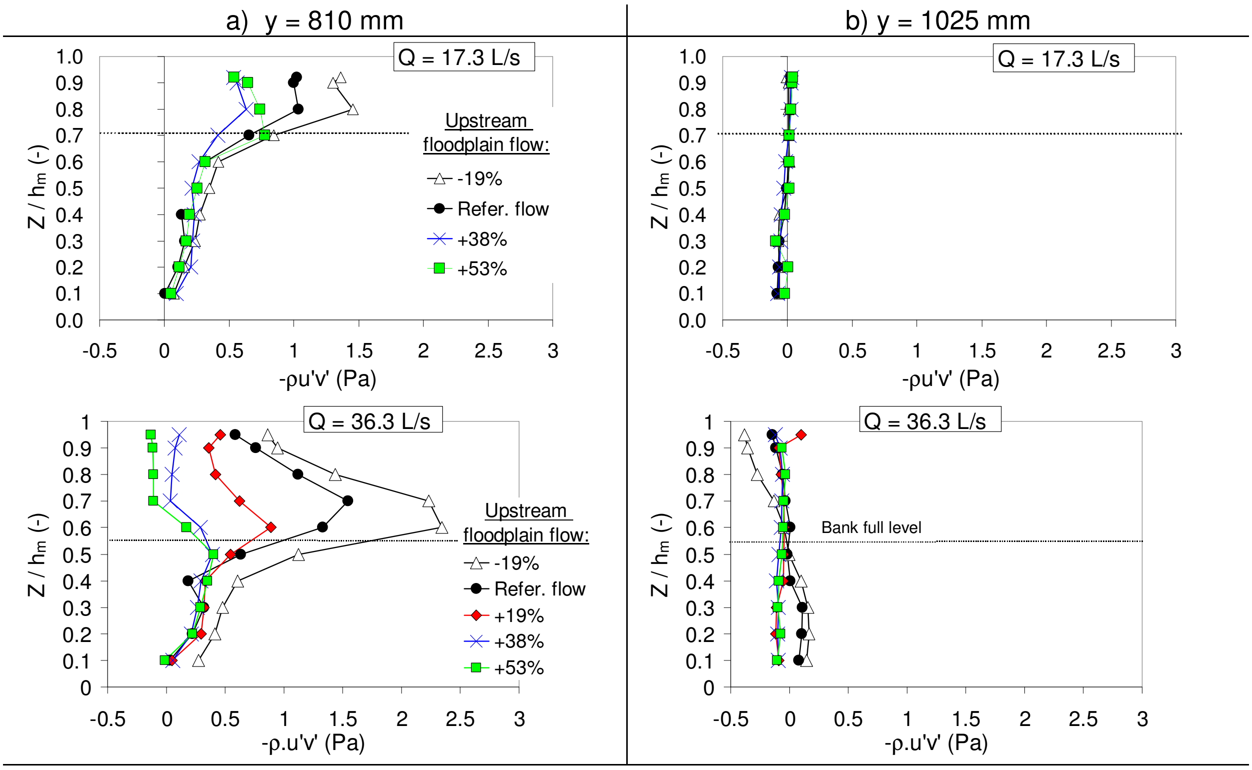

Figure 7 Vertical profiles of Reynolds stress τ_{xy} at two lateral positions in the main channel: a) y = 810 mm and b) y = 1025 mm. Downstream station x = 4.5 m

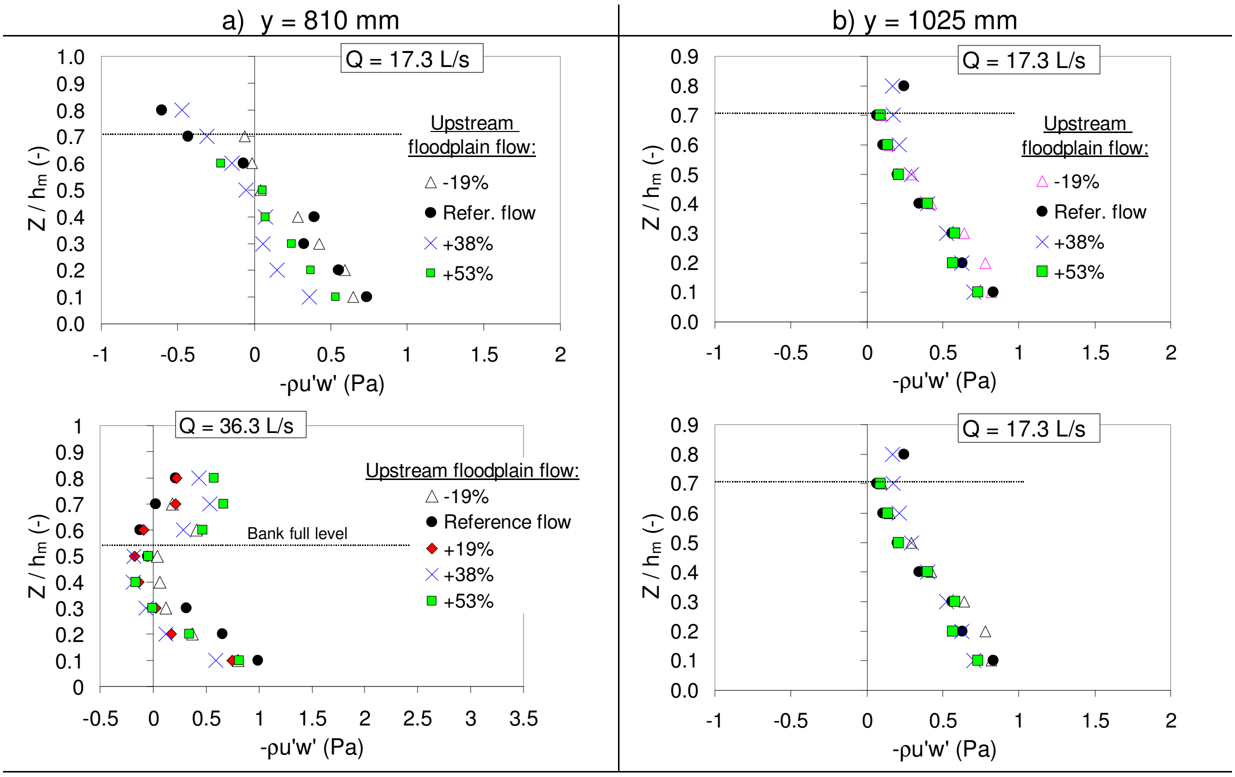

Figure 8 Vertical profiles of Reynolds stress τ_{xz} at two lateral positions in the main channel: a) y = 810 mm and b) y = 1025 mm. Downstream station x = 4.5 m

Figure 7 presents the shear stress $\tau_{xy}(z)$. Similarly to the transverse profiles, the values of Reynolds stress near the interface decreases when rising up the upstream floodplain flow. This is particularly marked above the bankfull level where the discrepancies between the flow cases are higher, highlighting the larger interaction between mass transfer and turbulence in this region. The results confirm what was observed in the horizontal profiles, *i.e.* mass transfer can enhance or diminish the turbulence depending on the direction of the lateral exchange.

For all the flow cases, the peak value of Reynolds stress τ_{xy} is mostly located right above the bank full level. For the two higher total discharges, a "D-shape" of the profile was observed. In the centre of the main channel, negligible shear stresses were measured as shown in Figure 7b.

The Reynolds stresses $\tau_{xz} = -\rho\overline{u'w'}$ presented in Figure 8 can be compared with the streamwise velocity *u* in Figure 6. Near the interface, negative values of τ_{xz} are associated with negative values of gradient *du/dz* for all flow cases. For the two higher discharges, a "C-shape" profile was obtained in close relation with the "S-shape" profile in Figure 6. In the centre of the main channel (Figure 8b), typical linear profiles are obtained.

4. CONCLUSIONS

Given a total discharge and at a given cross-section, reducing the difference in the streamwise velocity between the main channel and the floodplain leads to an increase in water level. That increase is attenuated along the flume. Analyzing the influence of mass transfer between the two channels on the turbulent shear layer, the results show that they are strongly linked. Mass transfer can enhance or diminish the turbulence depending on the direction of the lateral exchange. This was observed both in horizontal and vertical profiles of Reynolds stresses. The mass transfer influences the lateral spreading of the shear layer over the floodplain and the lateral position and magnitude of the shear stress peak. When rising the total discharge *Q*, the effect of mass transfer on turbulent shear layer is increasingly significant.

5. REFERENCES

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