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Coherent structures in compound channel flows at the presence of transverse currents

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Abstract

The paper presents results of experiments conducted in a laboratory flume with a compound cross-section consisting of a central main channel (MC) and two adjacent floodplains (FP). The focus of the study has been on turbulent mixing layers and large-scale coherent structures that form at the interfaces between the MC and two FP at non-uniform flow conditions in the streamwise direction. In the experiments, the streamwise non-uniformity is generated by imposing an imbalance in the discharge distribution between MC and FPs at the flume entrance, keeping the total flow rate ($Q = 114$ L/s) constant. The experiments started with initially uniform flows (8 L/s in each FP and 98 L/s in MC), which then have been modified by redistribution of the water discharge between MC and FPs. Three unbalanced inflow conditions have been tested, with a FP inflow of 4, 12 and 16 L/s at each FP. The discharge imbalance results in a transverse depth-averaged mean flow (termed herein ‘transverse flow’) from MC to FP or vice versa, quantified by the depth-averaged transverse velocity U_{yd} . Based on ADV measurements with 1 or 2 side-looking probes, it is shown that transverse currents towards the MC with a velocity ratio U_{yd} / U_{xd} higher than 5% can entirely displace the mixing layer, shear-layer turbulence, and coherent structures, shifting them into the MC. It is also found that streamwise uniformity is reached faster with a transverse flow towards the FP than with a transverse flow in the opposite direction.

1. Introduction

This study is conducted in a laboratory flume with a compound cross-section, aiming at investigating the effects of transverse currents on the shear-layer turbulence and on the coherent structures that form between the flow in the main channel and the flows in the adjacent floodplains. The transverse currents are generated by imposing an imbalance in the discharge distribution between the main channel (MC) and two floodplains (FP) at the flume entrance. The transverse flow is quantified by the depth-averaged transverse velocity U_{yd} . At the presence of this transverse flow, the time- and depth-averaged transverse exchange of streamwise momentum has three contributions [Proust et al., 2013]:

$$\overline{\frac{1}{h} \int_0^h -\rho u_x u_y dz} = -\overline{\rho (u_x' u_y')}_d - \rho U_{xd} U_{yd} - \rho [U_x (U_y - U_{yd})]_d \quad (1)$$

where h is the local flow depth; u_i , U_i and U_{id} are the instantaneous, local mean and depth-averaged velocities in the i -direction ($i=x, y$ refer to longitudinal and transverse directions); subscript d refers to depth-averaging and overbar defines time-averaging. The three contributions to the momentum flux are the depth-averaged Reynolds-stress, the momentum transfer by the transverse flow, and the depth-averaged momentum transfer due to secondary currents. In the present paper, we focus on the two first contributions and on the interrelations between the transverse flow of variable direction and magnitude and the large-scale turbulent structures that populate the mixing layer and predominantly drive the transverse Reynolds-stresses at the MC/FP interface.

2. Experimental set up and flow conditions

The experiments were conducted in an 18 m long and 3 m wide flume with a compound cross-section consisting of a central rectangular main channel and two adjacent floodplains. Each floodplain is 1m wide and covered with plastic grass (5mm high rigid blades). The bankfull level in the MC is 115 mm (from MC bottom to the top of the blades). The experiments started with initially uniform flows (8 L/s in each FP and 98 L/s in MC), which then have been modified by redistribution of the water discharge between MC and FPs, keeping the total flow rate ($Q = 114$ L/s) constant. Three unbalanced inflow conditions have been tested, with a FP inflow Q_f ($x = 0$) of 4, 12 and 16 L/s at each floodplain. The

discharge imbalance results in a transverse flow from MC to FP for $Q_f(x=0) = 4$ L/s, and from FP to MC for $Q_f(x=0) = 12$ and 16 L/s. The flow conditions of test cases are given in Table 1. To achieve uniform flow conditions (FP flow depth h_f constant in the streamwise direction, see Table 1), the inflows in the MC $Q_m(x=0)$ and in each of the two FPs $Q_f(x=0)$ were calculated using the formula developed by Nicollet and Uan [1979].

Inflow in each of the two floodplains $Q_f(x=0)$ [L/s]	Main channel inflow $Q_m(x=0)$ [L/s]	Variations ¹ in floodplain flow depth h_f [mm]
4	106	26.0 – 31.1
8	98	30.6 – 30.6
12	90	35.4 – 31.1
16	82	38.1 – 31.0

¹ between $x = 1.13$ m and $x = 16.93$ m.

Table 1: Flow conditions of test cases. Total flow rate $Q = 114$ L/s

Water surface elevation was measured with ultrasonic sensors (UNDK20I69, Baumer) with an acquisition time of 200 s at a rate of 50 Hz, with a standard error lower than 0.3 mm. Velocities were measured with 10 MHz side-looking ADV probes Vectrino+, with 5 min duration at a point and at a 100 Hz sampling rate. The ADV data were despiked using the phase-space thresholding technique [Goring and Nikora, 2002], and used to compute a range of flow parameters including a two-point space-time correlation function:

$$R_{ij}^k(x_k, \varepsilon_k, \tau) = \frac{\overline{u_i'(x_k, t)u_j'(x_k + \varepsilon_k, t + \tau)}}{(\overline{u_i'^2(x_k)} \cdot \overline{u_j'^2(x_k + \varepsilon_k)})^{0.5}} \quad (2)$$

where u_i' is velocity fluctuation, ε_k is spatial lag in the k -direction, τ is time lag. In general, $R_{ij}^k(x_k, \varepsilon_k, \tau)$ in Eq. (2) depends on the location of a reference point where a measurement probe is fixed with another probe moving away point. In the case of homogeneous (uniform) fields of the mean velocity the reference point is not required.

3. Results

In the following, we use the dimensionless positions $x^* = x/B_f$ and $y^* = y/B_f$ where B_f is the FP width ($x^* = 0$ at the outlet of the inlet tanks, $y^* = 0$ at the side wall of the right-hand FP; the two MC/FP interfaces are located at $y^* = 1$ and 2). Figure 1 shows streamwise distributions of the key flow parameters relevant to the problem. As shown in Figure 1, for the uniform flow (FP with 8L/s), more than a half-length of the flume is required to achieve a quasi-constant Reynolds stress $-\rho\overline{(u_x' u_y')_d}$. The parameters of the non-uniform cases evolve within the whole measuring domain, highlighting that the mass redistribution between MC and FP and mixing layer development are very slow processes. Figure 1 also shows that the turbulent quantities for case 4L/s reach the uniform flow values faster than for case 12 L/s, although the same amount of water has to be transferred from either side of the MC/FP interface.

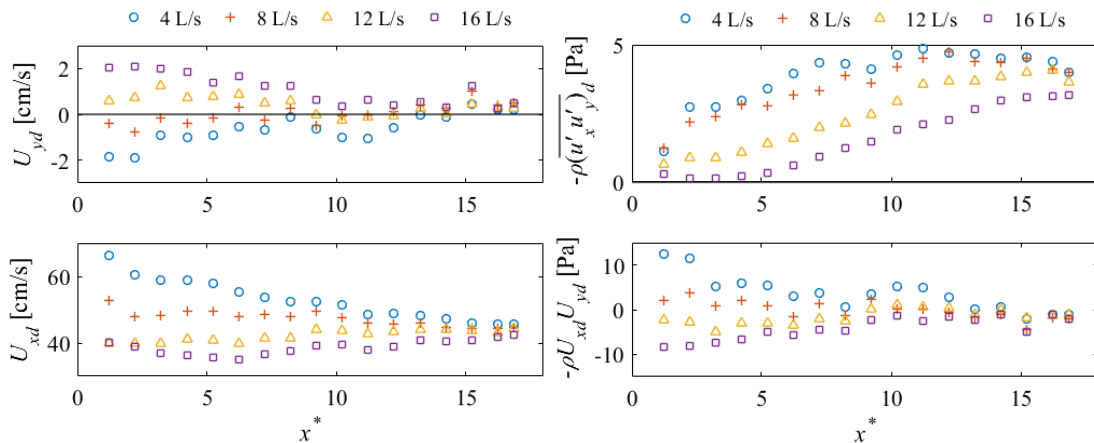


Figure 1: Test cases with FP inflow $Q_f(x^* = 0) = 4, 8$ (uniform flow), 12 and 16 L/s. (Left) Depth-averaged transverse and streamwise velocities U_{yd} and U_{xd} along the right-hand MC/FP interface ($y^* = 1$). (Right) Momentum fluxes over the depth by the transverse currents $-\rho U_{xd} U_{yd}$ and turbulent mixing $-\rho\overline{(u_x' u_y')_d}$.

Denoting $U_{x,int}$ as the mean local streamwise velocity at the interface, U_{x2} as the peak velocity in the MC, and U_{x1} as the velocity averaged across the ‘plateau’ region outside the mixing layer on the FP (Figure 2), we can define the dimensionless mean streamwise velocity and lateral Reynolds-stress as:

$$U_x^* = (U_x - U_{x,int}) / (U_{x2} - U_{x1}) \quad (3)$$

$$-\overline{u_x' u_y'}^* = -\overline{u_x' u_y'} / (U_{x2} - U_{x1})^2 \quad (4)$$

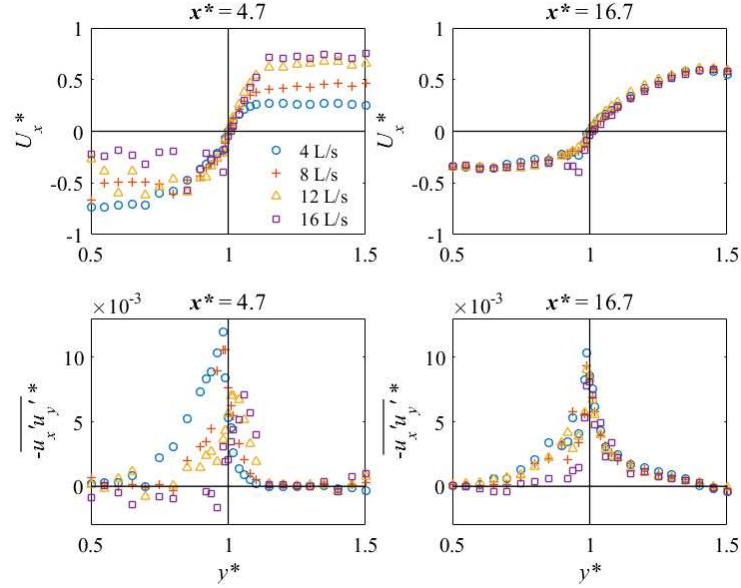


Figure 2: Transverse profiles of the normalised mean local streamwise velocity U_x^* and local Reynolds stress $-\overline{u_x' u_y'}^*$, at downstream distance $x^* = 4.7$ and 16.7 and at an elevation of 20 mm above the FP bottom.

Figure 2 shows that for the case of 16 L/s at $x^* = 4.7$, with a significant transverse flow from FP to MC (velocity ratio U_{yd} / U_{xd} higher than 5%, Figure 1): (i) the mixing layer based on the mean velocity profile; and (ii) the region of high Reynolds stress are shifted to the MC. Figure 3 additionally shows that no coherent structures are observed over the floodplain. The transverse flow prevents the shear layer turbulence from developing over the FP. At the last measuring section ($x^* = 16.7$), though the mean velocity profiles are very similar for all cases (Figure 2), significant differences in the Reynolds-stress distributions over the FP can be observed between case with 16 L/s and three other cases. The coherence of the structures over the FP is lower away from the interface for the case of 16 L/s (Figure 3).

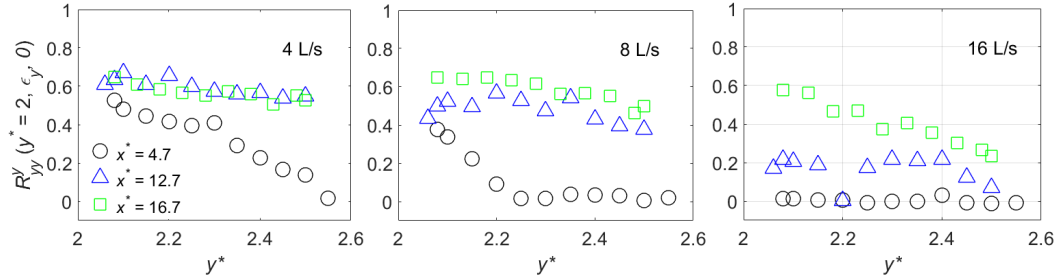


Figure 3: Two-point space-time correlation function R_{yy}^y over the left-hand-side FP located between $y^* = 2$ and $y^* = 3$ with a fixed (reference) ADV probe positioned at the MC/FP interface ($y^* = 2$), at $x^* = 4.7$, $x^* = 12.7$ and $x^* = 16.7$.

4. Conclusions

This laboratory study has shown that transverse currents towards the MC of a river with a velocity ratio U_{yd} / U_{xd} higher than 5% can entirely displace into the MC (i) the mixing layer (based on the mean velocity profiles), (ii) shear-layer turbulence, and (iii) large-scale coherent structures. It is also found that streamwise uniformity is reached faster with a transverse flow towards the FP than with a transverse flow in the opposite direction.

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