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1            Turbulent non-uniform flows in straight compound open-channels

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24 **ABSTRACT**

25 The reported experimental study assesses the effect of non-uniformity of flow on the momentum flux  
26 in straight compound channels. Two flumes were used, featuring vertical and sloping banks. Starting  
27 with uniform flow condition, various imbalances in the upstream discharge distribution were  
28 introduced. This resulted in a time-averaged lateral flow and an advective transport of momentum,  
29 which interacted with the shear-layer turbulence generated by the compound geometry. To investigate  
30 this interaction, the three contributions to transverse momentum flux (depth-averaged flow, shear-layer  
31 turbulence and dispersive term of spanwise velocity) are assessed. The first two contributions were  
32 strengthened by the sloping banks, while the third becomes important for the case of the vertical bank.  
33 With a lateral flow towards the main channel, the first contribution rises at the expense of the second.  
34 With a lateral flow towards the floodplain, the first two contributions have the same order of  
35 magnitude, and the Boussinesq approach is invalidated.

36 **Keywords:** compound open channel flow; laboratory studies; non-uniform flow; transverse  
37 momentum flux; turbulent mixing layers;

38 **1. Introduction**

39 River floods are characterized by overbank flows in compound open-channels. A  
40 compound channel consists of a main channel and one or two floodplains. The variation in  
41 depth and roughness across the section generates transversally sheared flows. Under uniform  
42 flow conditions, these flows are characterized by large-scale, coherent vortices that develop at  
43 the boundary between the main channel and the floodplain (herein called sub-sections). These  
44 macro-vortices enable the two parallel flows to exchange momentum, affecting the river  
45 conveyance (*e.g.* Sellin 1964, Knight and Shiono 1990, Tominaga and Nezu 1991,  
46 Nezu *et al.* 1999).

47 Overbank flows are frequently non-uniform. Non-uniformity may be the result of  
48 flow unsteadiness, but non-uniform steady flows are also observed in prismatic geometries  
49 when (i) a backwater effect is caused by the downstream boundary condition for sub-critical  
50 flows or when (ii) the upstream velocity distribution is far from equilibrium. This last flow  
51 configuration was considered in the present work to investigate turbulent non-uniform  
52 compound channel flows.

53 The motivation for this study stems from the fact that a change in cross-sectional  
54 shape, bottom slope and/or roughness occurs upstream from a prismatic reach, which  
55 necessarily leads to an upstream imbalance in the velocity distribution between the sub-  
56 sections. Three examples of flow configurations observed in natural streams are shown in  
57 Fig. 1: (a) diverging or (b) converging floodplains upstream from a prismatic reach; and (c)  
58 prismatic reach with a longitudinal transition in the hydraulic roughness on the floodplains.  
59 The flow deficit that was observed over diverging floodplains by Bousmar *et al.* (2006) leads  
60 to a flow redistribution from the main channel towards the floodplain along the prismatic  
61 reach. By contrast, the flow excess on converging floodplains (Bousmar *et al.* 2004 and  
62 Proust *et al.* 2006) results in a decelerating flow over the floodplains of the prismatic reach.

63 The third example is inspired by Vermaas *et al.* (2011), who experimentally studied the  
64 influence of a lateral increase in hydraulic roughness on an initially uniform flow in a single  
65 channel. A lateral mass exchange was observed from the decelerating flow over the rougher  
66 bed to the accelerating flow over the smoother bed. With a similar lateral change in roughness  
67 across a compound geometry, the third case shown in Fig. 1(c) features a lateral flow towards  
68 the main channel.

69 Bousmar *et al.* (2005) was one of the first studies dealing with steady flows in  
70 prismatic compound channels with an upstream imbalance in the velocity distribution. The  
71 streamwise evolution of the discharge distribution between the sub-sections was examined in  
72 three laboratory flumes. The lateral mass exchange was found to be a slow process acting on  
73 longitudinal distances ranging from  $8 \times B_f$  to  $35 \times B_f$  ( $B_f$  being the width of one floodplain).  
74 Using the same data, Proust *et al.* (2010) focused on the energy losses and showed that the  
75 streamwise profile of the total head was different from one sub-section to another.

76 In the two previously mentioned works, the turbulent quantities were not measured.  
77 In the present work, we investigated the interaction between the time-averaged transverse  
78 flow caused by the longitudinal non-uniformity and the shear-layer turbulence generated by  
79 the compound geometry. We estimated the three contributions to transverse momentum flux,  
80 namely the depth-averaged lateral Reynolds shear stress, a dispersive term of spanwise  
81 velocity over the depth, and the momentum flux by the depth-averaged velocity components.  
82 Specific attention was given to the vertical interface between the sub-sections, since it plays  
83 an important role in 1D (Bousmar and Zech 1999) or 1D+ numerical modelling  
84 (Proust *et al.* 2009, 2010). In particular, the validity of the Boussinesq approach is analysed.

85 The experiments were carried out in two flumes, presenting vertical and sloping  
86 banks. These two different geometries enable the assessment of the effect of the bank slope  
87 on the mass and momentum exchanges. Each data set is composed of a uniform flow and non-  
88 uniform flow cases, which are produced by an imbalance in the upstream discharges. An  
89 excess or a deficit in floodplain inflow were both investigated.

## 90 **2. Experimental procedure**

### 91 *2.1. The two laboratory flumes*

92 The experiments were performed in two compound channel flumes located at the  
93 Laboratory of Fluid Mechanics and Acoustics (LMFA), Lyon, France, and at the National  
94 Laboratory of Civil Engineering (LNEC), Lisbon, Portugal. The schematic top views and  
95 cross-sections of the flumes are shown in Fig. 2. The LMFA flume is 8 m long, 1.2 m wide,  
96 and is made of PVC with a bottom slope of 1.8 mm/m. The cross-section was asymmetrical,  
97 composed of a rectangular main channel and a floodplain, with a bank full height,  $h_b$ , of

98 53 mm. The LNEC flume is 10 m long, 2 m wide, and made of polished concrete with a  
99 bottom slope of 1.1 mm/m. The symmetrical cross-section was composed of two floodplains  
100 and one trapezoidal main channel with a bank slope of  $45^\circ$  and a height,  $h_b$ , of 100 mm. The  
101 Manning roughness was  $0.0091 \text{ m}^{-1/3}/\text{s}$  and  $0.0092 \text{ m}^{-1/3}/\text{s}$ , at LMFA and LNEC, respectively.  
102 These values were obtained by isolating one sub-section from another with a moveable  
103 vertical wall.

104 Following the recommendations of Bousmar *et al.* (2005), independent inlets for the  
105 main channel and for the floodplains were used in both flumes (see Fig. 2), and the discharges  
106 were measured with independent electromagnetic flow meters (uncertainty of 0.2 L/s to  
107 0.3 L/s). To adjust water levels, independent downstream tailgates (one per sub-section) were  
108 used in each flume.

109 A Cartesian coordinate system is used in which  $x$ ,  $y$  and  $z$  refer to the longitudinal,  
110 lateral and vertical directions, respectively (see Fig. 2), and  $u$ ,  $v$ ,  $w$  refer to the components of  
111 instantaneous velocity. The system origin is defined as:  $x = 0$  at the inlet cross-section;  $y = 0$   
112 at the sidewall of the right-hand floodplain; and at a given  $x$  station, elevation  $z$  is measured  
113 from the bed of the main channel.

## 114 2.2. Measurement of velocity and water level

115 In both flumes, velocity was measured with a 10 MHz micro ADV (Vectrino+),  
116 equipped with a two-dimensional side-looking probe. The sampling volume was a 7 mm long  
117 cylinder with 6 mm diameter. The acquisition time was 3 min at each measurement position,  
118 with a sampling rate of 100 Hz. With 18,000 samples, the convergence of first and second  
119 statistical moments of the velocity components was ensured and the error on Reynolds shear  
120 stress is expected to be  $\pm 3\%$  according to Chanson *et al.* (2007). The flow was seeded with  
121  $10 \mu\text{m}$  hollow glass spheres to get a signal-to-noise ratio higher than 20 dB as recommended  
122 by McLelland and Nicholas (2000). The ADV data were despiked using the phase-space  
123 thresholding technique of Goring and Nikora (2002), and correlations lower than 70% were  
124 excluded from the time-series.

125 To correct errors of misalignment of the ADV probe with respect to the longitudinal  
126 direction, the pitch angle was slightly modified during the post-processing. A single  
127 correction angle was used for each measured cross-section. At LMFA, the depth-averaged  
128 spanwise velocity,  $V_d$ , was assumed to be zero in the measuring volume that was nearest the  
129 main channel sidewall (5 mm from the wall). At LNEC, the value of  $V_d$  was minimized both  
130 on the main channel centreline and at the last measured position that was located 50 mm from  
131 the floodplain sidewall. The correction angle is in the range  $\pm 0.5^\circ$  in both flumes, and it was

132 accounted for when computing local time-averaged velocity and Reynolds stresses, as  
133 recommended by Roy *et al.* (1996) and Peltier *et al.* (2013b).

134 The measuring cross-sections were located at downstream distances  $x = 2.5, 4.5$  and  
135  $6.5$  m at LMFA, and at  $x = 1.1, 3.0, 5.0$  and  $7.5$  m at LNEC. The velocity measuring grids are  
136 shown in Fig. 2, with 43 to 45 lateral positions and with up to 10 vertical positions (interface  
137 between the sub-sections). At LMFA, velocity was also measured at  $x = 5.5$  m at floodplain  
138 edge. In both flumes, the flow rate computed from the integration of the velocity field was  
139 within 97 to 100% of the values measured by the flow meters.

140 Water levels were measured with an ultrasonic sensor (uncertainty of  $\pm 0.2$  mm) at  
141 LMFA, and with a point gauge (uncertainty of  $\pm 0.3$  mm) at LNEC.

### 142 2.3. Flow conditions

143 Uniform flow conditions were used as a reference situation. In both flumes, the  
144 relative flow depth,  $D_r = h_f / h_m$ , was chosen to be 0.3. As shown in Fig. 2,  $h_f$  is the mean flow  
145 depth on the floodplain and  $h_m$  is the mean flow depth in the main channel (outside the side-  
146 sloped region at LNEC). The flow is considered uniform when both the flow depth and the  
147 depth-averaged streamwise velocity,  $U_d$ , are constant along  $x$ -direction (see sections 4.1 and  
148 4.4). To obtain a constant flow depth all along the flume, both the height of the downstream  
149 tailgates and the upstream discharge distribution were adjusted. Then, the uniform flow was  
150 disturbed by varying the upstream discharges, but keeping the total flow rate and the height of  
151 the tailgates unchanged. Let us consider the variation in the floodplain discharge,  $Q_f$ , with  
152 respect to uniform flow conditions:  
153

$$154 \quad \Delta Q_f(x) = \frac{Q_f(x) - Q_f^u(x)}{Q_f^u(x)} \times 100 \quad (1)$$

155 where superscript  $u$  refers to uniform flow. The inflow conditions, which are defined by  
156  $\Delta Q_f(x = 0)$ , are reported in the first column in Table 1. The total flow rate  $Q$  is 27.4 L/s and  
157 80.6 L/s, at LMFA and LNEC, respectively. For each flow rate  $Q$  two or three excesses and  
158 one deficit in floodplains inflow were investigated (+19%, +38%, +53% and -19%).

159 To compare the non-uniform flows at position  $x$  with the uniform flow of same total  
160 discharge,  $Q$ , a non-uniformity parameter,  $N$ , was defined as:

$$161 \quad N(x) = \frac{U_m(x) - U_f(x)}{U_m^u(x) - U_f^u(x)} \quad (2)$$

162 where  $U_m$  and  $U_f$  are the mean velocities in the main channel and floodplain, respectively. A  
 163 time-averaged transverse flow from the floodplain to the main channel implies that  $N < 1$ .

164 The values of parameters  $N$ ,  $D_r$ ,  $U_f$ ,  $U_m$ , and  $h_f$ , which were measured in the most  
 165 upstream measuring section, are also shown in Table 1. The cases +53% at LMFA and +38%  
 166 at LNEC feature a small or nil upstream velocity difference,  $U_m - U_f$ , as observed at the outlet  
 167 of an abrupt contraction of the floodplain by Proust *et al.* (2006). The deficit of -19%  
 168 corresponds to flow conditions at the outlet of a diverging compound channel (see Fig. 1).  
 169 This table also presents the Froude numbers in the sub-sections,  $F_f$ , and  $F_m$ , ( $F_i = U_i / \sqrt{gR_i}$ ,  
 170 where  $i = m$  or  $f$ , and  $R_i$  is the hydraulic radius in one sub-section). Regarding the Reynolds  
 171 numbers in a sub-section ( $R_i = 4U_i R_i / \nu$ , with  $\nu$  = kinematic viscosity),  
 172  $R_f \in [6 \times 10^4 - 1.1 \times 10^5]$ , and  $R_m \in [2.4 \times 10^5 - 3.4 \times 10^5]$  at LNEC, and  
 173  $R_f \in [2.5 \times 10^4 - 4.2 \times 10^4]$ ,  $R_m \in [1.2 \times 10^5 - 1.6 \times 10^5]$  at LMFA. Considering the equivalent  
 174 sand roughness,  $k_s$ , in both flumes ( $1.5 \times 10^{-6}$  mm at LMFA, and  $1.5 \times 10^{-4}$  mm at LNEC), all  
 175 flow cases in both sub-sections are hydraulically smooth at LMFA, or transitional flow at  
 176 LNEC, according to the corrected Moody diagram (French 1985).

### 177 3. Theoretical background

#### 178 3.1. Lateral exchange of streamwise momentum

179 Under uniform flow conditions, an important issue is to identify the contributions of  
 180 turbulent diffusion and of secondary flows to the transverse momentum flux (see *e.g.* Shiono  
 181 and Knight 1991, van Prooijen *et al.* 2005, Kara *et al.* 2012). Under non-uniform flow  
 182 conditions, another source of transverse momentum flux has to be taken into account, i.e. the  
 183 advective transport of momentum by the bulk flow. In the present paper, these three  
 184 contributions to the lateral exchange of streamwise momentum were accounted for using a  
 185 depth-averaged approach.

186 The time average of the depth-averaged lateral exchange of streamwise momentum  
 187 yields:

$$188 \quad \overline{1/h \int_0^h -\rho u v dz} = -1/h \int_0^h \overline{\rho u' v'} dz - 1/h \int_0^h \overline{\rho u v} dz \quad (3)$$

189 where  $h$  is the local flow depth,  $(\overline{\quad})$  the time-averaging operator,  $\rho$ , the fluid density,  $u$  and  $v$ ,  
 190 the instantaneous longitudinal and lateral velocities,  $\overline{u}$  and  $\overline{v}$ , the time-averaged longitudinal  
 191 and lateral velocities, and  $u'$  and  $v'$ , the fluctuations of the velocity components about the  
 192 averaged values.

193 The first term on the right-hand side of Eq. (3) is the depth-averaged lateral Reynolds  
 194 shear stress, denoted  $T_{xy}$ :

$$195 \quad T_{xy} = 1/h \int_0^h -\rho \overline{u'v'} dz \quad (4)$$

196 The second term on the right-hand side of Eq. (3) is the lateral exchange of  
 197 streamwise momentum by the time-averaged flow, denoted  $M_{xy}$ :

$$198 \quad M_{xy} = -1/h \int_0^h \rho \overline{uv} dz = -\rho U_d V_d - 1/h \int_0^h \rho \overline{u} (\overline{v} - V_d) dz \quad (5)$$

199 where  $U_d$  and  $V_d$  are the depth-averaged, time-averaged longitudinal and lateral velocity.

200 According to Eq. (5), the term  $M_{xy}$  is the sum of the advective transport of momentum  
 201 by the depth-averaged flow and of a dispersive term of spanwise velocity  $\overline{v}$  over the depth,  
 202 denoted  $-\rho \overline{u} (\overline{v} - V_d) \Big|_d$  in the following. Under uniform flow conditions, the velocity  $V_d$  is nil,  
 203 but the depth-averaged value of  $\overline{uv}$  can be different from zero due to secondary currents.

### 204 3.2. The Boussinesq approach

205 The Boussinesq assumption was validated for uniform compound channel flows, *e.g.*  
 206 by Shiono and Knight (1991) or van Prooijen *et al.* (2005). If gradients  $\partial V_d / \partial x$  and  $\partial \overline{v} / \partial x$   
 207 are negligible compared to  $\partial U_d / \partial y$  and  $\partial \overline{u} / \partial y$ , respectively, a local transverse eddy  
 208 viscosity,  $\varepsilon_{xy}$ , and a depth-averaged transverse eddy viscosity,  $\varepsilon_{xy} \Big|_d$  can be defined as:

$$209 \quad -\overline{u'v'} = \varepsilon_{xy} \frac{\partial \overline{u}}{\partial y} \quad (6)$$

$$210 \quad T_{xy} / \rho = \varepsilon_{xy} \Big|_d \frac{\partial U_d}{\partial y} \quad (7)$$

211 We will also investigate in this paper, if the Boussinesq approach is still relevant  
 212 when the flow is non-uniform.

## 213 4. Results

### 214 4.1. Relative flow depth

215 The longitudinal variation in relative flow depth,  $D_r$ , is shown in Fig. 3(a) for the  
 216 various floodplain inflows  $\Delta Q_f(x=0)$ . The relative flow depth is constant along both



217 flumes when the flow is uniform. The analysis of non-uniform flows shows that the cases  
218 with an excess in the floodplains inflow tend towards the uniform relative flow depth more  
219 rapidly than the cases with a deficit in the floodplains inflow. Considering runs +19% and  
220 – 19% that are symmetric in terms of floodplains inflow relative to uniform flow, the profile  
221 of  $D_r$  for run –19% is further from the uniform flow profile along the two flumes.

222 Figure 3(a) also shows that the relative flow depth,  $D_r$ , increases from run –19% to  
223 run +53%, *i.e.* when the velocity difference between the sub-sections,  $U_m - U_f$ , decreases. The  
224 largest variation in  $D_r$  was observed in the first measuring section: the discrepancy from  
225 uniform relative flow depth ranges from –4% to +8% at LNEC, and from –6% to +8% at  
226 LMFA (see data of  $D_r$  in Table 1).

#### 227 4.2. Velocity difference between sub-sections

228 Figure 3(b) shows the longitudinal variation in the non-uniformity parameter,  $N$  (see  
229 Eq. (2)). The  $N$ -profiles prove that a time-averaged transverse flow occurs between the sub-  
230 sections until the most downstream measuring section for each non-uniform case in both  
231 flumes. The length of the flumes is not sufficient so that any of the non-uniform cases reaches  
232 equilibrium ( $N = 1$ ).

233 Figures 3(a) and 3(b) show that the relative flow depth,  $D_r$ , tends to equilibrium more  
234 rapidly than the  $N$ -parameter. In the LNEC flume at  $x/B_f = 10.7$ , the discrepancy from uniform  
235 relative flow depth ranges from –2% to +1%, while the parameter  $N$  significantly varies from  
236 0.49 to 1.25. When using dimensional variables, this means that several velocity differences  
237 between the sub-sections can be obtained with the same flow depth. In accordance with  
238 Bousmar *et al.* (2005), this shows that using constant water depth as the unique criterion of  
239 flow uniformity can lead to erroneous results.

#### 240 4.3. Depth-averaged transverse flow

241 The lateral distribution of time-averaged and depth-averaged spanwise velocity,  $V_d$ , is  
242 shown in Fig. 4 at  $x/B_f = 5.6$  and 4.3 at LMFA and LNEC, respectively. This velocity is  
243 scaled by the bulk velocity under uniform flow conditions,  $U_A^u = Q/A^u$ . When the flow is  
244 non-uniform, the transverse flow is not laterally uniform. In both flumes, the highest values of  
245  $|V_d|$  are observed on the floodplains near the vertical interface between sub-sections, and  
246 irrespective of the  $N$ -parameter. Beyond  $y/B_f = 1$ ,  $|V_d|$  decreases in the main channel. At  
247 LMFA, this decrease is sharp owing to low values of local spanwise velocity,  $\bar{v}$ , below the  
248 bank full height,  $h_b$ . At LNEC, the sloping bank ensures a smoother decrease in  $|V_d|$  between  
249 the top and the bottom of the bank.

250 4.4. *Mixing layer width*

251 The depth-averaged streamwise velocity,  $U_d$ , is shown in Fig. 5 in the most  
252 downstream measuring sections. At LMFA, a local decrease is observed near the centreline  
253 position in the main channel, irrespective of the direction and magnitude of the transverse  
254 flow. This decrease is the result of marked counter-rotating secondary flows that will be  
255 analysed further in section 4.5.

256 Let us consider a moving average with three consecutive values of  $U_d$ , such that the  
257 changes in this average are lower than 1 cm/s (uncertainty on velocity measurement). We can  
258 define two local plateaux of  $U_d$  and two associated velocities  $U_{d1}$  and  $U_{d2}$ , which are located  
259 out of the shear-layer on the floodplain and in the main channel, respectively (shown in Fig. 5  
260 for  $N > 1$ ). In LMFA,  $U_{d2}$  is, therefore, located on the left-hand side of the local decrease in  
261 velocity.

262 Similarly to Pope (2000) for unbounded mixing layers, we can define the lateral  
263 location  $y_\alpha(x)$  for  $0 < \alpha < 1$  such that depth-averaged velocity,  $U_d$ , can be defined as:

$$264 \quad U_d(x, y_\alpha(x)) = U_{d1} + \alpha(U_{d2} - U_{d1}) \quad (8)$$

265 and consider a characteristic width of the mixing layer  $\delta(x)$  as

$$266 \quad \delta(x) = y_{0.9}(x) - y_{0.1}(x) \quad (9)$$

267 with  $y_\alpha = 0$  at the sidewall of the right-hand floodplain (see Fig. 2)

268 The longitudinal variations in the scaled width,  $\delta/B_f$ , and the scaled position,  $y_{0.1}/B_f$ ,  
269 are shown in Fig. 6 for seven flow cases. Additional values of  $\delta$  are displayed for the uniform  
270 flow at LMFA (nine measuring sections). They were obtained from  $U_d$ -profiles that were  
271 measured by Peltier *et al.* (2013a) with identical flow conditions in the same flume. With the  
272 uniform flows in Fig. 6(a), after a phase of growth along the  $x$ -direction, the width of the  
273 mixing layer  $\delta$  reaches a constant value at  $x/B_f = 5.6$  and  $4.3$ , at LMFA and LNEC,  
274 respectively. Beyond these two downstream positions: (i) the mixing layer is self-sustained  
275 owing to the topographical forcing of the 2-stage channel (Jirka 2001); and (ii) the flow can  
276 rigorously be considered as uniform since no significant transverse flow occurs across the  
277 flumes (see Fig. 4).

278 It can be seen in Fig. 6(b) that for cases with an excess in floodplain flow, the lateral  
279 boundary of the mixing layer,  $y_{0.1}$ , is increasingly moved towards the main channel with an  
280 increase in the floodplain inflow. The high spanwise velocities near  $y/B_f = 1$  on floodplain  
281 side (see Fig. 4) are responsible for the displacement of the shear layer. With case +53% at  
282 LMFA or case +38% at LNEC, the lateral position,  $y_{0.1}$ , is displaced into the main channel  
283 until the most downstream measuring section. As shown in Fig. 6(a), this results in a

284 significant decrease in the mixing layer width,  $\delta$  relative to uniform flow case. The lateral  
285 displacement of the layer is constrained by the presence of the main channel sidewall at  
286 LMFA or the symmetry axis at LNEC, and by the high speed flow in the main channel of  
287 both flumes. For example, with the case +19% at LMFA, the flow that is the closest to  
288 equilibrium ( $N = 0.88$  at  $x/B_f = 8.1$  in Fig. 3(b)), a 30% decrease is observed relative to the  
289 mixing layer width of the uniform flow.

290 With cases -19%, the mixing layer in both flumes laterally spreads onto the  
291 floodplains in the downstream direction (see  $y_{0,l}$  in Fig. 6(b)), with a linear evolution.

292 These changes in the lateral position,  $y_{0,l}$  and the mixing layer width were also  
293 observed by Peltier *et al.* (2013a) in the LMFA flume with a transverse embankment set on  
294 the floodplain. With the same total flow rate  $Q = 24.7$  L/s, and with a 50cm-long  
295 embankment, the width  $\delta$  is zero close to the embankment owing to very large transverse  
296 flows.

#### 297 4.5. Time-averaged streamwise velocity

298 Under uniform flow conditions, preliminary measurements of the vertical profiles of  
299 the time-averaged streamwise velocity  $\bar{u}$  were carried out along the centreline position in the  
300 main channel, every  $\Delta x = 0.5$  m or 1 m. The vertical distribution of  $\bar{u}$  stops evolving from  
301 downstream positions  $x/B_f = 6.8$  at LMFA, and 8.6 at LNEC flume, with a log-law in the  
302 inner region. Figure 7 shows the cross-sectional distribution of  $\bar{u}$ , scaled by  $U_A^u$ , in the last  
303 measuring sections, at  $x/B_f = 8.1$  and 10.7, at LMFA and LNEC, respectively. In the main  
304 channel of LMFA flume, the presence of two counter-rotating secondary flows can be  
305 inferred from the inflection of the contours of velocity  $\bar{u}$ , upwards near the centreline  
306 position and downwards in the corners. In the results from LNEC, the presence of secondary  
307 flows is not so clear, despite of a similar aspect ratio  $B_m/h_b$ . As stated by Ikeda and McEwan  
308 (2009) for uniform flows, the presence of a vertical bank and a vertical sidewall strengthen  
309 secondary currents in comparison to the sloping banks of the LNEC flume. The present data  
310 set shows the maintenance of secondary currents cells when the flow is gradually varied.  
311 However, Fig. 7(a) and Fig. 5 (top plot) show that the region of local deficit in velocity is  
312 shifted towards the main channel sidewall by a mass transfer coming from the floodplain, i.e.  
313 for  $N < 1$ . Comparing cases  $N = 1$  and  $N = 0.64$ , the local decrease in velocity  $U_d$  in Fig. 5  
314 (top plots) is displaced from  $y/B_f = 1.2$  to 1.25, i.e. of 4 cm (10% of the main channel width).

315 In both flumes, in spite of the wide range of variation in the non-uniformity parameter  
316  $N$ , the general pattern of primary velocity  $\bar{u}$  is weakly affected by the transverse flow in the  
317 most downstream measuring section. However, some local changes can be observed close to  
318 the interface between sub-sections. At LNEC, near  $y/B_f = 1$ , the contours of  $\bar{u}$  for the cases

319 – 19% and +38% clearly differ, depending on the direction of the transverse flow. At LMFA,  
320 the contours of  $\bar{u}$  near the floodplain edge in the main channel are inclined where the  
321 floodplain flow gets into the faster flow (compare  $N = 1$  to  $N = 0.64$ )

#### 322 4.6. Lateral Reynolds shear stress

323 Figure 8 shows the lateral distribution of depth-averaged lateral Reynolds shear  
324 stress,  $T_{xy}$ , at  $x/B_f = [8.1, 10.7]$ , at LMFA and LNEC, respectively. Comparing Fig. 8 to Fig. 5  
325 indicates, at least from a qualitative point of view, a link between the lateral distributions of  
326  $T_{xy}$  and of the streamwise velocity  $U_d$ . The shear layer turbulence appears to be locally  
327 induced by the streamwise velocity field. The Boussinesq assumption, which was validated  
328 for uniform compound channel flows, could still be valid for non-uniform flows in both  
329 flumes. The link between  $T_{xy}$  and lateral gradient  $\partial U_d / \partial y$  is clear, irrespective of the  $N$ -value.  
330 For  $N < 1$ , the shear stress  $T_{xy}$  is negligible as velocity  $U_d$  is constant across the whole  
331 floodplain. For  $N > 1$ , the region of high shear stress  $T_{xy}$  coincides with the region of high  
332 gradients  $\partial U_d / \partial y$ , between  $y/B_f = 0.7$  and 1.0 in both flumes. In addition, the negative values  
333 of gradient  $\partial U_d / \partial y$  that are related to the secondary currents and to the sidewall effect in the  
334 main channel at LMFA lead to negative values of  $T_{xy}$ .

335 Figure 9 shows the cross-sectional distribution of lateral Reynolds shear stress  
336  $-\overline{\rho u'v'}$ , scaled by  $\rho(U_m - U_f)^2$ , as the velocity difference  $U_m - U_f$  is the natural source of  
337 the shear-layer turbulence. All cases feature a marked 2D pattern of  $-\overline{\rho u'v'}$  across the  
338 section. Under uniform flow conditions, the region of high Reynolds stress extends below the  
339 bank full level in both flumes. This is more pronounced in the LNEC flume. Since the aspect  
340 ratio  $B_m/h_b$  and the velocity difference are comparable in both flumes, the sloping bank  
341 appears to be responsible for a higher turbulent diffusion at LNEC. Under non-uniform flow  
342 conditions, the cross-sectional pattern of Reynolds stress is highly altered by the time-  
343 averaged transverse flow in the most downstream measuring sections of both flumes.

344 In the presence of a transverse flow towards the main channel ( $N < 1$ ), different flow  
345 characteristics are observed depending upon whether the main channel is rectangular or  
346 trapezoidal. As mass exchange progressively increases at LMFA from  $N = 0.88$  to  $N = 0.64$ ,  
347 the high shear region is laterally stretched towards the main channel sidewall. The highest  
348 shear region remains located at the floodplain edge (see also Fig. 8), while a second local  
349 maximum detaches from the floodplain edge and is horizontally shifted towards the main  
350 channel sidewall (to  $\approx y/B_f = 1.1$  for  $N = 0.64$ ). The region of negative values of Reynolds  
351 stress associated with the local deficit in velocity is also displaced in the same direction.  
352 Simultaneously, the high shear region in the main channel is increasingly extended in the

353 vertical direction from  $N = 0.88$  to  $N = 0.64$ , highlighting the interaction between the  
354 transverse plunging flow and the shear-layer turbulence. At LNEC, as the transverse flow  
355 increases, the high shear region is first horizontally displaced towards the main channel  
356 ( $N = 0.76$ ), and then vertically towards the sloping bank for  $N = 0.49$ . With this latter flow,  
357 the farthest from equilibrium in Fig. 9, the high shear region is stretched towards the bottom  
358 of the slope by the transverse plunging flow and a second region of shear is produced near the  
359 centre of the main channel, as observed at LMFA.

360 In the case of a transverse flow towards the floodplains ( $N > 1$ ), different flow  
361 conditions are also observed in both flumes, although the velocity difference,  $U_m - U_f$ , is  
362 comparable with  $N = 1.31$  and  $1.25$ . The lateral Reynolds shear stresses are significantly  
363 higher at LNEC than at LMFA from  $y/B_f = 0.7$  to  $1.1$  (see also Fig. 8). This is particularly  
364 noticeable (i) below the bank full level, and (ii) within the near-surface layer on the  
365 floodplain. Since the lateral gradients  $\partial U_d / \partial y$  shown in Fig. 5 are lower at LNEC than at  
366 LMFA, an increase of depth-averaged transverse eddy viscosity (see Equation 7 in section  
367 3.2) is observed in this flume. Hence, in comparison with the vertical bank, the sloping bank  
368 enhances the shear-layer turbulence when the flow is uniform and when mass is transferred  
369 onto the floodplains.

#### 370 4.7. Momentum flux at floodplain edge

371 As previously said, an accurate estimate of the transverse momentum flux at  
372 floodplain edge ( $y/B_f = 1$ ) is required for 1D or 1D+ modelling. In this section, we investigate  
373 this momentum flux at comparable distances  $x/B_f$  in both flumes, *i.e.* 6.8 and 7.1 at LMFA  
374 and LNEC, respectively. Figure 10 shows the three contributions to this flux, namely the  
375 depth-averaged lateral Reynolds shear stress  $T_{xy}$ , the advective transport term  $-\rho U_d V_d$  and  
376 the depth averaging of  $-\rho \bar{u}(\bar{v} - V_d)$  (see Eqs. 4 and 5).

377 Because of the shallowness of the floodplain flow, the development of secondary  
378 currents is severely restricted. The dispersive term  $-\rho \bar{u}(\bar{v} - V_d)$  is negligible compared to the  
379 other two terms. With higher values of velocity components  $U_d$  and  $V_d$  at LNEC, the variation  
380 range of  $-\rho U_d V_d$  is larger at LNEC than LMFA, while the variation range of  $T_{xy}$  is  
381 comparable in both flumes. With a transverse flow to the floodplain ( $N > 1$ ),  $T_{xy}$  and  
382  $-\rho U_d V_d$  are positive and of the same order of magnitude in both flumes. With an opposite  
383 transverse flow ( $N < 1$ ): a) at LMFA, the advective momentum transport  $-\rho U_d V_d$  increases  
384 with flow non-uniformity at the expense of the Reynolds stress  $T_{xy}$ , with the particular case

385 “ $N = 0.84$ ”, for which the total momentum flux is cancelled; b) at LNEC, the momentum flux  
386 is essentially advective.

387 Figure 11 shows the vertical distributions of lateral Reynolds shear stress  $-\overline{\rho u'v'}$   
388 and of flux  $-\overline{\rho uv}$ , at same locations as in Fig. 10. With  $N < 1$  at LNEC in Fig. 11(b), the  
389 shear stress  $-\overline{\rho u'v'}$  is always negligible compared to  $-\overline{\rho uv}$  at each elevation and for all  
390 cases. For  $N > 1$  in Fig. 11(a,b), the shear-layer turbulence seems to be enhanced by the  
391 sloping bank at LNEC, as the  $N$ -parameter is comparable in both flumes and the velocity  
392 difference is similar (0.35 m/s vs 0.33 m/s). Hence, the following conclusions may be drawn:  
393 (1) for an increasing transverse flow to the main channel, the advective momentum transport  
394  $\rho|U_d V_d|$  progressively rises at the expense of the shear-layer turbulence; (2) for a transverse  
395 flow to the floodplains, the two fluxes  $-\rho U_d V_d$  and  $T_{xy}$  are of the same sign and order of  
396 magnitude; (3) both  $-\rho U_d V_d$  and  $T_{xy}$  are strengthened by a sloping bank relative to a  
397 vertical one, irrespective of the lateral flow.

#### 398 4.8. Eddy viscosity at floodplain edge

399 Given the qualitative link between the lateral shear stress  $T_{xy}$  and gradients  $\partial U_d / \partial y$  in  
400 section 4.6, a quantitative analysis of the relevance of the Boussinesq approach was  
401 performed at the floodplain edge ( $y/B_f = 1$ ) and  $x/B_f = 6.8$  in the LMFA flume. Using a  
402 centred difference with  $\Delta x = 1$  cm and  $\Delta y = 0.5$  cm, streamwise gradients  $\partial V_d / \partial x$  were  
403 found to be one or two orders of magnitude lower than  $\partial U_d / \partial y$  (same results holds for local  
404 gradients  $\partial \bar{v} / \partial x$  and  $\partial \bar{u} / \partial y$ ). The definitions of the local and depth-averaged transverse  
405 eddy viscosities presented in Eqs. 6 and 7 were thus used. The distribution over the depth of  
406 the eddy viscosity,  $\epsilon_{xy}$ , is shown in Fig. 12(a). It noticeably varies with the magnitude and  
407 direction of the time-averaged lateral flow. When mass is transferred to the floodplain  
408 ( $N = 1.32$ ), a strong increase of  $\epsilon_{xy}$  from bed to surface is observed. In contrast, with a mass  
409 transfer to the main channel,  $\epsilon_{xy}$  decreases when approaching the water surface for the case  
410 that is the furthest from equilibrium ( $N = 0.57$ ). Hence, these profiles clearly highlight the  
411 interaction between the transverse flow and the shear-layer turbulence.

412 In this context, we tested the model of depth-averaged eddy viscosity developed by  
413 van Prooijen *et al.* (2005). The total eddy viscosity  $\epsilon_{xy}|_d$  is the sum of the bed-induced eddy  
414 viscosity,  $\epsilon_{xy}^b|_d$ , and of the shear-layer-induced viscosity,  $\epsilon_{xy}^s|_d$ :

$$\varepsilon_{xy}|_d = \varepsilon_{xy}^b|_d + \varepsilon_{xy}^s|_d = \alpha h \sqrt{\frac{1}{8} f U_d} + \frac{h_f + h_m}{2h} \beta^2 \delta^2 \left| \frac{\partial U_d}{\partial y} \right| \quad (10)$$

416 The bed-induced turbulence is modelled by the Elder's model, in which  $\alpha$  is a  
 417 constant ( $\alpha \approx 0.1$  for wide open channel flows according to Rodi (1980)), and  $f$  is the Darcy-  
 418 Weisbach friction coefficient. The shear-layer turbulence is modelled by a Prandtl's mixing  
 419 length model with a length scale that is proportional to the mixing layer width,  $\delta$  (defined here  
 420 in Eq. 9). With unbounded mixing layers, the proportionality constant  $\beta$  is related to the  
 421 spreading rate  $d\delta/dx$  of the mixing layer, and ranges from 0.088 to 0.124 according to van  
 422 Prooijen *et al.* (2005). In the LMFA flume,  $d\delta/dx = 0$  for the uniform flow at  $x/B_f = 6.8$ , where  
 423 the eddy viscosity model is estimated (see Fig. 6). Moreover, the mixing layer is shallow, and  
 424 the geometry is compound. The  $\beta$ -parameter will thus be considered as a new constant,  
 425 calibrated for the uniform flow ( $\beta = 0.026$ ), which was then used to model the non-uniform  
 426 cases.

427 Figure 12(b) shows the results at LMFA at  $y/B_f = 1$  and  $x/B_f = 6.8$ . White and black  
 428 circles are used for the total eddy viscosity  $\varepsilon_{xy}|_d$ , and the shear-layer-induced viscosity,  $\varepsilon_{xy}^s|_d$   
 429 , respectively. The  $f$ -coefficient is estimated with a modified Colebrook formula (French  
 430 1985). Its value is approximately constant (0.021-0.022). This leads to very small variations  
 431 in the bed-induced eddy viscosity,  $\varepsilon_{xy}^b|_d$ , from 0.052 to 0.058 (difference between white and  
 432 black circles in Fig. 12(b)).

433 Figure 12(b) shows that, with the  $\beta$ -parameter calibrated for uniform flow, accurate  
 434 values of eddy viscosity  $\varepsilon_{xy}|_d$  are obtained for  $N < 1$ . In contrast,  $\varepsilon_{xy}|_d$  is greatly under-  
 435 estimated for  $N = 1.32$ . This flow is characterized by the highest shear-layer turbulence at  
 436 LMFA, as shown in Fig. 10 (top plots). The underestimation of  $\varepsilon_{xy}|_d$  could thus be attributed  
 437 to the limitations of the mixing length model. Firstly, this model assumes a local equilibrium  
 438 between turbulence production and dissipation (*e.g.* Rodi 1980). Secondly, the local turbulent  
 439 diffusion is exclusively related to the local gradients of time-averaged flow (Boussinesq  
 440 approach), which can be erroneous if some structures are advected from upstream by the bulk  
 441 flow. When mass is transferred to the floodplain, this advective transport of turbulent  
 442 quantities can become important. In this case, Prandtl's model is not valid. In addition,  
 443 considering the strong increase in eddy viscosity  $\varepsilon_{xy}$  in the near-surface layer (Fig. 12(a)), the  
 444 depth averaging of  $\varepsilon_{xy}$  constitutes a rough approximation.

#### 445 4.9. Momentum flux in the main channel

446 The three contributions to transverse momentum flux,  $-\rho U_d V_d$ ,  $-\rho \bar{u}(\bar{v} - V_d)\Big|_d$  and  
447  $T_{xy}$  were estimated in the main channel of the LMFA flume, in which the dispersive term of  
448 spanwise velocity  $\bar{v}$  is important. The vertical distributions of velocity  $\bar{v}$ , flux  $-\rho \bar{u}\bar{v}$  and  
449 Reynolds shear stress  $-\rho \overline{u'v'}$  are shown in Fig. 13 at  $x/B_f = 5.6$ , near the vertical interface at  
450  $y/B_f = 1.01$ , and near the centreline position at  $y/B_f = 1.28$ . Table 2 shows at these two  
451 locations, the depth-averaged value of  $-\rho \overline{uv}$ , namely  $M_{xy}$ , the sum of terms  $-\rho U_d V_d$  and  
452  $-\rho \bar{u}(\bar{v} - V_d)\Big|_d$ , and shear  $T_{xy}$ .

453 At  $y/B_f = 1.01$ , inside the shear-layer, the three fluxes can be of the same order of  
454 magnitude for the non-uniform cases (see Table 2). Figure 13(a) shows that the peak of lateral  
455 shear  $-\rho \overline{u'v'}$  is located at the bank full level, irrespective of the value of the  $N$ -parameter. It  
456 is also shown that the variations in the  $\bar{v}$ -profiles are mostly located above the bank full  
457 level.

458 At  $y/B_f = 1.28$ , outside the shear-layer, the momentum flux is essentially driven by  
459 the time-averaged flow for the non-uniform cases. In this case, the dispersive term  
460  $-\rho \bar{u}(\bar{v} - V_d)\Big|_d$  is lower than the advective transport of momentum  $-\rho U_d V_d$ , but of the same  
461 order of magnitude. Figure 13(b) shows that the overall shape of the  $\bar{v}$ -profiles is constant  
462 for all  $N$ -values, but with a lateral displacement towards the main channel sidewall when  $N$   
463 decreases. Table 2 also shows that the relative weight of the dispersive term of  $\bar{v}$  decreases  
464 with  $N$ -parameter.

#### 465 5. Conclusions

466 Turbulent non-uniform flows were experimentally investigated in two compound  
467 channels, with vertical and sloping banks in the main channel. A time-averaged transverse  
468 flow and an advective transport of momentum occurred until the most downstream measuring  
469 sections. The water depth reaches equilibrium more rapidly than the velocity difference  
470 between the sub-sections, and this latter can significantly vary for a given flow depth.

471 The advective transport of mass and momentum interacts with the shear-layer  
472 turbulence as follows:

- 473 (1) With a lateral flow to the main channel, the mixing layer and the shear-layer  
474 turbulence are laterally displaced in the same direction. The region of high values of  
475 lateral Reynolds stress  $-\rho \overline{u'v'}$  is transversally stretched by the plunging flow into the



476 main channel. As non-uniformity increases, the advective transport of momentum by  
477 the depth-averaged flow,  $-\rho U_d V_d$ , rises at the expense of the depth-averaged value  
478 of  $-\rho \overline{u'v'}$ ,  $T_{xy}$ , at floodplain edge and in the main channel.

479 (2) With a lateral flow to the floodplains, the shear layer turbulence widely extends on  
480 the floodplains, with higher values of  $-\rho \overline{u'v'}$  and of transverse eddy viscosity  $\epsilon_{xy}$   
481 in the near-surface layer. Both the flux  $-\rho U_d V_d$  and shear stress  $T_{xy}$  are of the  
482 same order of magnitude.

483 The shear-layer turbulence and the flux  $-\rho U_d V_d$  are enhanced by the sloping bank,  
484 relative to the vertical bank. With this latter, the dispersive term of spanwise velocity,  
485  $-\rho \overline{u(\bar{v} - V_d)} \Big|_d$ , can be of the same order of magnitude as  $-\rho U_d V_d$ , and is dependent on the  
486 flow direction. As a result, a 2D-depth-averaged model that does not account for the vertical  
487 dispersion of velocity  $\bar{v}$ , or a depth-averaged model that is based on uniform flow hypotheses  
488 ( $\partial h / \partial x = 0$  and  $V_d = 0$ ) may poorly reproduce the actual transverse momentum flux.

489 The two data sets showed that the Boussinesq approach was qualitatively appropriate  
490 for non-uniform flows. Using the depth-averaged model of eddy viscosity developed by van  
491 Prooijen *et al.* (2005) for uniform flows, we found that the model was still valid with a lateral  
492 flow to the main channel. In contrast, it significantly underestimates the eddy viscosity with  
493 an opposite lateral flow, *i.e.* when the horizontal vortices are widely extended on the  
494 floodplains. Both the Boussinesq approach and the mixing length models are not valid in this  
495 case.

496 An excess (resp. a deficit) in floodplain discharge is observed in a compound channel  
497 with converging (resp. diverging) floodplains. As a result, a part of the physical processes  
498 depicted in this paper, notably the interaction between time-averaged transverse flow and  
499 shear-layer turbulence, may be valid for non-prismatic geometries.

500 Since these results were obtained with a single relative flow depth,  $D_r = 0.3$  under  
501 uniform flow conditions, this work will be continued by an investigation of the shallowness  
502 effect on the turbulent non-uniform flows.

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508

509

510 **Notation**

511 Superscript  $u$  refers to uniform flows  
 512 Subscripts  $m$  and  $f$  refer to main channel and floodplain, respectively  
 513 Subscript  $d$  refers to a depth averaging  
 514  $A$  = compound channel cross-section area [m<sup>2</sup>]  
 515  $B_f$  = width of one floodplain [m]  
 516  $f$  = Darcy-Weisbach friction coefficient [-]  
 517  $h$  = local water depth [m]  
 518  $h_f, h_m$  = mean water depths on the floodplain and in the main channel [m]  
 519  $h_b$  = bank full height in the main channel [m]  
 520  $M_{xy}$  = depth-averaged value of transverse momentum flux  $-\overline{\rho uv}$  [N/m<sup>2</sup>]  
 521  $Q$  = total discharge [m<sup>3</sup>/s]  
 522  $Q_f$  = floodplain discharge [m<sup>3</sup>/s]  
 523  $T_{xy}$  = depth-averaged value of lateral Reynolds shear stress  $-\overline{\rho u'v'}$  [N/m<sup>2</sup>]  
 524  $U_A$  = bulk velocity,  $Q/A$  [m/s]  
 525  $u, v$  = instantaneous longitudinal and lateral velocity components [m/s]  
 526  $\bar{u}, \bar{v}$  = time-averaged longitudinal and lateral velocity components [m/s]  
 527  $-\overline{\rho u'v'}$  = lateral Reynolds shear stress [N/m<sup>2</sup>]  
 528  $U_d, V_d$  = depth-averaged, time-averaged longitudinal and lateral velocity [m/s]  
 529  $U_f, U_m$  = mean longitudinal velocity in the floodplain and main channel [m/s]  
 530  $x, y, z$  = longitudinal, lateral and vertical distances [m]  
 531  $\epsilon_{xy}$  = local transverse eddy viscosity [m<sup>2</sup>/s]  
 532  $\epsilon_{xy|d}$  = depth-averaged transverse eddy viscosity [m<sup>2</sup>/s]  
 533

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597

598 Table 1 Flow conditions

Inflow ( $x = 0$ )		<sup>b</sup> Most upstream measuring section							
<sup>a</sup> $\Delta Q_f$	$Q_f / Q$	$N$	$D_r$	$h_f$	$U_f$	$F_f$	$U_m$	$F_m$	
[%]	[%]	[-]	[-]	[mm]	[cm/s]	[-]	[cm/s]	[-]	
LMFA	-19	20.6	1.42	0.286	21.2	31.0	0.69	70.0	0.94
	0	25.4	1.00	0.303	23.0	33.3	0.71	60.7	0.81
	+19	30.2	0.66	0.311	24.0	38.5	0.80	56.6	0.75
	+38	35.0	0.45	0.324	25.4	40.7	0.83	53.0	0.70
	+53	38.8	0.32	0.329	25.9	42.3	0.85	51.0	0.67
LNEC	-19	26.6	1.54	0.275	38.0	41.8	0.70	79.6	0.78
	0	32.8	1.00	0.285	40.1	47.9	0.79	72.5	0.70
	+19	39.0	0.52	0.297	42.2	53.0	0.85	65.7	0.63
	+38	45.2	0.00	0.304	43.8	58.6	0.92	58.6	0.56

599 <sup>a</sup> Imbalance in floodplain inflow, relative to uniform flow (see Eq. 1)

600 <sup>b</sup>  $x = 2.5$  m at LMFA,  $x = 1.1$  m at LNEC

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602 Table 2 Transverse momentum flux in the main channel at LMFA,  $x/B_f = 5.6$ .

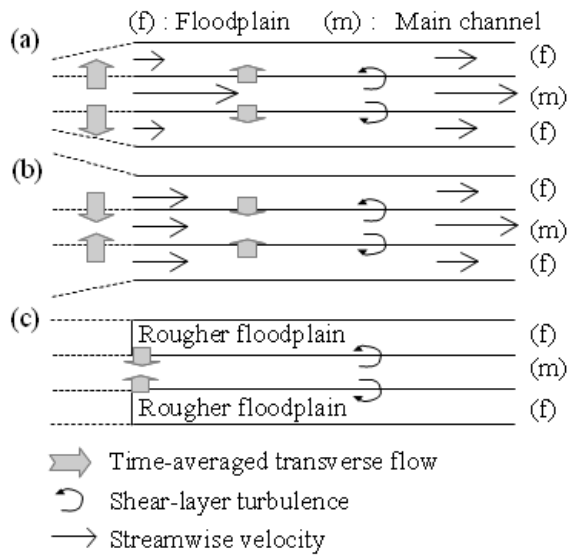
$y/B_f$	$N$	$M_{xy}$	$-\rho U_d V_d$	$-\rho U(V - V_d)l_d$	$T_{xy}$
[-]	[-]	[Pa]	[Pa]	[Pa]	[Pa]
1.01	1.33	4.2	4.2	0.0	0.7
	1	0.0	0.0	0.0	0.6
	0.79	0.0	-0.1	0.1	0.3
	0.64	0.0	-0.2	0.2	0.2
	0.50	-1.1	-1.2	0.1	0.1
1.28	1.33	1.0	1.6	-0.6	0.0
	1	-0.5	0.0	-0.5	0.1
	0.79	-0.6	-0.3	-0.3	0.0
	0.64	-2.6	-2.3	-0.3	0.0
	0.50	-2.8	-2.6	-0.2	0.0

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FIGURES

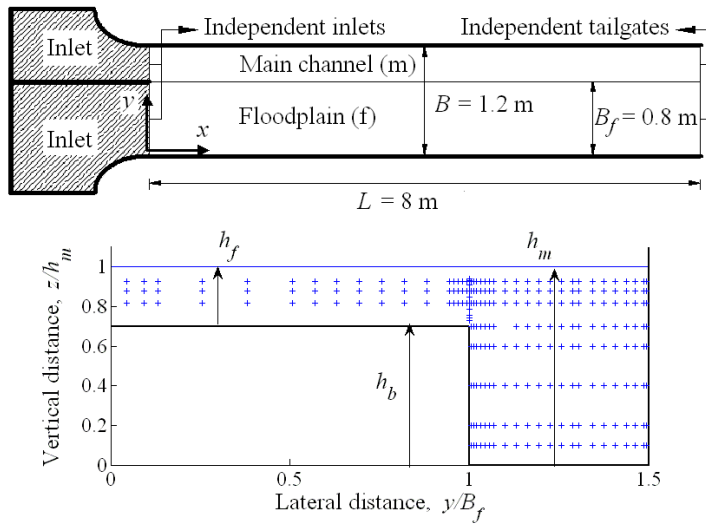


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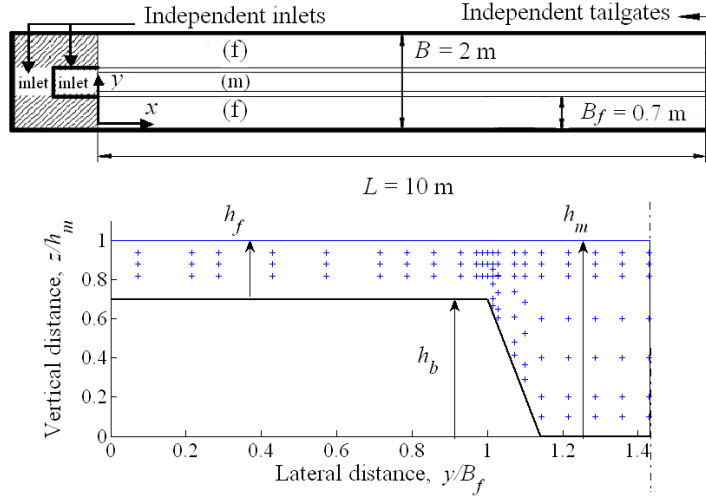
608 Figure 1 Various flow conditions for natural compound channels: (a) diverging or (b)  
609 converging floodplains upstream from a prismatic reach, (c) prismatic reach with a  
610 longitudinal increase in roughness on the floodplains

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LMFA flume



LNEC flume



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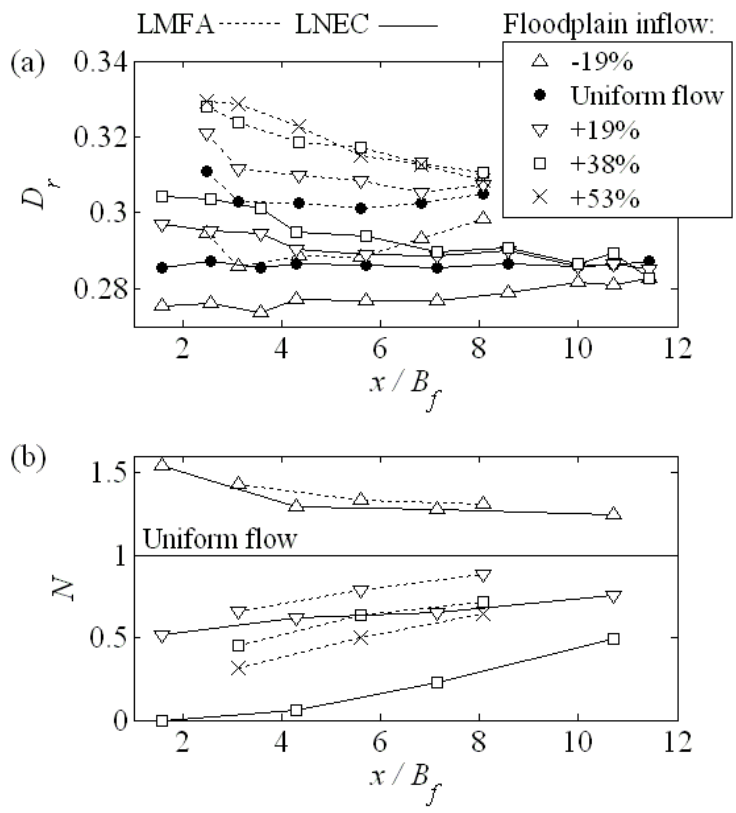
621 Figure 2 Schematic top view and cross-section of the two flumes (markers '+': ADV  
 622 measuring grid)

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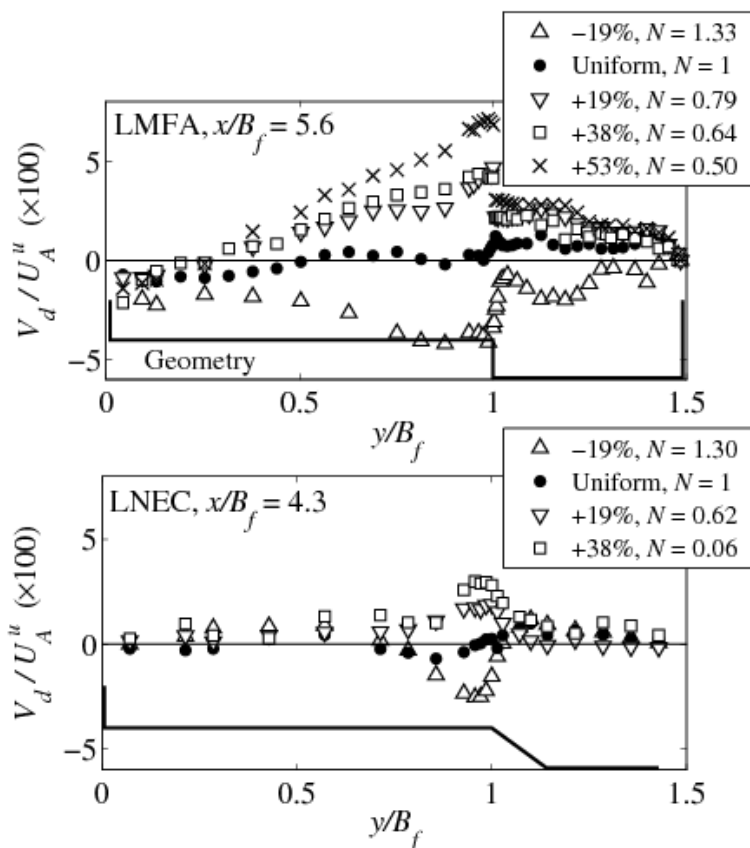
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629 Figure 3 (a) Relative flow depth,  $D_r$ , and (b) velocity difference between sub-sections relative  
 630 to uniform flow conditions,  $N = (U_m - U_f) / (U_m^u - U_f^u)$ , against downstream distance,  $x/B_f$

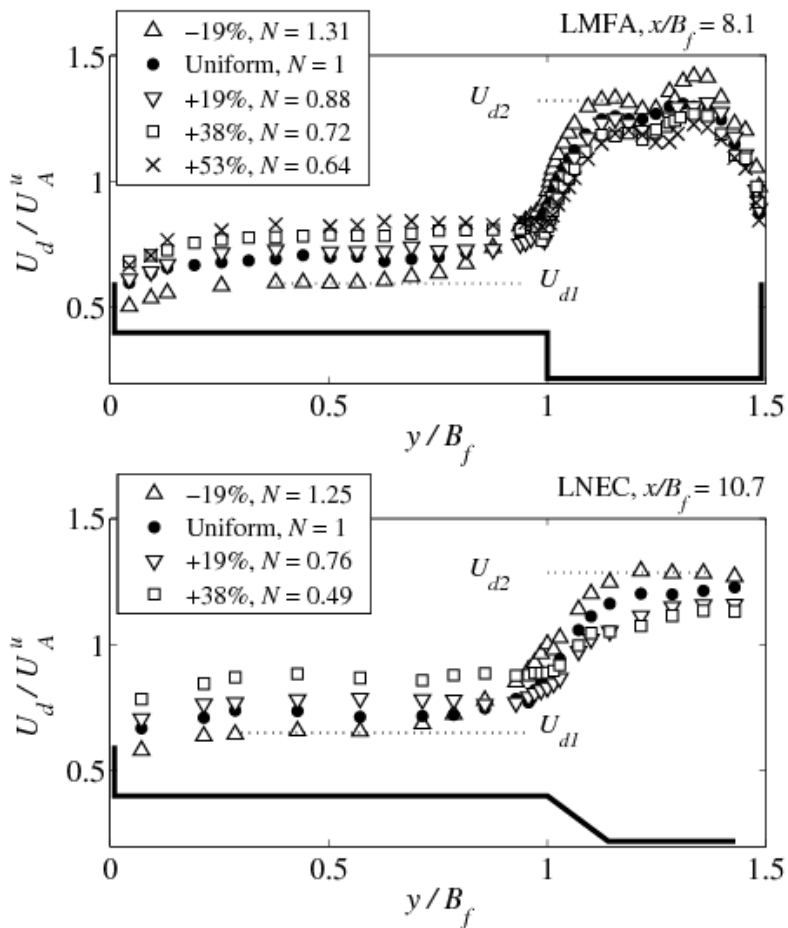


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632 Figure 4 Lateral distribution of depth-averaged spanwise velocity,  $V_d$ , scaled by bulk velocity,  
633  $U_A^u$ , for various  $N$ -parameters.

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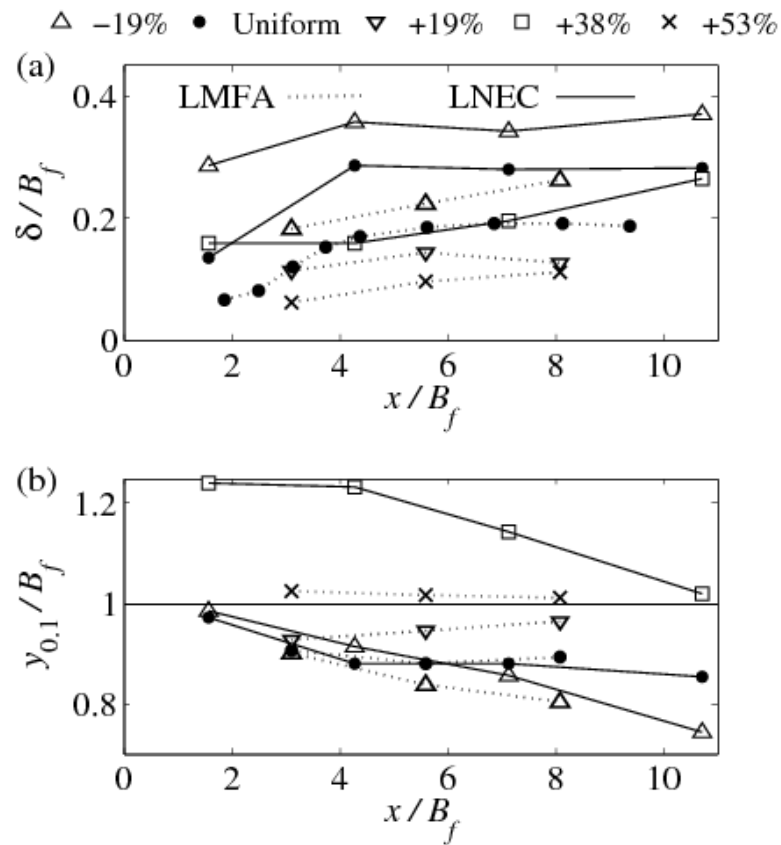




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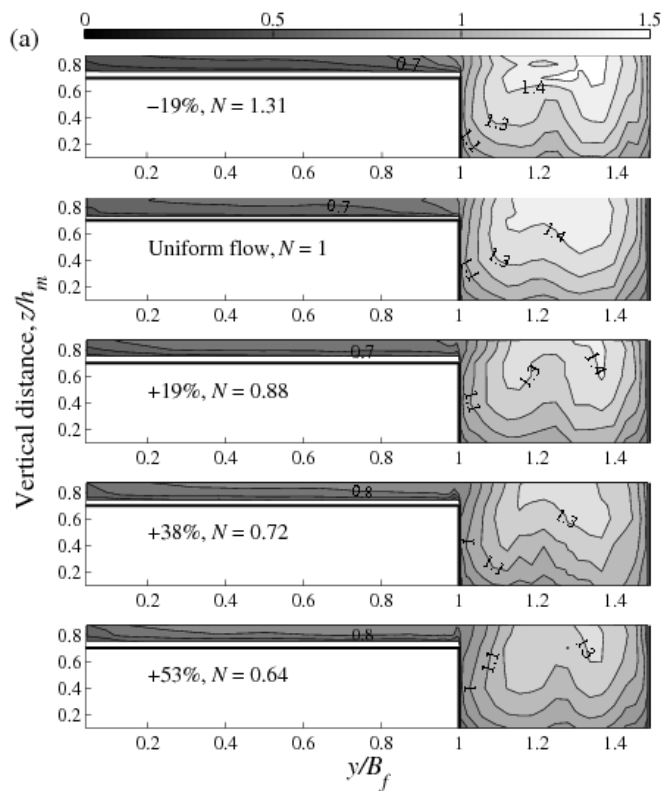
636 Figure 5 Lateral distribution of depth-averaged streamwise velocity,  $U_d$ , scaled by  $U_A^u$

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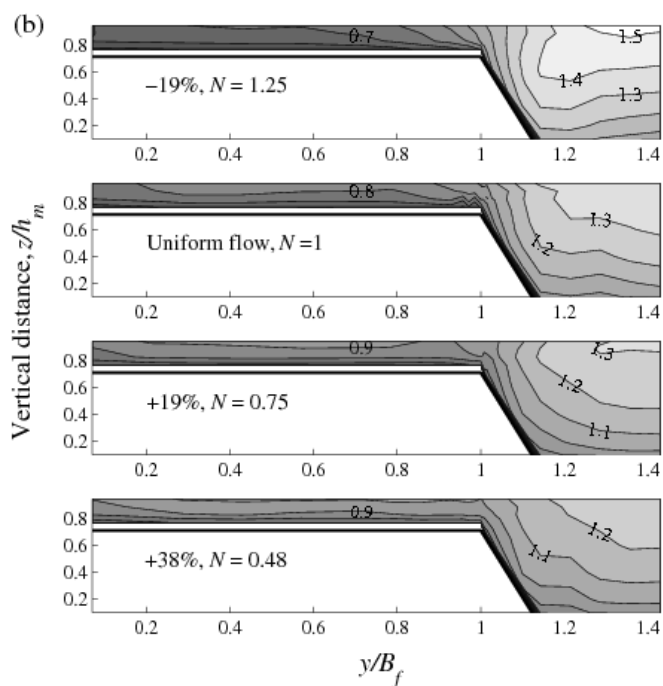


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639 Figure 6 Longitudinal profile of (a) mixing layer width,  $\delta$  and (b) lateral boundary,  $y_{0.1}$  (see  
 640 Eq. 9), scaled by  $B_f$ .  
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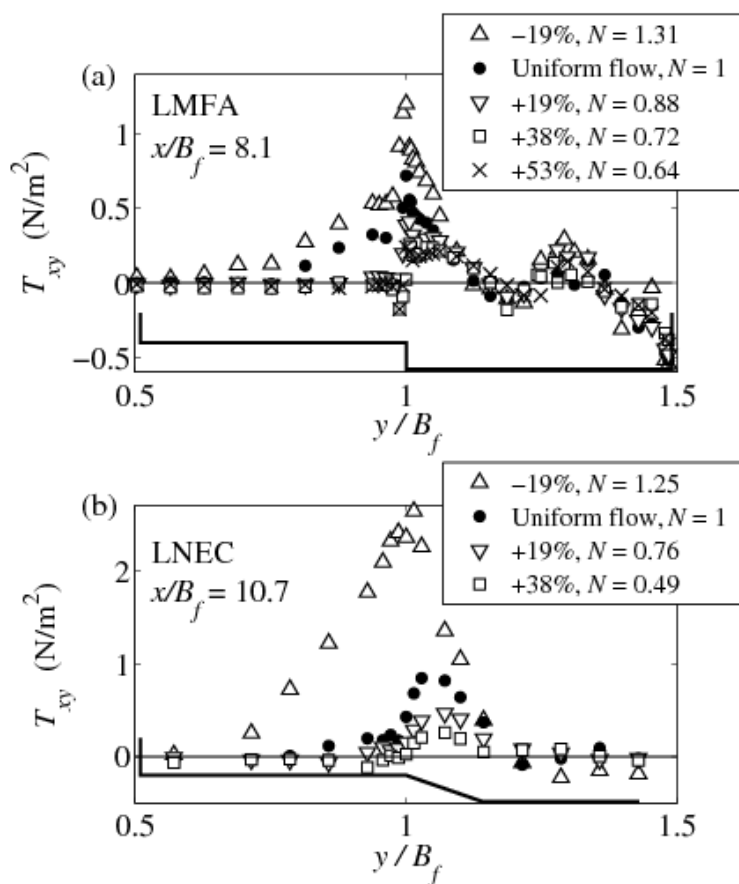
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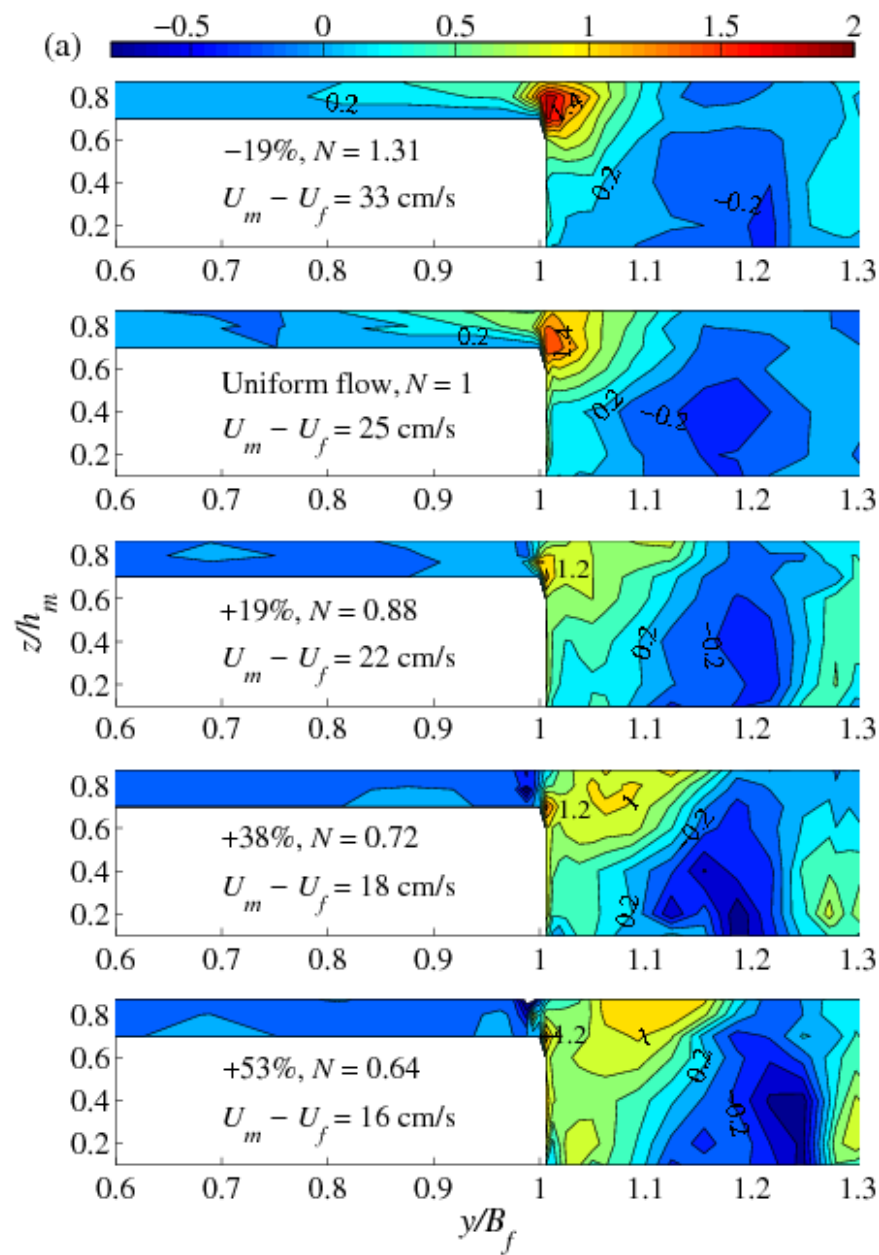
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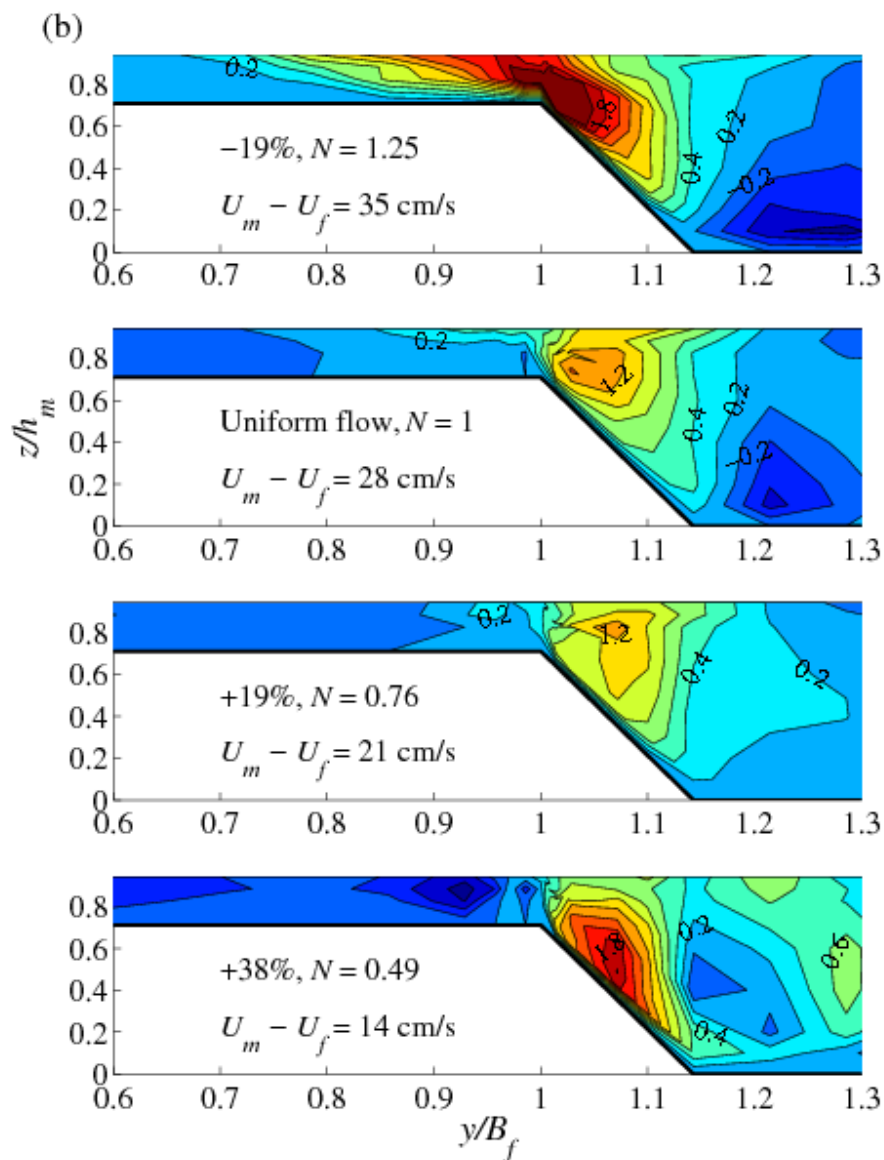
Figure 7 Time-averaged streamwise velocity,  $\bar{u}$ , scaled by  $U_A^u$ , for various  $N$ -parameters: (a) LMFA,  $x/B_f = 8.1$ ; and (b) LNEC,  $x/B_f = 10.7$



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648 Figure 8 Depth-averaged lateral Reynolds shear stress,  $T_{xy}$ , against lateral distance,  $y/B_f$ .



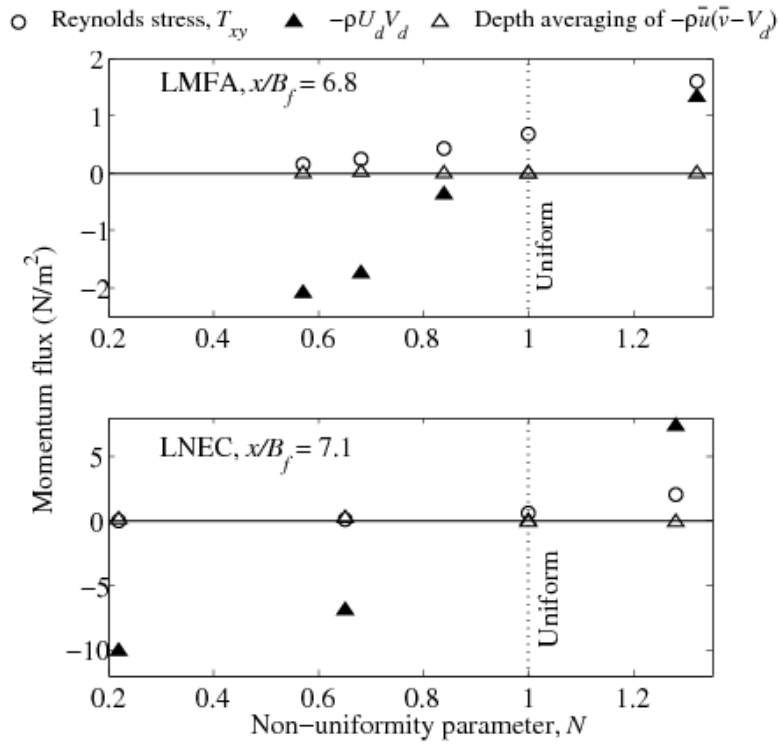


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651 Figure 9 Normalized lateral Reynolds shear stress,  $-\overline{u'v'}/(U_m - U_f)^2 (\times 100)$ . (a) LMFA,

652  $x/B_f = 8.1$ ; and (b) LNEC,  $x/B_f = 10.7$

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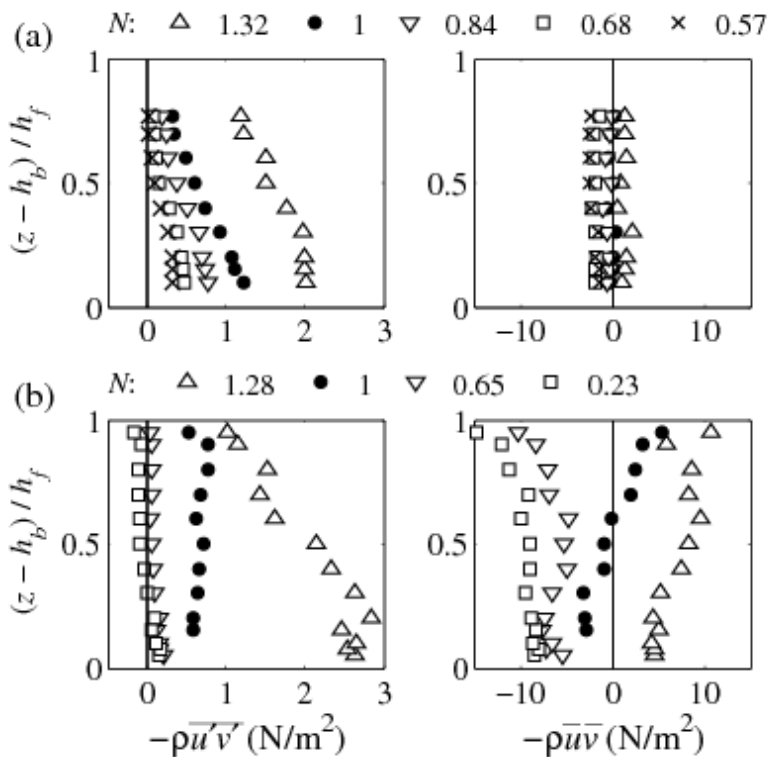


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655 Figure 10 The three contributions to transverse momentum flux at floodplain edge ( $y/B_f = 1$ )

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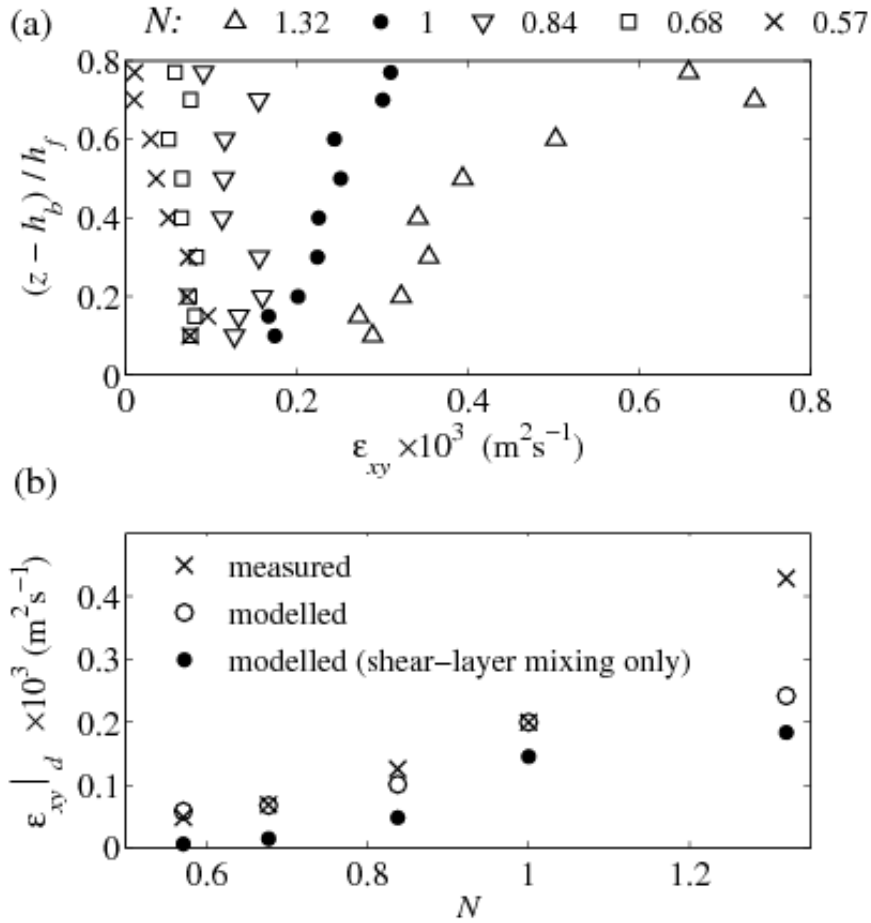
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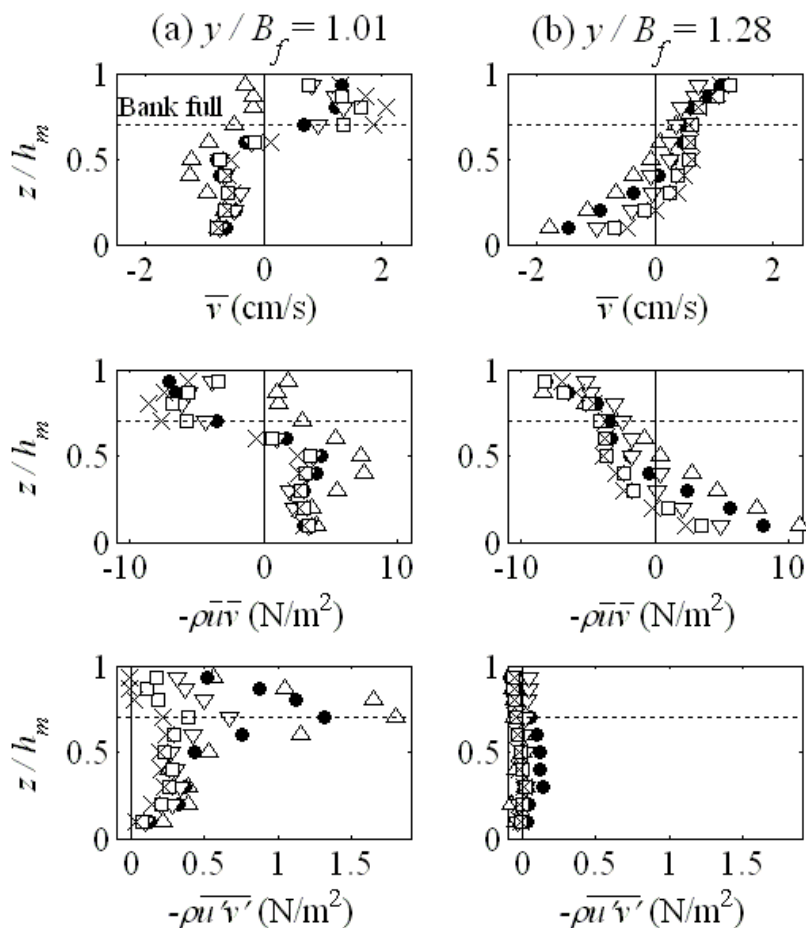
659 Figure 11 Vertical distribution of lateral Reynolds shear stress  $-\rho \overline{u'v'}$  and of momentum  
 660 flux  $-\rho \overline{uv}$  at floodplain edge ( $y/B_f = 1$ ). (a) LMFA,  $x/B_f = 6.8$ ; (b) LNEC,  $x/B_f = 7.1$





661

662 Figure 12 (a) Vertical distribution of eddy viscosity,  $\varepsilon_{xy}$ , and (b) depth-averaged eddy  
 663 viscosity,  $\varepsilon_{xy|_d}$ , measured and modelled data (see Eq. 10). LMFA flume, floodplain edge  
 664 ( $y/B_f = 1$ ),  $x/B_f = 6.8$ .  
 665  
 666



667

$N$ :  $\triangle$  1.33  $\bullet$  1  $\nabla$  0.79  $\square$  0.64  $\times$  0.50

668

Figure 13 Vertical distribution of spanwise velocity  $\bar{v}$ , flux  $-\rho\bar{u}\bar{v}$  and Reynolds shear stress

669

$-\rho\bar{u}\bar{v}'$ , in the main channel of LMFA flume,  $x/B_f = 5.6$

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