

# 1 **Experimental study of flow characteristics around floodplain single groyne**

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## 10 **Abstract**

11 This study investigated the flow around river's floodplain single groynes. Two different  
12 compound channels with one and two symmetrical floodplains having widths of 1- and 2-times of  
13 the main channel width, respectively, were used. Both impermeable and permeable groynes with  
14 three different relative lengths (relative to the floodplain width) and having three different  
15 permeability values of 40, 60, and 80% were investigated. The 3D flow velocities were measured  
16 in the horizontal plane at 0.25 and 0.5 of floodplain water depth ( $h_f$ ), and in the vertical plane at  
17 the main channel's centerline. Therefore, the flow velocities in the longitudinal, lateral, and  
18 vertical directions, and the flow water surfaces were measured and analyzed. The results showed  
19 that, as the groyne permeability increased up to 60%, a reduction of up to 30% to the maximum  
20 velocity and 22 % to the tip velocity were observed. The permeable groyne length had limited  
21 influence on the flow structure. Both the groyne permeability and the length ratio had significant  
22 effects on the floodplain water depth. The scouring and the deposition activities resulting from  
23 impermeable groynes can be avoided, should the groyne length be kept below half of the  
24 floodplain width.

25 **Keywords:** Compound channel; Flow pattern; Groyne permeability; Groyne relative length;  
26 water surface.

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## 27 1. Introduction

28 Groyne are hydraulic structures used to protect banks from erosion and maintain the stream  
29 water level. They can also be used for controlling the flow for navigation safety, improving the  
30 channel alignment, and trapping littoral drift or retard erosion of the banks and shores. The groyne  
31 field is very beneficial to river ecosystem. Groynes can be either permeable or impermeable. The  
32 impermeable groynes are generally constructed using local rocks, gravel, or gabions while the  
33 permeable ones consist of rows of piles, bamboo, or timbers. Groynes may be built as a single  
34 structure, namely a single groyne, or as a series of groynes built in a row along one or both sides  
35 of a river (Ahmed et al., 2010; Alauddin et al., 2011; Alvarez, 1989; Ettema and Muste, 2004; Gu  
36 and Ikeda, 2008; Muraoka et al., 2008; Uijttewaai, 2005; Teraguchi et al., 2008; Yeo et al., 2005).

37 Of interest in the design of groynes, is the disturbance the structure causes to the flow.  
38 Within the vicinity of these structures, a complex three-dimensional, highly turbulent flow field is  
39 generated. They induce adverse pressure gradients which separate the approach flow and  
40 consequently the so-called horseshoe vortices (HVs) are formed (Constantinescu et al., 2009;  
41 Koken, 2011; Koken and Constantinescu, 2008). The construction of groynes has a considerable  
42 effect on upstream water levels. In spite of their impact during the flood stages, the backwater  
43 effect due to groynes is usually neglected in their design (Soliman et al., 1997). It is therefore  
44 necessary to find out how far of the downstream of such structures the disturbance extends  
45 (Francis et al., 1968; Koken, 2011).

46 Various experimental and numerical studies were conducted to investigate the influences of  
47 different structures such as groynes, on the flow characteristics and patterns in their vicinity in  
48 open channels (e.g. Alauddin et al., 2011; Alvarez, 1989; Constantinescu et al., 2009; Ettema and

49 Muste, 2004; Francis et al., 1968; Gu and Ikeda, 2008; Koken, 2011; Ahmed, 2011,2013; Koken  
50 and Constantinescu, 2008; Liu et al., 1994; McCoy et al., 2008; McCoy et al., 2007, 2006a, 2006b;  
51 Muraoka et al., 2008; Rebhock, 1929; Teraguchi et al., 2008; Uijttewaai, 2005, 1999; Uijttewaai  
52 et al., 2001; Yeo et al., 2005). In order to better understand the effect of groynes installation on the  
53 flow, an accurate description of the flow characteristics in compound channel without groyne is  
54 needed. A significant momentum exchange between the main channel and floodplains occurs,  
55 causing flow deceleration in the main channel and acceleration on the floodplains. It is postulated  
56 that large-scale plan-form vortices, rotating about a vertical axis and stream wise secondary flows  
57 are the reason for the main momentum exchange/transfer between the main channel and the  
58 floodplain (Ali et al., 2007; Ali and Mohamed, 1991; Prooijen et al., 2005; Tominaga et al., 1997;  
59 Tominaga and Nezu, 1991).

60 Koken (2011) investigated experimentally and numerically the turbulent flow structure  
61 around an isolated spur dike with semi-circular end on rectangular flume at three different  
62 approach flow angles. The spur dike length and width relative to the flume width were 0.233 and  
63 0.067, respectively. Both the size and the orientation of the horseshoe vortex system changed  
64 considerably with the approach flow angle. The main necklace vortex was largest in size and most  
65 coherent for the approach flow angle  $90^\circ$ , and within this orientation, it had larger amplitude  
66 bimodal oscillations compared to the  $60^\circ$  and  $120^\circ$  orientation cases. Jong and Tominaga (2008)  
67 measured the velocities in a compound open channel by setting groynes of different lengths on the  
68 floodplain. The floodplain groynes deflected the main flow and produced 3-D flow structures  
69 around them. These local flow features generated strong secondary flows in the main channel.

70 The flow characteristics, the velocity distribution around single groyne in combination with

71 the relative depth  $H_r$  (the ratio of the water depth in the floodplain and main channel) and the  
72 longitudinal length of the recirculation zone were discussed (Baba et al., 2010; Peltier et al., 2009).  
73 The flow structure, velocity, and water depth mainly depend on the floodplain impermeable  
74 groyne relative length and the distance between the two series groynes (relative to the groyne  
75 length) (Ahmed et al., 2010).

76 The large-scale groyne system has been introduced and widely used in some rivers  
77 floodplains for various purposes such as flood attenuation, river banks protection and safety of  
78 downstream areas; especially, in rivers with large floodplains such as Japanese Rivers (e.g.  
79 Arakawa River). In some reaches of the Arakawa River, the floodplain width relative to the main  
80 river width is more than 10 (Ahmed et al., 2010, 2011).

81 Impermeable groynes, transverse levees, and bridge embankments are considered as  
82 contractions on the stream-wise flow direction. The flow structures around groynes on the  
83 floodplain are presumably different from those in a single main channel (Ahmed et al., 2011;  
84 Ahmed et al., 2010; Jong and Tominaga, 2008). The flow characteristics and patterns in the  
85 floodplain groynes vicinity and main channel vary according to groyne type and size. The flow  
86 through a permeable groyne penetrates the structure partly so that the downstream velocity is  
87 reduced. The permeable groyne resistance to the flow is less than that of the impermeable one.  
88 Nonetheless, the permeable groyne has the advantages of better stability and relatively easy  
89 maintenance. Therefore, analysis of groynes and their influences is necessary to select the  
90 appropriate groyne type in the field (Ahmed et al., 2010; Fukuoka et al., 2000; Gu et al., 2011; Gu  
91 and Ikeda, 2008; Jong and Tominaga, 2008; Kang et al., 2011; Yeo et al., 2005).

92 Going through the literature shows that the influences of the floodplain's width and groyne's

93 type and length on the flow in the floodplain and main channel of natural and artificial rivers still  
94 need more quantitative and extensive analyses. Therefore, the main objectives of the present study  
95 are: (1) to investigate and verify the influences of large-scale floodplain single permeable and  
96 impermeable groyne on the flow structure, velocity, and water depth, and (2) to evaluate the  
97 advantages and disadvantages of using groynes on channels' floodplain as flood protection work.

98 To achieve these objectives, two compound channels with flat and fixed bed were used. The  
99 first one has two symmetrical floodplains with relative width =2, normalized to the width of the  
100 main channel and only impermeable groynes were used here. The second one consisted of the  
101 main channel and one floodplain with relative width=1, and both impermeable and permeable  
102 groynes (permeability = 40, 60, and 80%) were tested in this case. In both cases, the relative  
103 lengths of the groyne models  $L_r$  (where,  $L_r =$  groyne length  $L_g$ / floodplain width  $b_f$ ) were  $L_r = 0.5$ ,  
104 0.75, and 1.0, respectively. The 3D flow velocities (in the longitudinal, lateral and vertical  
105 directions), and the water surface elevation were measured and analyzed in the horizontal plane  
106 (HP) at 0.25 and 0.5 of floodplain water depth ( $h_f$ ), and in the vertical plane (VP) at the main  
107 channel's centerline.

## 108 2. Materials and methods

109 A general functional relationship characterizing the flow structure around groynes in  
110 compound channel floodplains (Fig 1a) can be written among physical variables that include:  
111 floodplain width  $b_f$ , main channel width  $b_m$ , channel total width  $B=(b_f+b_m)$ , floodplain water  
112 depth  $h_f$ , floodplain bed height  $z_f$ , main channel water depth  $H= z_f+h_f$ , channel longitudinal slope  
113  $S_o$ , longitudinal distance measured from the groyne centerline in the flow direction  $X$ , lateral  
114 distance measured from the right side wall of the main channel  $Y$ , vertical distance measured from

115 main channel bed  $Z$ , groyne length  $L_g$ , permeability  $P\%$  and its orientation angle to the channel  
 116 main direction  $\alpha$ , flow discharge  $Q$ , approach velocity  $U_o$  which is the counter approach velocity  
 117 measured at the same streamline, local longitudinal velocity  $U$ , local lateral velocity  $V$ , local  
 118 vertical velocity  $W$ , maximum velocity  $U_{max}$ , minimum velocity  $U_{min}$ , groyne tip velocity  $U_{tip}$ ,  
 119 inclination angle of tip velocity to the horizontal direction  $\theta$ , and gravity acceleration  $g$ , density  $\rho$   
 120 and kinematic viscosity  $\nu$ ):

$$121 \quad \Phi(b_f, b_m, B, h_f, H, S_o, X, Y, Z, L_g, P, \alpha, Q, U_o, U, V, W, U_{max}, U_{min}, U_{tip}, \theta, g, \rho, \nu) = 0 \quad (1)$$

122 Using the dimensional analysis Buckingham's "π" theorem, in which  $U_o$ ,  $b_f$  and  $\rho$  are  
 123 selected as repeated variables representing the flow characteristics, channel geometrical  
 124 characteristics and fluid parameters respectively, and considering such dimensionless parameters  
 125 that have been fixed and are constant as  $(B/b_f, b_m/b_f, h_f/b_f, H/b_f, S_o, \alpha, \theta, \text{Reynold and Froude}$   
 126 numbers), Eq. (1) can be reduced to:

$$127 \quad U^*/U_o = \Phi(X/b_f, Y/b_f, Z/h_f, L_g/b_f, P) \quad (2)$$

128 In which,  $U^*$  is a characteristic velocity  $(U, V, W, \text{ or } U_{tip}, U_{max}, U_{min})$ ,  $X/b_f = X_r = \text{Relative}$   
 129 distance along the channel centerline,  $Y/b_f = Y_r = \text{Relative channel width}$ ,  $Z/h_f = Z_r = \text{Relative}$   
 130 depth, and  $L_g/b_f = L_r = \text{groyne relative length}$ .

131 Finally the relationship between the above mentioned parameters could be as:

$$132 \quad U^*/U_o = \Phi(X_r, Y_r, Z_r, L_r, P\%) \quad (3)$$

133 In the case of the compound channel with only one floodplain, the flume was 0.30 m in both  
 134 depth and width directions, and 13.5 m in length, which incorporates transparent test section of 10  
 135 m length. The flume was adjusted to a longitudinal slope of 0.0025. The rectangular flume section  
 136 was converted into Perspex-Acrylic unsymmetrical compound channel section having a main

137 channel width  $b_m = 0.15 \text{ m}$  and one left side floodplain with the same width of main channel  $b_f =$   
138  $0.15 \text{ m}$  (where  $b_f/b_m = 1.0$ ). The roughness coefficients of the main channel and the floodplain  
139 were kept constant and equal. A steady discharge  $Q$  was regulated to be  $17.50 \text{ l/s}$  and the  
140 floodplain flow water depth  $h = 0.08 \text{ m}$  ( $h/H = 0.34$ ). Reynolds number was always sufficiently high  
141 (from  $6.1 \times 10^4$  to  $9.2 \times 10^4$ ) to guarantee a fully turbulent flow whereas Froude number was kept  
142 constant at 0.30.

143 The longitudinal velocity  $U$ , lateral velocity  $V$ , and vertical velocity  $W$  of the steady flow  
144 were measured in both the HP, which was located at a depth of  $0.25 h_f$  from the floodplain bed  
145 and in the VP at the main channel centerline. The flow velocities components in the HP and VP  
146 were measured at several locations at relative distances  $X_r$  within the range from  $-7.5$  to  $+17.5$   
147 using an Acoustic Doppler Velocimeter (16-MHz MicroADV, Sontek) with sampling frequency  
148  $20 \text{ Hz}$  and duration time ranged from one to two minutes. At each measuring point, the mean  
149 velocities in longitudinal, transverse and vertical directions,  $U$ ,  $V$  and  $W$  were obtained by  
150 averaging the velocities readings of the velocimeter due to the steady flow conditions. The water  
151 surface elevation was measured at several locations of the upstream and the downstream of the  
152 groyne by a point gauge with accuracy of  $0.10 \text{ mm}$  mounted on a movable sliding carriage. The  
153 experiments were conducted using groyne models with three different permeability values of 40,  
154 60, and 80%, in addition to the case of impermeable groynes. The permeable groynes were made  
155 of glass piles with cross sectional diameter of  $0.50 \text{ cm}$ , and the groyne relative lengths  $L_r$  were 0.5,  
156 0.75, and 1.0 (Fig. 1b). All groynes were kept perpendicular to both the main channel centerline  
157 and the longitudinal flow direction. Other experiments are a part of a series of experiments that  
158 were conducted using models of straight impermeable groynes with the same  $L_r = 0.5, 0.75,$  and

159 1.0 installed perpendicularly on one or two sides of symmetrical compound channel with two  
160 large floodplains (Table 1). The flume is 0.50 m in depth and width, and 15 m in length. The  
161 working section of the flume is the middle section with a length of 13 m, starting from a point 1 m  
162 downstream of the inlet to a point 1 m upstream of the outlet. The cross-section of the flume was  
163 converted into a wooden symmetrical compound channel section consisting of main channel with  
164 width  $B = 0.1$  m and two symmetrical floodplains with width  $b = 0.2$  m (the floodplain relative  
165 width  $b_f/B = 2$ ). The main channel total water depth  $H$  was 0.24 m while the floodplain water  
166 depth  $h$  was 0.08 m ( $h/H = 0.33$ ). A steady flow with discharge  $Q = 15$  l/s and Froude number of  
167 0.26 were used. The flow velocities were measured by an electromagnetic velocity meter (type of  
168 main amplifier: VM-2000, type of sensor: VMT2-200-04P, KENEK Co., Ltd.). The sensor is 15.0  
169 mm in length and 4.0 mm in diameter. The measurement point is located at the mid height of the  
170 sensor with 20.0 s and 50 Hz sampling frequencies. The flow velocities were measured at the  
171 horizontal plane HP at the floodplain mid water depth, and at the vertical plane VP at the main  
172 channel centerline (Ahmed *et al.*, 2010).

### 173 3. Results and discussion

#### 174 3.1 Flow velocity profiles and patterns

##### 175 3.1.1 Flow velocity profiles and patterns in the horizontal plane

176 In the case of floodplain impermeable groyne at one side of symmetrical compound channel,  
177 the groyne relative length  $L_r$  significantly affected the flow velocity and water depth, downstream  
178 of the groyne, while at the upstream side, only little effects were noticed (Figs. 2 and 3). At the  
179 downstream side of the groyne, a recirculating flow region was generated. The centre of the eddy  
180 zone moved toward the groyne as  $L_r$  increased while the flow moved towards the main channel  
181 and the opposite floodplain. The relative longitudinal velocity ( $U/U_o$ ) on the opposite floodplain  
182 increased by 75, 125, and 175% for  $L_r = 0.5, 0.75,$  and 1.0, respectively and the location of the



183 maximum value also existed there for  $L_r = 0.75$  and  $1.0$ ; the corresponding location was in the  
184 region of the main channel for  $L_r = 0.5$  (Figs 2 and 3). The value of the negative velocity  
185 downstream of the groyne was more than 55% of its original approach velocity value (this  
186 happened for  $L_r = 1.0$ ).

187 Figure 4 shows the experimental results of two symmetrical single impermeable groynes  
188 installed in both floodplains of the symmetrical compound channel (i.e. arranged in one-line) with  
189 the same flow and channel properties. Increasing the relative length of the groyne reduced the  
190 downstream velocities of floodplains. Region of the negative velocities appeared downstream of  
191 the groynes, its magnitude reached the same value of the original approach velocity in the  
192 opposite direction of the flow or even more. For instance, the main channel downstream velocity  
193 was greater than 200% of its original approach velocity in case of  $L_r = 1.0$ . Also in the floodplain  
194 area, the center of the negative velocity region moved upstream towards the groyne. Both the  
195 separation width and length upstream and downstream of the groynes increased as the  
196 cross-sectional area of the floodplain flow was reduced at the groyne. The average separation  
197 width and length were 0.4- and 8-times the groyne length, respectively. Most of the changes on  
198 the water depth occurred downstream of the groyne and they were within the distance of about 6  
199 times the groyne length.

200 In the cases of single impermeable groyne in compound channel with one floodplain, the  
201 upstream flow was deviated by the groyne from the floodplain towards the main channel in the  
202 downward direction; this has greatly affected the main channel flow. As a consequence, the  
203 contraction caused by the groyne increased the velocity in the main channel at the groyne tip. A  
204 large recirculation vortex was formed downstream of the groyne with larger size for large  $L_r$ . A

205 spiral vortex downstream of the groyne was created, due to the velocity difference between the  
206 main channel and the floodplain and because of the deviated flow at the floodplain bed toward the  
207 main channel (Fig. 5). The spiral vortex caused a strong transverse velocity from the main  
208 channel to the floodplain and an upward-flow at the interface zone. The spiral vortex may cause  
209 sediment transportation in the compound open channel.

210 The cases of floodplain permeable groynes in compound channel with one floodplain are  
211 presented in Figs. (6-8). For groynes having same permeability, as  $L_r$  increased the velocity  
212 reduction in the floodplain zone extended in the two directions downstream of the groyne and  
213 towards the main channel. The longitudinal approach velocity upstream of the groyne was slightly  
214 affected by the groyne permeability  $P$  and  $L_r$ . Also, the location where the velocity was reduced,  
215 moved towards the downstream and became closer to the groyne. Comparing the permeable  
216 groynes with the impermeable ones shows that, the permeable groynes caused a disappearance of  
217 the vortex downstream of the groynes. Also, the longitudinal velocity decreased in the floodplain  
218 zone and slightly increased in the main channel. The floodplain velocity was reduced as the  
219 groyne's permeability decreased. The flow velocity in the main channel was slightly affected as  
220 the groyne relative length decreased and its permeability increased.

221 The significant effect of the impermeable groynes in the one floodplain compound channel  
222 on the flow occurred at a relative distance  $X_r$  from -2 to 14. Beyond this range, the flow was  
223 slightly affected by the groynes installation (Figs. 5 and 7). The maximum relative velocity  
224  $(U/U_o)_{max}$  has a direct relationship with  $L_r$ , while  $(U/U_o)_{min}$  was slightly affected. The  $(U/U_o)_{max}$   
225 were 1.85, 1.7 and 1.5 for  $L_r = 1, 0.75$  and  $0.5$  respectively (Fig. 7). In the case of impermeable  
226 groyne at one or two sides of symmetrical compound channel, the  $(U/U_o)_{max}$  were about 2.75, 2.4

227 and 1.75 for  $L_r = 1, 0.75$  and  $0.5$ , respectively (Figs. 3 and 4). These changes in the maximum  
228 velocity values may be attributed to the difference in the floodplain relative width. The minimum  
229 relative velocity changed with the same rate for all cases of the impermeable groyne where its  
230 minimum value was  $-0.5$ . In the case of impermeable groynes, a reverse flow occurred on the  
231 floodplain outer zone close to the bank, but it gradually disappeared.

232 With the permeability increase, values of  $(U/U_o)_{max}$  and  $(U/U_o)_{min}$  dropped down and the  
233 reverse flow downstream of the groynes disappeared (Fig. 7). The effect of the relative length of  
234 permeable groyne was smaller than that of impermeable groynes. In the case of permeable  
235 groynes, the maximum transverse velocity towards the main channel near the groyne tip was  
236 about 80, 70, and 50% of the floodplain approach velocity for  $L_r = 1, 0.75$ , and  $0.5$  respectively  
237 (Figs 7-9). For the cases with small permeability, the lateral velocity downstream of the groyne  
238 was mainly heading towards the main channel but its value was smaller compared with the  
239 impermeable cases. As  $L_r$  decreased, the direction of the lateral flow downstream of the groyne  
240 was towards the floodplain. The spiral vortex, which was formed in the cases of impermeable  
241 groyne, disappeared and an upward flow with small values occurred at the interface between main  
242 channel and floodplain. This upward-flow is responsible for the generation of secondary flow in  
243 the compound channels. The secondary flow slightly reduced when the  $L_r$  was small.

244 For all the cases, there was a downward flow occurred at the groyne tip. The lateral and  
245 down-flow velocities, upstream of the groyne tip, caused the well known horseshoe vortex (HVs),  
246 which is the reason for strong scour around the groyne (Ettema, 2004; Jong and Tominaga, 2008;  
247 Koken, 2011). This phenomenon occurred and formed for all cases but it dropped down as the  
248 groyne permeability increased (Fig. 9).

249 Figure 10 shows the relationships between the ultimate maximum and minimum relative velocities and  
250 both the groyne permeability  $P$  and  $L_r$  for the case of floodplain single groynes in compound channel with one  
251 floodplain being compared with results of Kang (2011). The ultimate value is the absolute value of the  
252 maximum and minimum relative velocity values of the measured cross sections (floodplain and main channel)  
253 down and upstream of the groyne. Exponential empirical formulae describing those relationships were  
254 suggested in Table 2. The groyne relative length had no obvious effect on the relative minimum velocity value.  
255 The average values of the relative minimum velocities were found to be -0.5, 0.4, 0.6 and 0.8 for groyne with  
256 permeability  $P= 0, 40, 60$  and  $80\%$ , respectively. The influences of groyne permeability on the flow pattern over  
257 the floodplain area could be divided into two groups: the first one when,  $0 < P \leq 20\%$  and the second one when,  
258  $20\% < P \leq 80\%$ . In the low range of permeability when  $0 < P \leq 20\%$ , small vortexes were formed over the  
259 floodplain just downstream of the groyne. In the second range of  $P > 20\%$ , the vortex vanished and the minimum  
260 velocity was more than 25% of the approach velocity.

### 261 ***3.1.2 Velocity profiles and flow pattern in the vertical plane.***

262 In most of the cases, the velocity  $U$  in the main channel increased near the bed and reached  
263 a maximum value of 1.4-, 1.7- and 1.85-times the approach velocity in the case of one-side  
264 floodplain groyne, and 1.85-, 2.5-, 3-times the approach velocity in the case of groyne at both  
265 sides. This happened for  $L_r= 0.5, 0.75$  and  $1$  respectively. The velocity  $U$  decreased near the water  
266 surface (Figs. 11 and 12).

267 The impermeable groyne with  $L_r=1.0$  caused a strong increase of the longitudinal velocity at  
268 VP with a strong gradient (Fig. 13(a)). The eddy zone and the vortex generated downstream of the  
269 groyne field did not allow a fully developed vertical profile; this result is in agreement with the  
270 results of Ahmed et al. (2010) and Uijttewaal (2005). The gradient of the longitudinal velocity in

271 the VP became smaller for low value of  $L_r$ . Values of  $(U/U_o)_{max}$  were 1.45, 1.65, and 1.85 for  $L_r =$   
272 0.5, 0.75 and 1, respectively.

273 The permeable groyne effect on the main channel flow was limited compared with the  
274 impermeable one (Fig. 13). Most of the changes in the flow were found around the groynes on the  
275 floodplain and the velocity distribution was rather uniform over the entire flow depth. Uijttewaal  
276 (2005) found that the permeable groynes that were extended into the main channel, where the  
277 effect of the piles was present over the entire water depth, gave uniform vertical profile of  
278 velocity  $U$ . The maximum relative velocity in the vertical plane was dependent on the  
279 permeability of the floodplain groynes for all values of  $L_r$  and could be estimated as averaged  
280 values as 1.35, 1.25, and 1.2 for groyne with permeability  $P=0.40, 0.60, \text{ and } 0.80$ , respectively.

### 281 3.1.3 Tip velocity

282 The tip velocity is the flow velocity measured away from the groyne tip by approximately 5  
283 mm. The flow at the groyne tip had been steeply directed to the main channel increasing its  
284 velocity downstream of the groyne in both the HP and VP. The increase of the velocity at the VP  
285 occurred near the channel bed helping in generating intensive vortices that lead to a local scour.  
286 The analysis focused on the influences of both  $L_r$  and  $P$  on the relative tip velocity  $U_{tip}$  and  
287 deflection angle  $\theta$  (*tip velocity* is the resultant flow velocity ( $U, V$ ) measured at the nearest point  
288 to the groyne tip at the horizontal plane (HP) and deflection angle is the resultant flow velocity  
289 angle to x axis in clockwise direction). Fig. 14(a) presents a comparison between the present  
290 results with those of Kang *et al.* (2011) and Yeo *et al.* (2005). In the cases of groynes with relative  
291 length (relative to the channel total width) equal to 0.375, 0.25 and 0.2, the measured relative tip  
292 velocity decreased from 1.6 to 1.1 as the groyne permeability increased from 0 to 80%. In the case

293 of floodplain impermeable groyne with the relative length to the total width of the one floodplain  
294 compound channel of 0.5, the relative tip velocity increased up to 1.78. The floodplain flow was  
295 deviated and combined with the main channel flow resulting in maximizing the tip velocity. The  
296 relative tip velocity has varied inversely with the groyne permeability. Empirical equations were  
297 suggested to describe the relationship between the relative tip velocity and the permeability of the  
298 floodplain groyne (Table 3).

299 Figure 14(b) shows a comparison of the present measured data with the results of Kang *et al.*  
300 (2011); Wallingford (1997) and Yeo *et al.* (2005). The results of the permeable groyne coincided  
301 with the formula suggested by Yeo *et al.* (2005) within the range of  $0.02 < A^* < 0.35$ , where the  
302 area ratio  $A^* = A_g / (A_c - A_g)$ ,  $A_g$  is the groyne's project area and  $A_c$  is the cross sectional area of the  
303 flow (Table 3).

304 The relationship between the measured values of the deflection angle ( $\theta$ ) of the tip velocity  
305 in this study, Kang *et al.* (2011) and Yeo *et al.* (2005) indicated that, the groyne permeability  
306 inversely affected the tip velocity deflection angle (Fig. 14(c) and Table 3).

### 307 **3.2 Water surface profiles around the groyne field**

308 The measurements of the changes of the flow water depth (where; % change = ((depth with  
309 groyne – depth without groyne)/ depth without groyne) x 100) in the longitudinal direction at the  
310 floodplains and main channel are shown in Figs (15-17). The flow, which was totally or partially  
311 obstructed by the groyne projection area, caused water surface fluctuations in the groyne field and  
312 a rise in the water level upstream of the groyne. Also, a heading up and pressure difference  
313 between the upstream and downstream sides of the groyne were observed (Figs 11-17). This  
314 results from the floodplain groyne installations. In the upstream side of the groyne, as  $L_r$  increased

315 the water depth in the floodplain increased and the location of the highest point of the water  
316 surface moved towards the groyne inner edge. In the downstream side of the groyne, the water  
317 surface was significantly decreased as a result of increasing  $L_r$ . The greatest value of the water  
318 rise and reduction occurred just upstream and downstream of the groyne at relative distance  $X_r$   
319 from -0.25 to +0.20. In the case of impermeable groyne on one side of the compound channel  
320 with one or two floodplains, the maximum rise in the upstream water depth was estimated as 8,  
321 4.5 and 3.5% for  $L_r = 1.0, 0.75$  and  $0.5$ , respectively. This happened for all widths of floodplain.

322 The influence of the permeable groyne on the water depth was greater at the floodplain  
323 upstream and downstream of the groyne than at the main channel. The water depth was slightly  
324 affected by the permeability. Thus, for permeable groyne with  $P=60\%$ , the changes of floodplain  
325 water depth was only about 2.5, 2, and 1.5% for  $L_r = 1.0, 0.75$ , and  $0.5$ , respectively. For all values  
326 of permeability and  $L_r$ , the change of water depth downstream of the groyne had a mean value of  
327 about -4.5%.

#### 328 4. Conclusions

329 The present study was conducted to determine how much the physical dimensions and  
330 permeability of floodplain groyne influence the flow field using single groyne installed in  
331 compound channel floodplains. The findings can be of use to river system with respect to ecology,  
332 floodplain and banks protection, and bed scour prevention. The main conclusions that can be  
333 drawn are:

334 (1) Using impermeable groyne in rivers with large single or two floodplains generates a  
335 massive flow eddy and separation zones downstream of the groyne and at the upper region of the  
336 main channel. The velocity in the main channel near the surface decreases, while it increases in

337 the middle and lower regions. In the case of floodplain with impermeable groyne in one side of  
338 compound channel with two floodplains, both the other floodplain flow velocity and the groyne  
339 tip velocity increase. The velocity changes downstream of the groynes- may lead to floodplain  
340 bed and banks erosion, while a degradation in the main channel bed can occur due to the  
341 acceleration in its flow velocities. To mitigate those effects, the floodplain impermeable groyne  
342 length should be less than half of the floodplain width.

343 (2) For floodplain single groyne regardless of its permeability and length, its great influences  
344 on the flow patterns occur in region located from 2 times the groyne length upstream the groyne  
345 to 14 times the groyne length in the downstream side; beyond this range, the flow was slightly  
346 affected.

347 (3) In the case of floodplain single impermeable groyne on one side of symmetrical  
348 compound channel, when  $L_r = 0.5, 0.75$  and  $1.0$ , negative velocities were generated and reached  
349 to  $-20, -30$  and  $-55\%$  of the original approach velocity. Those negative velocities are substituted  
350 by increasing the flow velocity on the main channel and the opposite floodplain. The increase  
351 reaches  $1.4-, 1.6-,$  and  $1.85-$ times the original velocity in the main channel and to  $1.75-, 2.25-,$   
352  $2.75-$ times the original ones in the opposite floodplain; respectively.

353 (4) For the floodplain permeable groynes ( $P=40, 60$  and  $80\%$ ), the groyne relative length  
354 slightly affects the flow compared with the impermeable ones and the great effect is only due to  
355 the permeability. The permeability inversely affects the maximum and tip velocities, while the  
356 minimum and bank velocities increased by increasing it.

357 (5) For floodplain permeable groyne, the water depth varies just upstream and downstream  
358 of the groyne while it was slightly affected at the main channel centerline. In the case of



359 impermeable groyne, the water surface (depth) is greatly affected. This effect extends more in the  
360 upstream side of groynes (backwater effects) while it can be weakened shortly downstream of  
361 groyne within a distance of 12-14 times the groyne length.

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## Experimental study of Flow characteristics around floodplain single groyne

### Figures Captions

Figure 1 Sketches of flumes, measuring points, and permeable groynes models.

Figure 2 Velocity distribution maps of  $U$  (cm/s) on HP for single impermeable groyne and double floodplains (Ahmed et al. 2010).

Figure 3 Values of  $(U/U_0)_{max}$  and  $(U/U_0)_{min}$  on the horizontal plane HP for single impermeable groyne and double floodplains (Ahmed et al. 2010).

Figure 4 Symmetrical single groynes arranged in one-line in both floodplains.

Figure 5 Single impermeable groynes in one floodplain compound channel.

Figure 6 Velocity distribution maps of the flow longitudinal velocity  $U$  at HP for single permeable groyne and single floodplain.

Figure 7 Values of  $(U/U_0)_{max}$  and  $(U/U_0)_{min}$  in the horizontal plane (HP) for single permeable groyne and single floodplain.

Figure 8 The lateral velocity ( $V$ ) distribution at HP for single permeable groyne and single floodplain ( $P=40\%$ ).

Figure 9 Vertical velocity ( $W$ ) distribution in VP for single permeable groyne and single floodplain ( $L_r = 1.0$ ).

Figure 10 Single groyne and single floodplain, the relationship between the groyne permeability and the ultimate values of the longitudinal relative maximum and minimum velocities.

Figure 11 Velocity profiles and flow maximum relative longitudinal velocity  $U$  at VP for single impermeable groyne and double floodplains.

Figure 12 Velocity profiles and maximum relative longitudinal flow velocity at VP for one-line two symmetrical impermeable groynes and double floodplains.

Figure 13 Maximum relative longitudinal velocity at VP for single floodplain and single groyne.

Figure 14 Variation of the Tip velocity.

Figure 15 Changes of water depth at the floodplains and main channel centerlines for single impermeable groyne and double floodplains.

Figure 16 Changes of water depth at the floodplains and main channel centerlines for single impermeable groyne and single floodplain.

Figure 17 Changes of water depth across the lateral section of the flume for Single groyne and single floodplain.

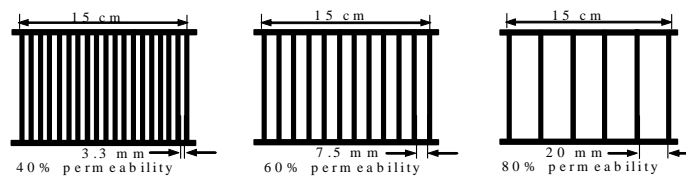
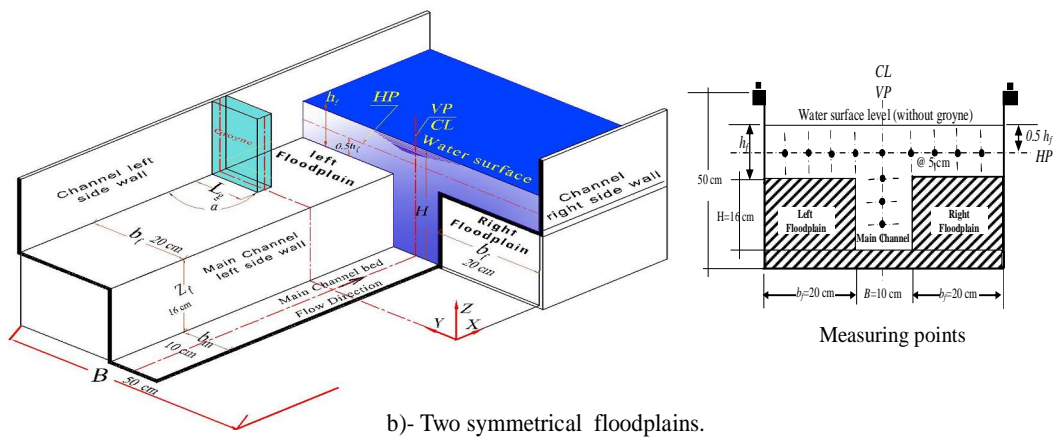
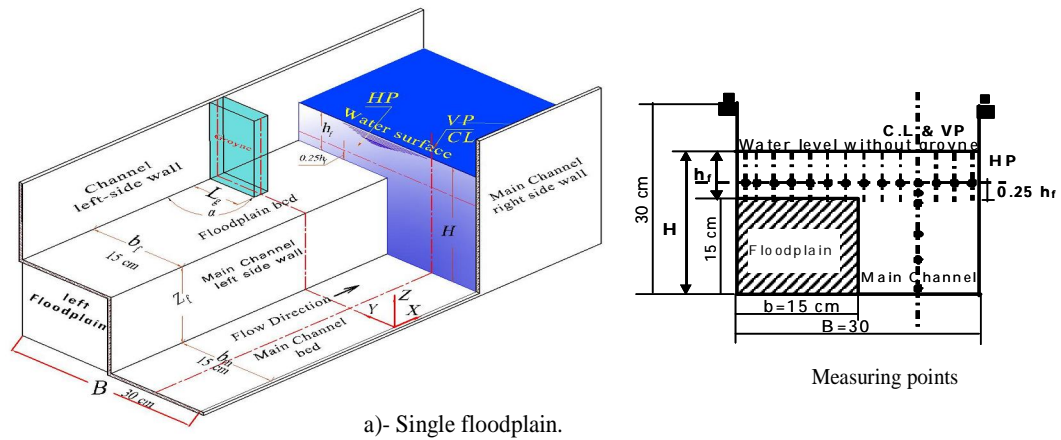


Figure 1

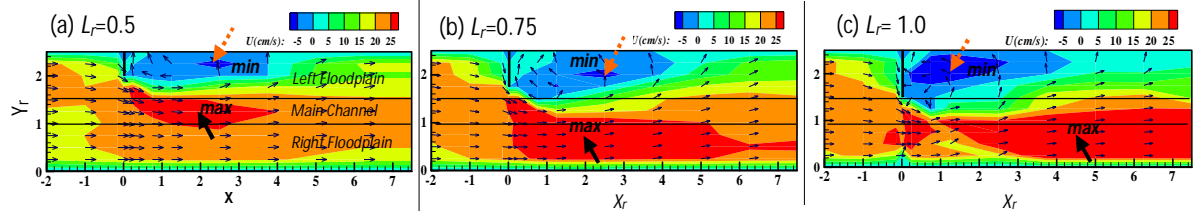


Figure 2



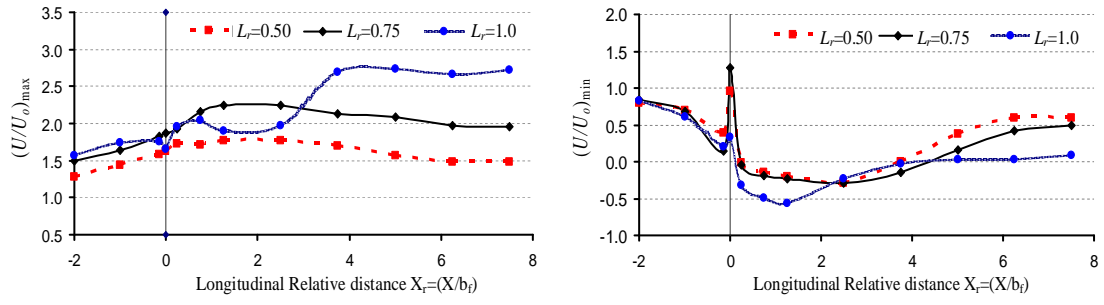
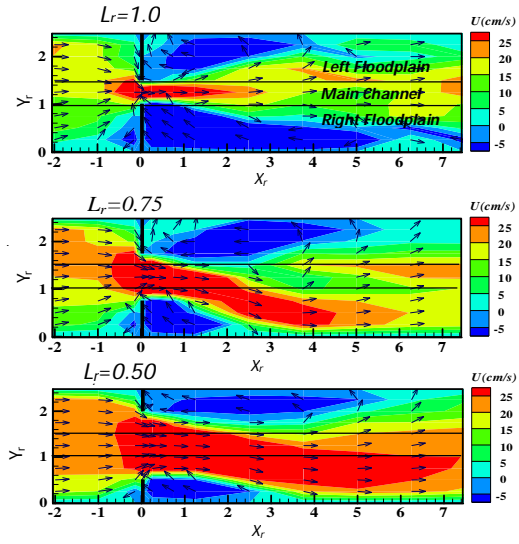
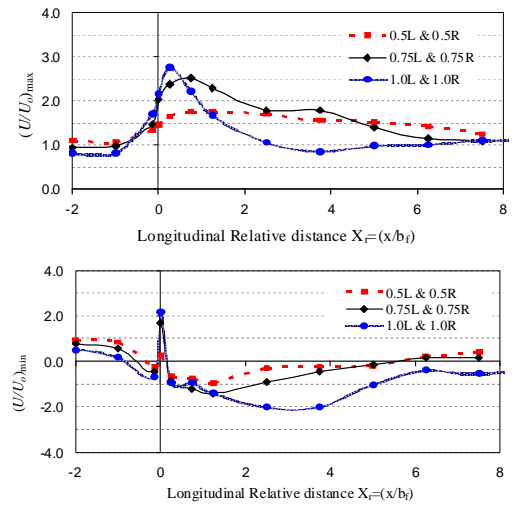


Figure 3

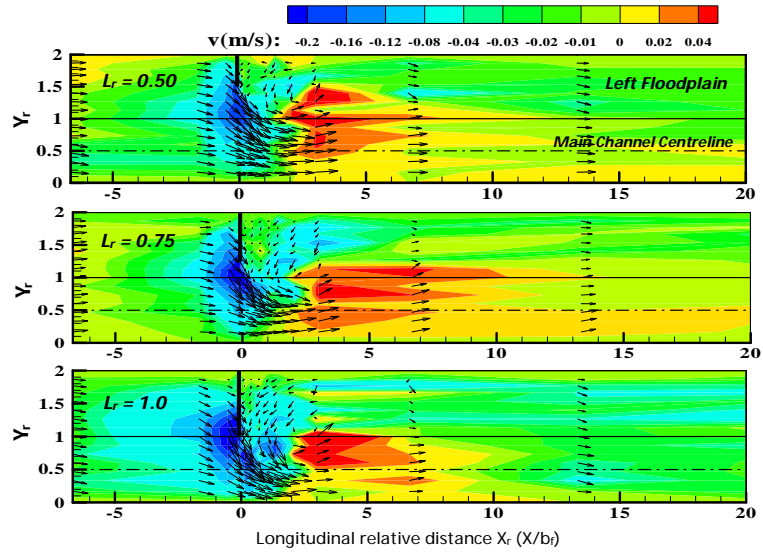


(a) Distribution map of the flow longitudinal velocity  $U$  at HP



(b) Values of the flow maximum and minimum longitudinal velocity relative to the approach velocity at HP

Figure 4



(b) Velocity distribution maps of the flow lateral velocity ( $V$ ) at HP

Figure 5

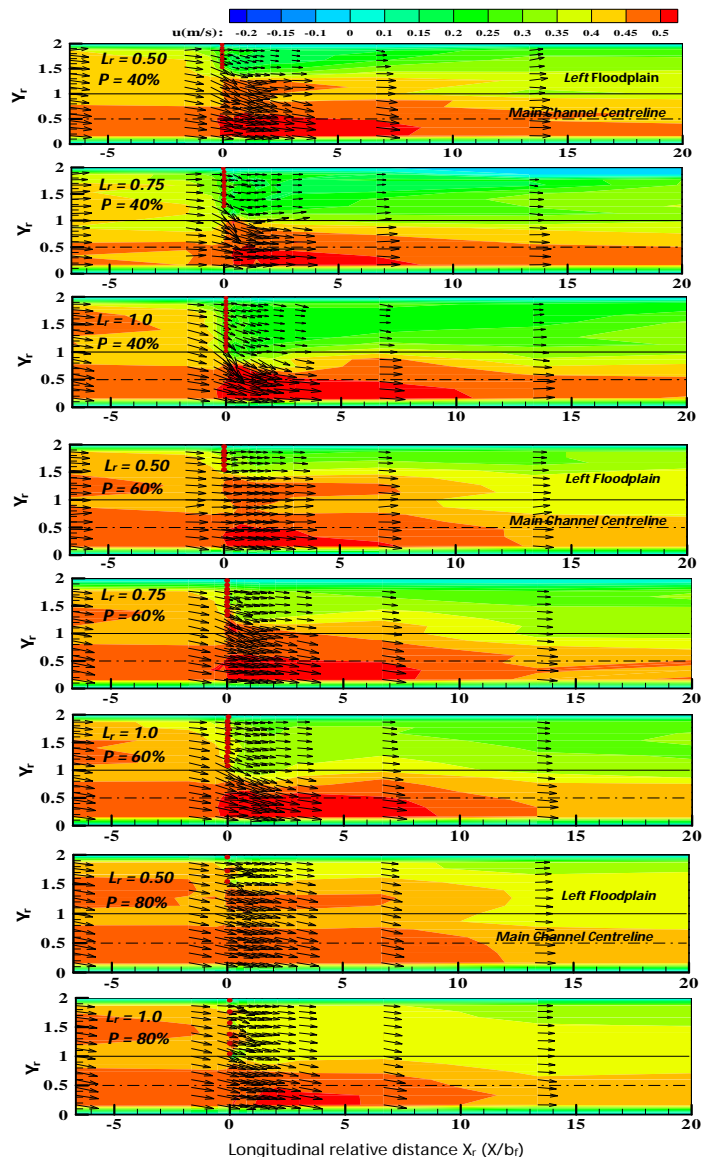


Figure 6

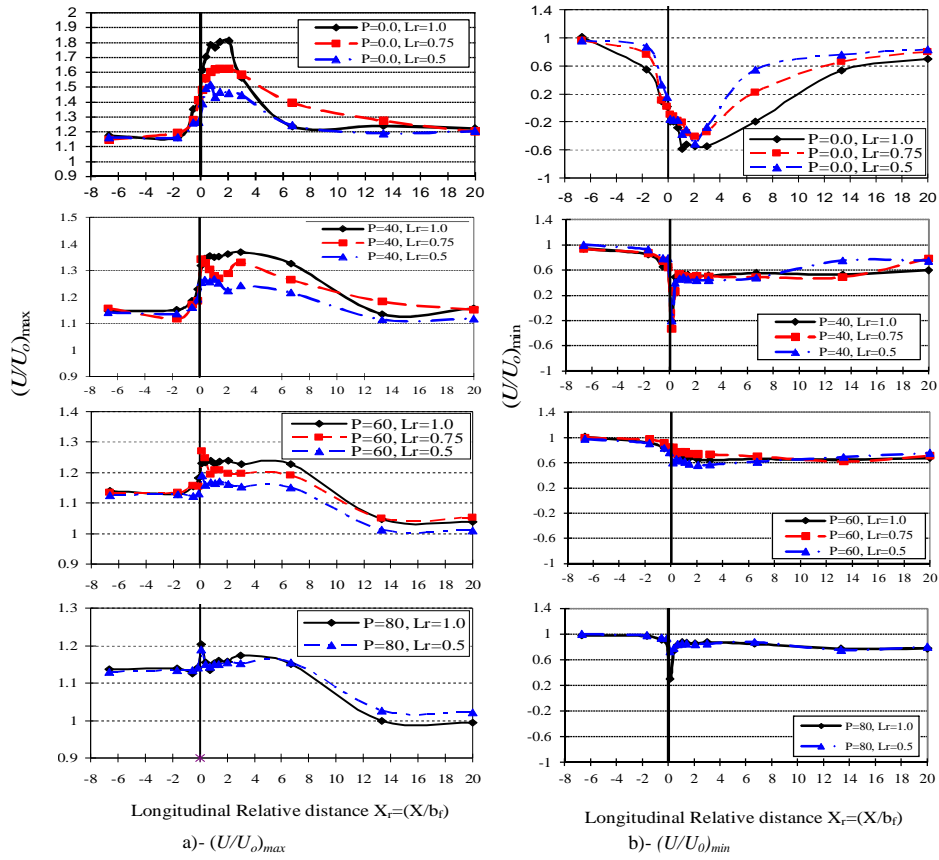


Figure 7

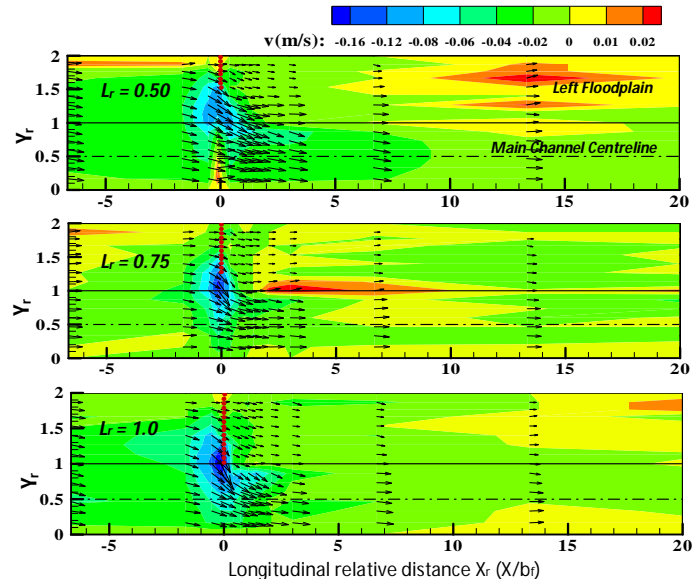


Figure 8

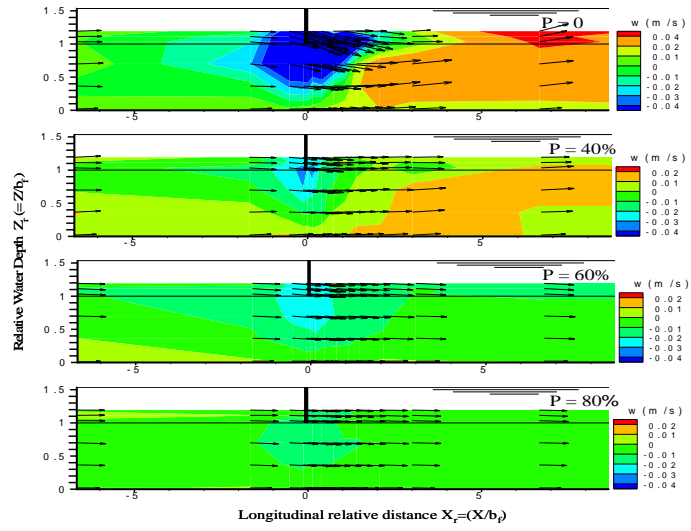
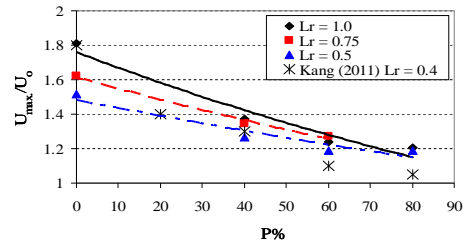
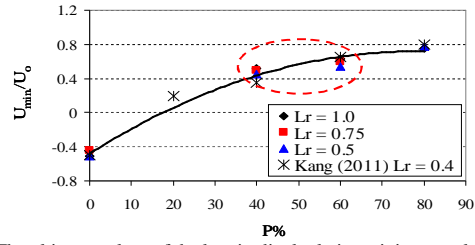


Figure 9



(a) The ultimate values of the longitudinal relative maximum velocities



(b) The ultimate values of the longitudinal relative minimum velocities

Figure 10



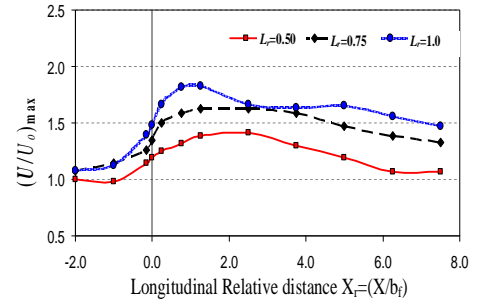
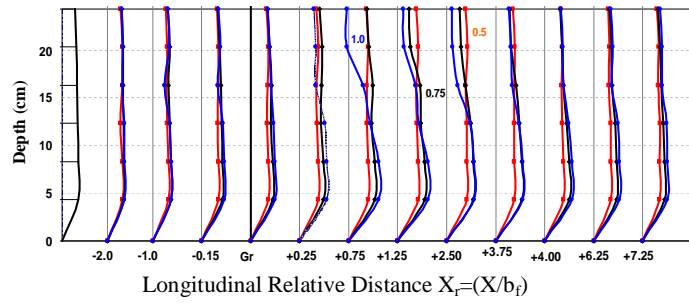


Figure 11

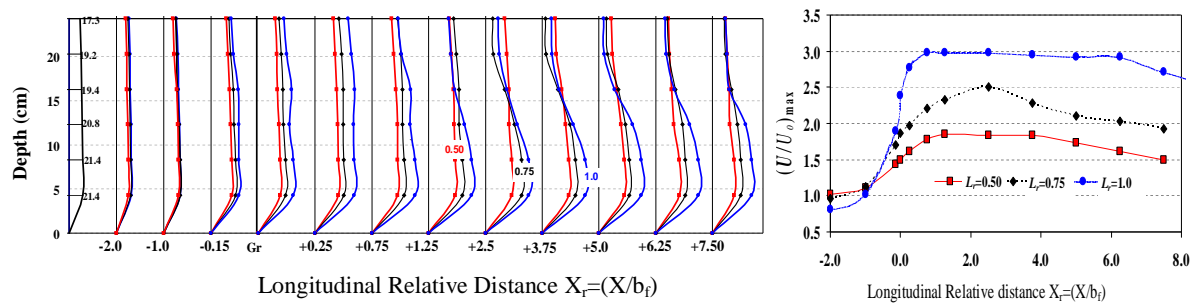
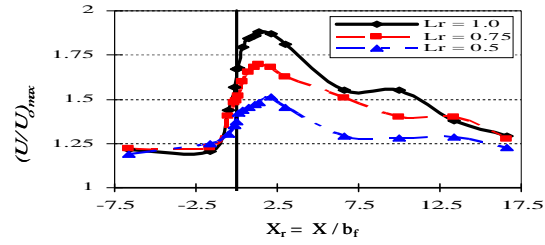
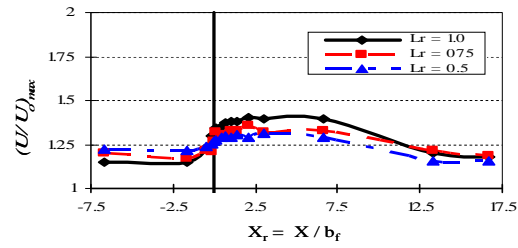


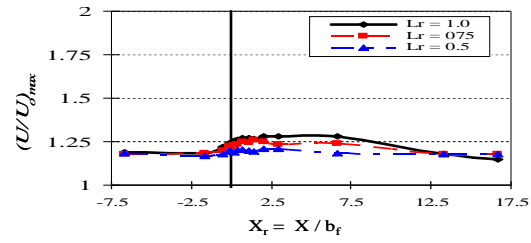
Figure 12



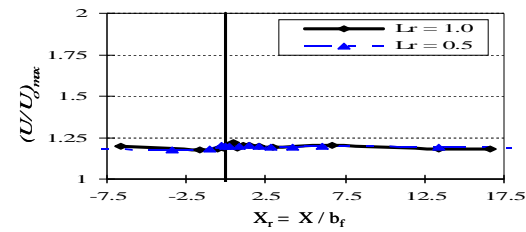
(a) Impermeable groyne



(b) Permeable groyne with P= 40%

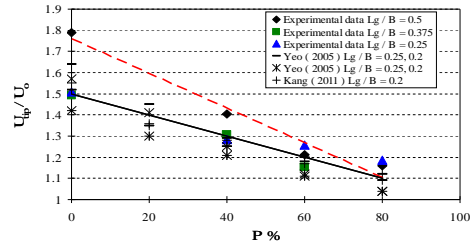


(c) Permeable groyne with P= 60%

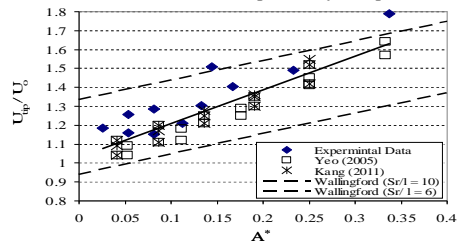


(d) Permeable groyne with P= 80%

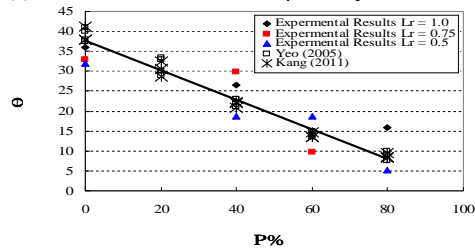
Figure 13



(a) Relation between the relative tip velocity and permeability

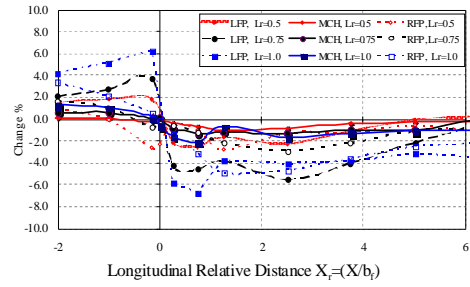


(b) Relation between the relative tip velocity and area ratio

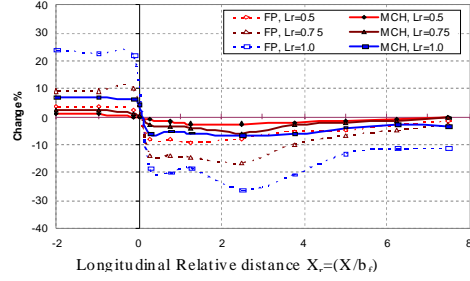


(c) Relation between flow separation angle ( $\theta$ ) and groyne permeability  $P$

Figure 14

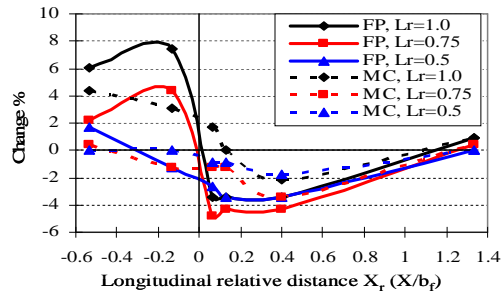


(a) Single groyne on the left side floodplain (LFP)

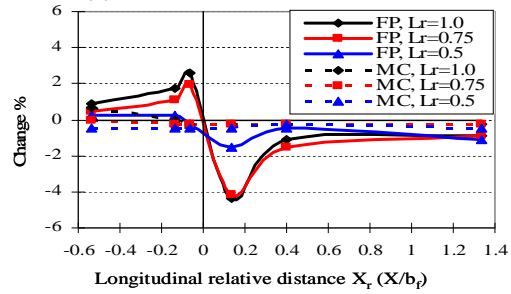


(b) Symmetrical single groyne on both floodplains (in one-line).

Figure 15

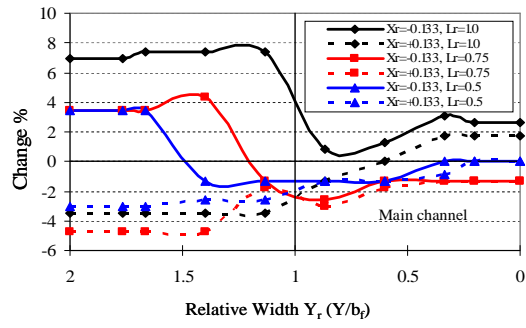


(a) Impermeable groynes

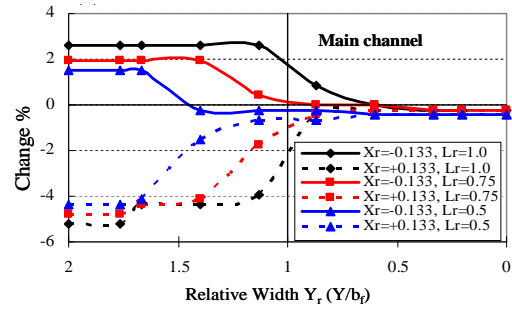


(b) Permeable groynes ( $P=60\%$ )

Figure 16



(a) Impermeable groynes



(b) Permeable groynes ( $P=60\%$ )

Figure 17