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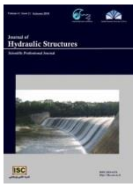

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Prediction of Percentage Discharge Distribution in Non-Prismatic Compound Channels with Skewed Floodplains

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Abstract

In rivers with non-prismatic compound cross-sections, due to the change in cross-section along the channel, mass exchange between the main channel and floodplains. Therefore, discharge distribution in non-prismatic compound channels is an important task for river and hydraulic engineers. In this paper, some results of experiments performed in non-prismatic compound channels with skewed and inclined floodplains have been explained. Two skew angles of 3.81° and 11.31° and three discharges were investigated. The effects of relative depth and relative distance on percentage discharge distribution in each sub-section of the skewed compound channels are presented. The experimental results show that the percentage discharge in each sub-section relies upon the parameters like relative depth, relative distance, skew angle, and floodplain side slope. By using the experimental results, multivariable regression models have been developed to estimate the percentage of discharge in the main channel and on the floodplains. Investigations indicate that the regression models presented in this research, in the validation range, can predict the percentage of discharge in each sub-section of the skewed compound channel fairy well. So that for the results used in this research, the coefficient of determination (R^2) for predicting discharge regression model in the main channel is 0.96, on the diverging floodplain is 0.92, and on the converging floodplain is 0.91. Also, the mean absolute percentage errors (MAPE) between the calculated and measured value of percentage discharge in the main channel, on the diverging floodplain, and the converging floodplain are equal to 1.47%, 14.29%, and 21.7%, respectively.

Keywords: Skewed Channels, Inclined Floodplains, Regression Model, Discharge Distribution, Percentage of Discharge.

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1. Introduction

Prediction of discharge distributions in the main channel and on the floodplains are important in river engineering. A compound channel consists of a deeper main channel in the middle and one or two floodplains around the main channel with lower flow depth. Many researchers such as Sellin [1], Knight and Demetriou [2], Ackers [3], Lambert and Sellin [4], Bousmar et al. [5], and Khatua et al. [6] investigated the discharge distributions on straight and prismatic compound

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channels. However, straight compound channels are rare in nature, and many rivers have a non-prismatic compound cross-section, especially in flood events.

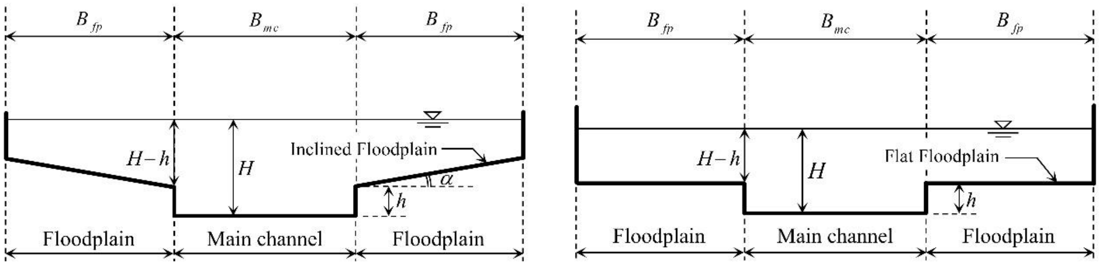
Due to the discharge exchange between sub-sections, the structure of the flow in non-prismatic compound channels, is more complex than straight compound channels [7-8]. Bousmar [7], Bousmar et al. [9], Rezaei [10], Rezaei and Knight [11], and Naik et al. [12] performed experiments on compound channels with converging floodplains and stated that the mass exchange in the second half of the converging reach is higher than that in the first half. Bousmar et al. [13], Yonesi et al. [14], and Das and Khatua [15] carried out their research on diverging compound channels and found that the discharge on the floodplains is lower than their conveyance capacity in a prismatic (straight) compound channel with the same cross-section. For both converging and diverging compound channels, by increasing the flow depth (rising relative depth, D_r) the discharge evolution on floodplains changes in a non-linear manner.

In skewed compound channels, one of the floodplain is convergent, and the other is divergent. James and Brown [16] and Jasem [17] performed some experiments on compound channels with skewed main channel, while Elliott and Sellin [18], Sellin [19], Chlebek [8], Bousmar et al [20], Dolati Mahtaj [21], and Dolati Mahtaj and Rezaei [22] studied the flow behaviour in compound channels with skewed floodplains. Studies shown that the flow velocity and discharge on diverging floodplains are always greater than those on converging floodplains. In this research, evolution discharge distributions in skewed compound channels with inclined floodplains for two different skew angles have been investigated. The results of the research were then compared with discharge distributions in skewed compound channels with the same skew angles but horizontal floodplains. Using the experimental results, the multivariable regression models have been developed to estimate the percentage discharges for each sub-section of the skewed compound channel.

2. Materials and methods

Experiments were performed in a flume with 18 m long, 1.2 m wide, 0.6 m deep, and with a bed slope of $S_0 = 1.63\times10^{-3}$ at Bu-Ali Sina University, Department of Civil Engineering. In this flume, a compound cross-section was constructed by using PVC material with the main channel 0.4m wide, 0.05m deep, and also two inclined floodplains with 0.4m wide and lateral side slope of 0.075 (equal to lateral angle of $\alpha = 4.3^o$). Figure 1a shows the cross-section of the compound channel with inclined floodplains.

For experiments in skewed compound channels, by using the L-shaped steel profiles, floodplains were isolated to make two skew angles of $\theta = 3.81^o$ and 11.31^o. Figure 2 shows the plan view of skewed compound channels with different skew angles. In some stage, the results of experiments have also been compared with Chlebek's data. Chlebek [8] performed experimental study in a skewed compound channel with flat floodplains (see Fig. 1b). General views of compound channels with the two skew angles ($\theta = 3.81^o$ and $\theta = 11.31^o$) and Chlebek's flume are also shown in Fig. 3.



(a) **(b)**

Fig. 1. Cross-section of a compound channel with (a) Inclined floodplains, and (b) flat floodplains

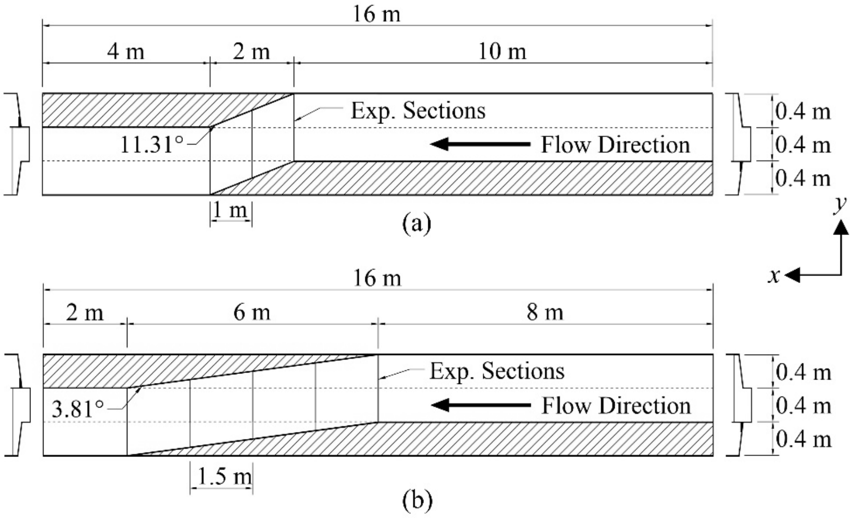
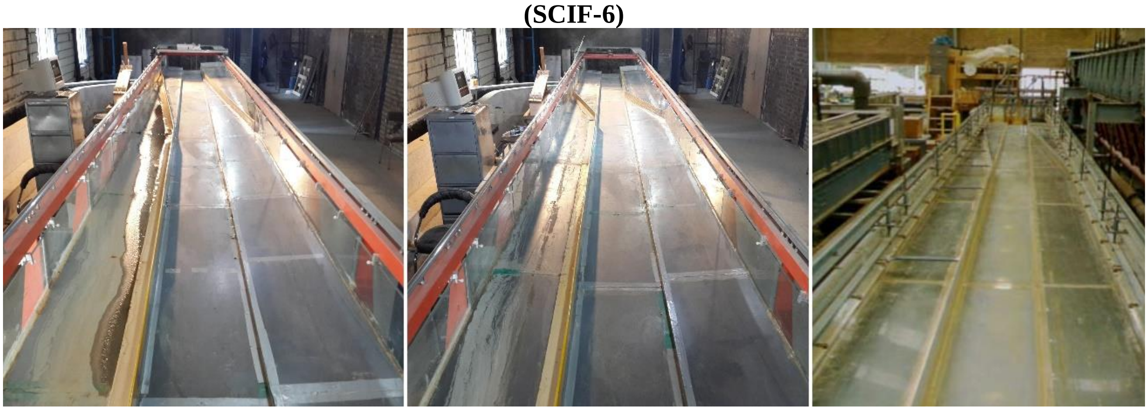


Fig. 2. Plan view of skew compound channel with the skew angles of (a) 11.31° (SCIF-2), (b) 3.81° (SCIF-6)



(a) **(b)** **(c)**

Fig. 3. General view of the skewed compound channel with the skew angles of (a) 3.81° (SCIF-6), (b) 11.31° (SCIF-2), (c) 3.81° Chlebek's flume [8]

Overbank flow in skewed compound channels with inclined floodplains for skew angles of 3.81° and 11.31° are denoted by SCIF-6 and SCIF-2, respectively. Since the flow depth vary along the skew part of the channel, the relative depth, $D_r = (H\text{-}h)/H$ are not constant and vary along the skewed portion. where H is the water depth in the main channel and h is the bankfull height.

More details of the flow characteristics for experimental research and Chlebek [8] are summarized in Table 1.

Table 1. Summary of flow conditions and geometry characteristics

Exp. series	Discharge Q (l/s)	Water depth H (m)	Relative depth D_r (–)	Skew length L (m)	Skew angle θ (°)	Floodplain lateral angle α (°)
SCIF-6	23.9	0.085–0.089	0.41–0.48	6	3.81	4.3
	28.5	0.095–0.107	0.47–0.53	6	3.81	4.3
	42.7	0.113–0.120	0.56–0.58	6	3.81	4.3
SCIF-2	23.7	0.081–0.090	0.38–0.44	2	11.31	4.3
	30.3	0.093–0.101	0.46–0.50	2	11.31	4.3
	42.5	0.108–0.113	0.53–0.56	2	11.31	4.3
Chlebek [8]	16.2	0.062–0.067	0.19–0.25	6	3.81	0
	21.4	0.071–0.076	0.30–0.34	6	3.81	0
	29.6	0.083–0.088	0.40–0.43	6	3.81	0
	43.4	0.102–0.106	0.51–0.53	6	3.81	0

In this research, velocity measurements were performed by use of a three-dimensional (3D) Acoustic Doppler Velocimeter (ADV). The velocity measurements were done at five and three sections along the skew part of the flume for experimental series of SCIF-6 and SCIF-2, respectively (see Fig. 2). The velocity record time was fixed in 60 s, at a sampling frequency of 200 Hz. Only correlations and signal-to-noise ratio (SNR) higher than 75% and 15 dB were selected from the velocity data. Also, the local velocities at the selected sections were measured laterally every 20 mm and vertically every 10 mm. The water depth profile was also measured using a point gauge with ±0.1 mm, accuracy at different sections along the skew part of the flume.

3. Results and discussion

The point velocity data were numerically integrated over the contributing depth to give discharge per unit width and then divided by the local flow depth giving the depth-averaged velocity:

$$U_d = \frac{1}{H}\sum_{i=1}^{n} u_i \Delta h_i \tag{1}$$

Where H is the local water depth, u_i is the local longitudinal velocity and Δh_i is the depth associated with the velocity.

Figure 4 shows the lateral distributions of depth-averaged velocity at different sections along the skewed portion of the flume for different experimental cases. As seen in Fig. 4, by moving along the skewed transition, the location of the maximum velocity moves from the centreline (where the velocity reaches a maximum in prismatic channels) toward the diverging floodplain in the direction of skew. Also, the average flow velocity on the diverging floodplain is always greater than the value on the converging floodplain. The same results were reported by Chlebek [8] and Bousmar et al. [20]. In the skewed compound channels with inclined floodplains (SCIF cases), the differences between velocities on the diverging and converging floodplains are more than the values in the skewed compound channel with horizontal floodplains (Chlebek's experimental case). Also, by increasing the relative depth and decreasing the skew angle, the velocity difference between the diverging and converging floodplain decreases.

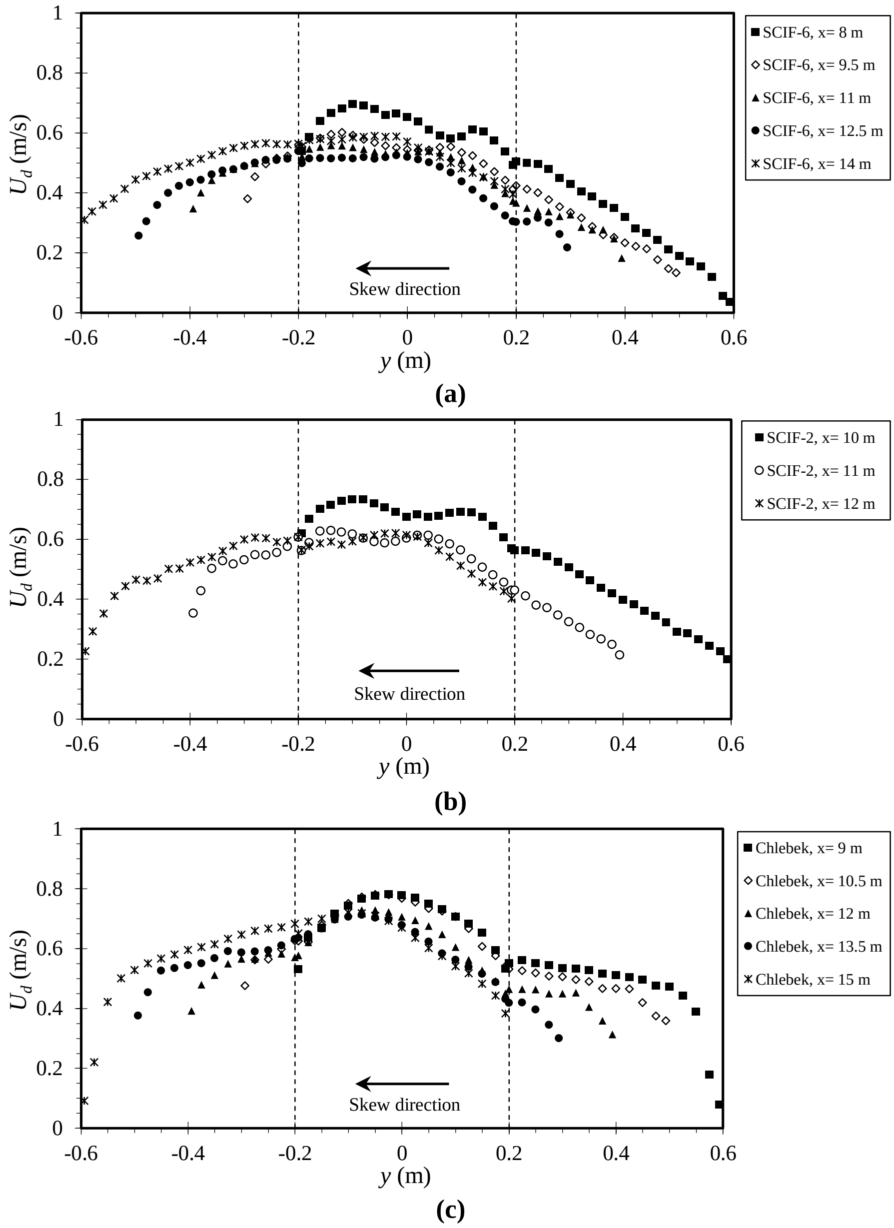


Fig. 4. Lateral distributions of depth-averaged velocity at the different sections along the skewed transition for (a) SCIF-6, *Q*= 28.5 l/s, (b) SCIF-2, *Q*= 30.3 l/s, (c) *Q*= 29.6 l/s, Chlebek [8]

The flow discharge in each sub-section of the skewed compound channel was calculated by numerically integration of the point velocity distributions (Eq. 2).

$$Q_s = \sum_{i=1}^{n} u_i \Delta A_i \tag{2}$$

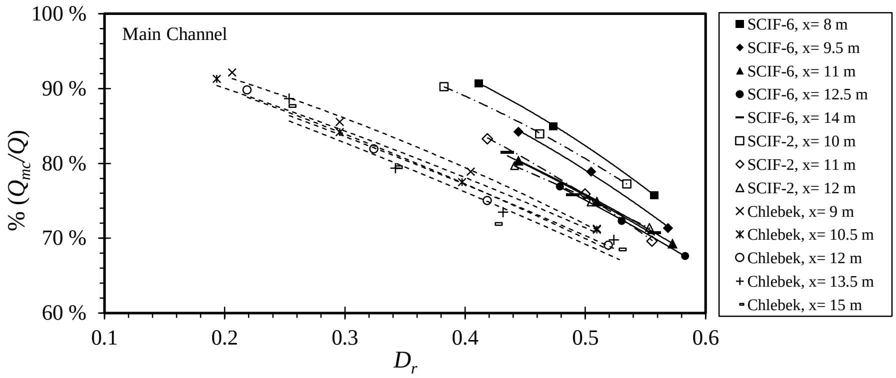
where Q_s is the sub-section discharge (i.e., Q_{mc}= main channel discharge, Q_{Dfp}= diverging floodplain discharge, and Q_{Cfp}= converging floodplain discharge), u_i is the point velocity component at the longitudinal direction, and ΔA_i is the surrounding sub-area.

The study indicates that in the compound channels with skewed and inclined floodplains, the flow discharges on diverging floodplain are bigger than the values on converging floodplains with the same geometry. This phenomenon is in accordance with the average velocity. In the middle of the skewed transition, where floodplains width are 200 mm, the discharge on the diverging floodplains are up to 2, 2.3, 1.6 times that of the converging floodplains for SCIF-6, SCIF-2, and Chlebek's cases, respectively. As the relative depth decrease, the difference between the discharge on the diverging and converging floodplains are also increase.

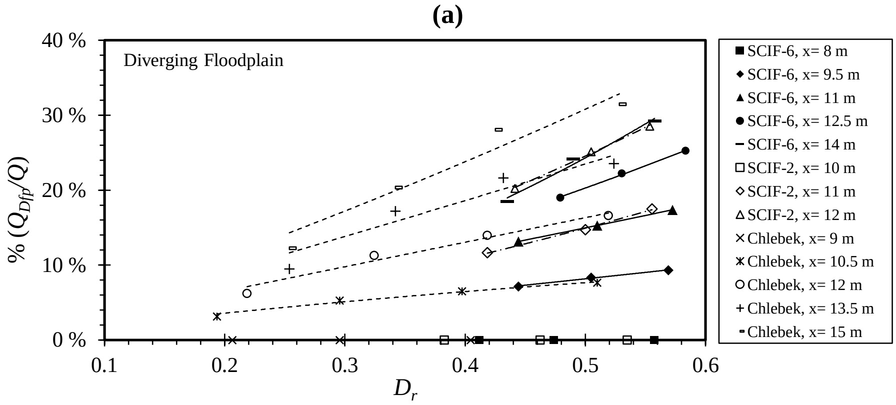
The percentage of discharge at different measurement sections in the main channel and on the floodplains were calculated and plotted against relative depths, see Fig. 5. The figures indicate that the second-order relationship (Eq. 3) can predict the percentage of flow on each sub-section:

$$\%(\frac{Q_s}{Q}) = aD_r^{\ 2} + bD_r + c \quad (3)$$

where a, b and c are constants.



(a)



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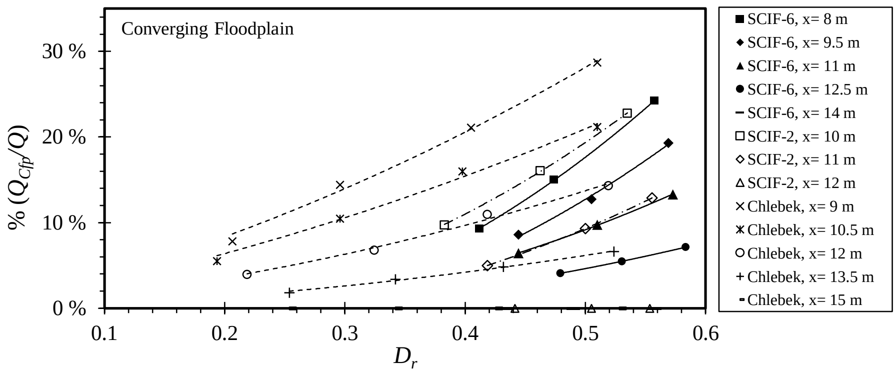


(c)

Fig. 5. Percentage of discharge distribution against the relative depth, (a) in the main channel, (b) on the diverging floodplain, (c) on the converging floodplain

From the figure, it can be seen that, by increasing the relative depth, the percentage of discharges in the main channel ($\%Q_{mc}/Q$) decreases while those values on both floodplains ($\%Q_{Dfp}/Q$ and $\%Q_{Cfp}/Q$) increase. In the experimental series of SCIF, as the skew angle increases from 3.81° to 11.31°, the effect of relative depth on increasing the percentage of discharge on the floodplains also increases. Also, the percentage of discharges carried by the main channel and floodplains in the skewed compound channels with a skew angle of 11.31° are greater than those in compound channels with a skew angle of 3.81°.

Figure 6 shows the evolution of discharge against the relative distance ($\Delta L/L$) for different relative depths, in which ΔL is distance measured from the beginning of the skewed flume portion, and L is the total length of skewed transition.

The figure also indicates that the percentage of flow along the converging floodplain decreases while on the diverging floodplain increases. However, at the floodplains with similar cross-sections, the percentage of discharge on the diverging floodplain is bigger than the converging floodplain.

The second-order mathematical relationship (Eq. 4), can also be established between the relative distance ($\Delta L/L$) and the percentage of flow in each sub-section ($\%Q_s/Q$):

$$\%(\frac{Q_s}{Q}) = a(\frac{\Delta L}{L})^2 + b(\frac{\Delta L}{L}) + c \quad (4)$$

where a, b and c are all constants.

An overview of Figs 5 and 6 shows that the percentage of discharge in each sub-section ($\%Q_s/Q$) relies on parameters like relative depth (D_r), relative distance ($\Delta L/L$), skew angle (θ), and floodplain lateral angle (α).

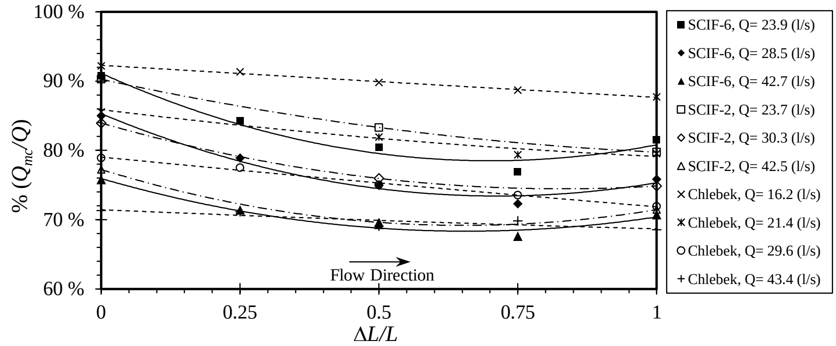
$$\%(\frac{Q_s}{Q}) = f(D_r, \frac{\Delta L}{L}, \tan\theta, \tan\alpha) \quad (5)$$

Using the experimental data, three regression models were developed for predicting for predicting the percentage of discharge in each sub-section of the skewed compound channel. Equations 6 to 8 are presented to estimate the percentage of discharge in the main channel ($\%Q_{mc}/Q$), on the diverging floodplain ($\%Q_{Dfp}/Q$), and on the converging floodplain ($\%Q_{Cfp}/Q$), respectively.

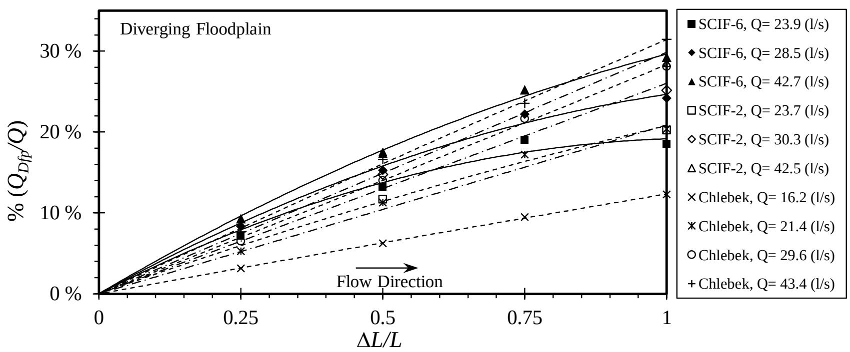
$$\%\left(\frac{Q_{mc}}{Q}\right) = -49.67D_r^{\,2} - 33.92D_r + 6.94\left(\frac{\Delta L}{L}\right)^2 - 11.59\left(\frac{\Delta L}{L}\right) - 3.88\tan\theta \cdots$$
$$+101.64\tan\alpha + 102.75 \quad (6)$$

$$\%\left(\frac{Q_{Dfp}}{Q}\right) = 24.08D_r^{\,2} + 23.04D_r - 7.06\left(\frac{\Delta L}{L}\right)^2 + 30.26\left(\frac{\Delta L}{L}\right) + 1.66\tan\theta \cdots$$
$$-41.01\tan\alpha - 13.29 \quad (7)$$

$$\%\left(\frac{Q_{Cfp}}{Q}\right) = 50.68D_r^{\,2} + 10.84D_r - 5.18\left(\frac{\Delta L}{L}\right)^2 - 15.46\left(\frac{\Delta L}{L}\right) + 5.79\tan\theta \cdots$$
$$-95.22\tan\alpha + 6.3 \quad (8)$$



(a)



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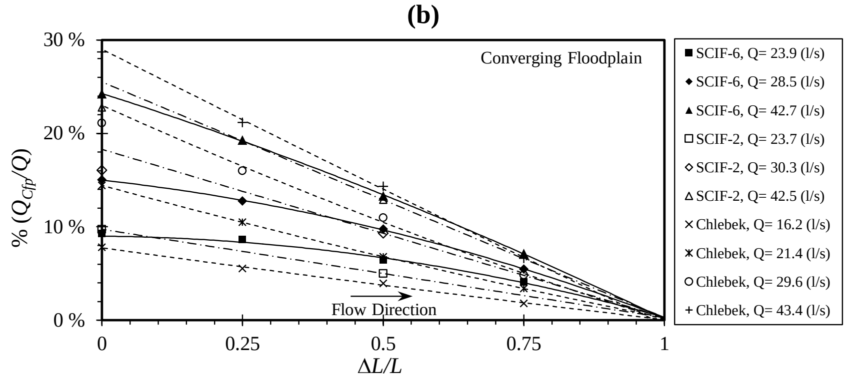

(c)

Fig. 6. Evolution of discharge distributions along the skew part of the channel, (a) in the main channel, (b) on the diverging floodplain, (c) on the converging floodplain

To study the accuracy of the proposed models (Eqs. 6 to 8), the error analysis has been performed in terms of the coefficient of determination (R^2), the mean absolute percentage error (MAPE) and the root mean square error (RMSE).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Pre_i - Exp_i)^2}{\sum_{i=1}^{n}(\overline{Exp} - Exp_i)^2} \tag{9}$$

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Exp_i - Pre_i}{Exp_i}\right| \times 100 \tag{10}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pre_i - Exp_i)^2} \tag{11}$$

In which Pre_i is the predicted values, Exp_i is the measured values, $\overline{Exp}$ is the average of the measured values, and n is the number of data.
Based on the error analysis, the R^2, MAPE and RMSE values for the percentage of discharges, predicted in the main channel and on the floodplains are calculated and shown in Table 2.

Table 2. The coefficient of determination (R^2) and the mean absolute percentage error (MAPE) in each sub-section

	Main channel	Diverging floodplain	Converging floodplain
R^2	0.96	0.92	0.91
MAPE	1.47%	14.29%	21.7%
RMSE	1.41	2.02	1.91

From the table, it is clear that among those proposed multivariable regression models, Eq. 6 has the highest accuracy for predicting the percent of discharge in the main channel. The scattering diagrams of percentage discharge on each sub-section, for the actual and predicted data against the ideal line of $y = x$, are shown in Fig. 7. As seen in Fig. 5, the dispersion of data is very close to the ideal line, especially for the main channel.

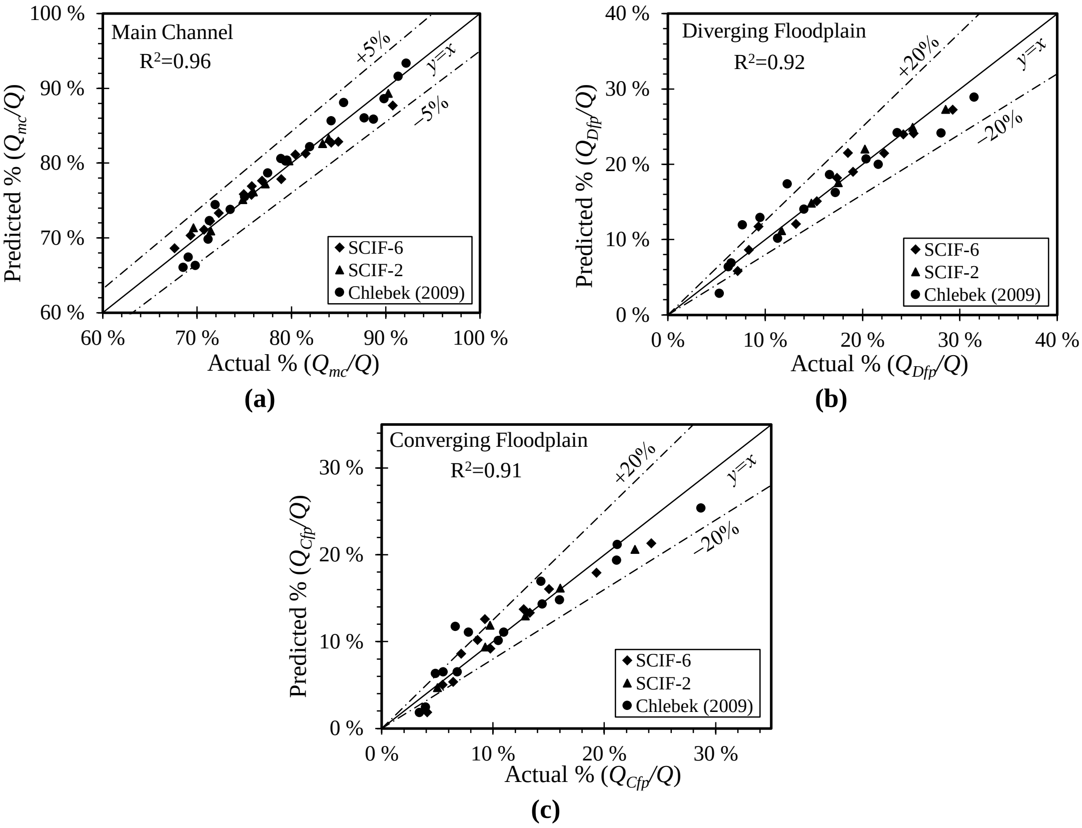

Fig. 7. Scatter diagram between predicted and actual discharge (a) in the main channel (% Q_{mc}/Q, Eq. 5), (b) on the diverging floodplain (% Q_{Dfp}/Q, Eq. 6), and (c) on the converging floodplain (% Q_{Cfp}/Q, Eq. 7)

4. Conclusions

Experimental results of flow in skewed compound channels with inclined floodplains were investigated. The evolution of percentage discharge distributions against the relative depths and the relative distances were presented. Based on four variables (the relative depth, relative distance, skew angle, and floodplain lateral angle) multivariable regression models for predicting the percentage of discharge in the main channel and on the diverging and converging floodplains, were developed. The error analysis indicates that the proposed regression model is able to predict the percentage of discharge in the main channel quite well.

References

1. Sellin, R. H. J. (1964). A Laboratory Investigation into the Interaction between the Flow in the Channel of a River and that over its Flood Plain. La Houille Blanche, pp: 7: 793-802.
2. Knight, D. W., Demetriou, D. (1983). Flood Plain and Main Channel Flow Interaction. Journal of Hydraulic Engineering. ASCE, pp: 109(8): 1073-1092.
3. Ackers, P. (1993). Flow Formulae for Straight Two-Stage Channels. Journal of Hydraulic Research. IAHR, pp: 31(4): 509-531.
4. Lambert, M. F., Sellin, R. H. J. (1996). Discharge Prediction in Straight Compound Channels Using the Mixing Length Concept. Journal of Hydraulic Research. IAHR, pp: 34(3): 381-394.
5. Bousmar, D., Rivière, N., Proust, S., Paquier, A., Morel, R., Zech, Y. (2005). Upstream Discharge Distribution in Compound-Channel Flumes. Journal of Hydraulic Engineering. ASCE, pp: 131(5): 408-412.
6. Khatua, K. K., Patra, K. C., Mohanty, P. K. (2012). Stage-Discharge Prediction for Straight and Smooth Compound Channels with Wide Floodplains. Journal of Hydraulic Engineering. ASCE, pp: 138(1): 93-99.
7. Bousmar, D. (2002). Flow Modelling in Compound Channels: Momentum Transfer between Main Channel and Prismatic or Non-Prismatic Floodplains. PhD Thesis, University of Catholique de Louvain, Louvainla, Belgium.
8. Chlebek, J. (2009). Modelling of Simple Prismatic Channels with Varying Roughness Using the SKM and a Study of Flows in Smooth Non-Prismatic Channels with Skewed Floodplains. PhD Thesis, University of Birmingham, Birmingham, UK.
9. Bousmar, D., Wilkin, N., Jacquemart, J. H., Zech, Y. (2004). Overbank Flow in Symmetrically Narrowing Floodplains. Journal of Hydraulic Engineering. ASCE, pp: 130(4): 305-312.
10. Rezaei, B. (2006). Overbank Flow in Compound Channels with Prismatic and NonPrismatic Floodplains. PhD Thesis, University of Birmingham, Birmingham, UK.
11. Rezaei, B., Knight, D. W. (2011). Overbank Flow in Compound Channels with Nonprismatic Floodplains. Journal of Hydraulic Engineering. ASCE, pp: 137(8): 815-824.
12. Naik, B., Khatua, K. K., Wright, N. G., Sleigh, A. (2017). Stage-Discharge Prediction for Converging Compound Channels with Narrow Floodplains. Journal of Irrigation and Drainage Engineering, pp: 143(8): 04017017-10.
13. Bousmar, D., Proust, S., Zech, Y. (2006). Experiments on the Flow in a Enlarging Compound Channel. Proceedings of the River Flow 2006, Lisbon, Portugal, Taylor and Francis\Balkema, pp: 1: 323-332.
14. Yonesi, H. A., Omid. M. H., Ayyoubzadeh, S. A. (2013). The Hydraulics of Flow in Non-Prismatic Compound Channels. Journal of Civil Engineering and Urbanism, pp: 3(6): 342-356.
15. Das, B. S., Khatua, K. K. (2018). Flow Resistance in a Compound Channel with Diverging and Converging Floodplains. Journal of Hydraulic Engineering. ASCE, pp: 144(8): 04018051-21.
16. James, M., Brown, B. J. (1977). Geometric Parameters that Influence Floodplain Flow, Waterways Experiment Section. Report H-77-1, Hydraulics Laboratory, US Army Corps of Engineering, Vicksburg, Mississippi.
17. Jasem, H. K. (1990). Flow in Two-Stage Channels with the Main Channel Skewed to the Flood Plain Direction. PhD Thesis, University of Glasgow, Glasgow, Scotland.

18. Elliott, S. C. A., Sellin, R. H. J. (1990). SERC Flood Channel Facility: Skewed Flow Experiments. Journal of Hydraulic Research. IAHR, pp: 28(2): 197-214.
19. Sellin, R. H. J. (1995). Hydraulic Performance of a Skewed Two-Stage Flood Channel. Journal of Hydraulic Research. IAHR, pp: 33(1): 43-64.
20. Bousmar, D., Jacqmin, T., Wyseur, S., Van Emelen, S. (2012). Flow in Skewed Compound Channels with Rough Floodplains. Proceedings of the River Flow 2012., San Jose, Costa Rica, CRC Press, pp: 1: 217-224.
21. Dolati Mahtaj, M. (2021). Experimental Study of Flow in Skewed Compound Channel with Inclined Floodplains. MSc Thesis, Bu-Ali Sina University, Hamedan, Iran. (in Persian)
22. Dolati Mahtaj, M., Rezaei, B. (2021). Experimental Study of Force Balance and Interaction between Flow in the Main Channel and on the Floodplains in Skewed Compound Channel with Inclined Floodplains. Ferdowsi Civil Engineering, pp: 34(2): 87-102. (in Persian)