Chapter 10
Flow Distributions in a Compound Channel with Diverging Floodplains

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Abstract During flood, the flow distribution in main channel and floodplain is always an important factor for river engineer to model, accordingly, the measures can be taken in the floodplain area. Experiments on diverging compound channel show that the flow distribution in main channel and floodplains are found to be a function of four non-dimensional geometric and hydraulic parameters such as width ratio, relative flow depth, relative longitudinal distance and flow aspect ratio. This paper presents an empirical-non-linear-multivariable regression model by considering the aforementioned parameters to compute discharge distribution in diverging compound channels. The model is developed using discharge distribution data obtained from present laboratory experiments and with the published data of other researchers on diverging compound channels. The predictive strength of the developed regression model is validated using several major statistics. All deployed statistics have indicated that the developed model is highly significant. The outcome for all diverging compound channels resulted in minimum RMSE and MAPE values as 0.0092 and 4.35%, respectively, when the discharge is predicted using the developed multivariable regression model.

Keywords Flow distribution · Diverging compound channel · Multivariable regression analysis · Width ratio · Aspect ratio; relative flow depth

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10.1 Introduction

Flow modelling in the compound channel is a challenging task for the river engineer as the shape of floodplain and main channel significantly affect the conveyance capacity. Natural river generally exhibits non-prismatic cross-sectional shape during flooding and known as non-prismatic compound channels. These type of compound channels are broadly classified into three types, viz., diverging, converging and skewed types compound channel depending on the floodplains shape (Chlebek 2009). Overestimation of floodplain discharge leads to extra cost for protection near floodplain area, whereas underestimation leads to loss of life and property of the country. Thus, knowledge on flow distribution in main channel and floodplain in such channel is very essential. Diverging and converging geometry of floodplains affect significantly to the conveyance estimation process. Flooding rivers usually present flow-width variations that give rise to non-uniform flows in non-prismatic compound geometries. Flow distribution in the diverging compound channel (DCC) is a very important topic in river hydraulics to be investigated from a practical point of view in relation to flood risk assessment, bank protection, navigation and sediment-transport depositional pattern. Very few works were found from the literature on a compound channel with diverging floodplains. Proust (2005) is the first to work on diverging compound channels and presented an independent subsection method to model the flow depth and velocity at the different subsections of prismatic and non-prismatic compound channels. He categorized the compound channel into three subsections such as left floodplain, main channel and right flood plain. Das et al. (2018) divided the compound channel into four sub zone such as left flood plain, right floodplain, upper main channel and lower main channel. Bousmar et al. (2006) discuss the flow behaviour in the compound channel with diverging floodplain for two different diverging angles 3.81° and 5.7°. Later Yonesi et al. (2013) worked on diverging compound channels with differential bed roughness for diverging angles 3.81°, 5.7° and 11.3°. Das et al. (2020) use the soft computing technique to estimate the discharge in converging and diverging compound channels. Das et al. (2017) and Devi et al. (2021) developed the numerical and analytical model for prediction of depth averaged velocity and boundary shear distribution in prismatic and non-prismatic compound channels without incorporating any flow distribution calculation in the model. Due to non-prismatic effect of the floodplain, the existing traditional methods like single channel method (SCM), divided channel method (DCM) and numerical methods like lateral distribution method (LDM), Shiono and Knight method (SKM) failed to provide accurate stage, discharge and velocity at different sections of the non-prismatic portion (Das et al. 2019).

Wormleaton et al. (1982), Knight and Demetriou (1983), Devi et al. (2017), Devi and Khatua (2019) and Khuntia et al. (2019) show that the vertical apparent shear exists on the interface between the main channel and the floodplain which generally accelerates the flow on the floodplain and resists the flow in the main channel. Knight and Demetriou (1983) developed the flow percentage in main channel (%Qmc) model by considering the two non-dimensional parameters, width ratio and relative flow

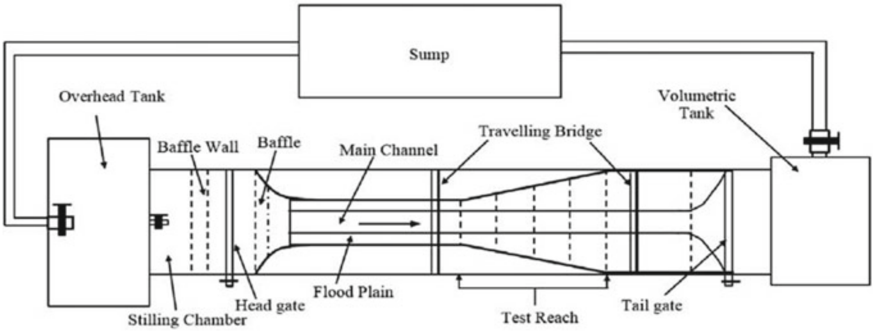

Fig. 10.1 Plan view of diverging compound channel setup at Hydraulics Engineering Laboratory, NIT Rourkela, India

depth for the prismatic compound channel for width ratio ranges from 1.0 to 3.0. Khatua and Patra (2009) developed the %Qmc model for up to 4.0 width ratio. Devi et al. (2016) developed the %Qmc model for the straight prismatic compound channel for width ratio ranges from 2.0 to 15.75 by considering four different non-dimensional parameters such as width ratio, relative flow depth, channel side slope and flow aspect ratio. To develop the model for main channel discharge in a diverging compound channel, a large number of data sets is necessary. Therefore, experiments have been conducted in three diverging compound channels at Hydraulics Engineering Laboratory of NIT Rourkela, India, for different flow conditions to study the flow distributions pattern in the floodplain and main channel (Fig. 10.1).

10.2 Experimental Setup

Three sets of compound channels with diverging floodplains made up of perspex sheet were fabricated inside a tilting flume of size 22 m long × 2 m width × 0.5 m depth. Keeping the geometry of the main channel constant, the diverging length of the fabricated channels were changed to 5 m, 3 m and 2 m. The diverging angles of the floodplains were estimated to be 5.93°, 9.83° and 14.57°, respectively. Figure 10.2 shows the experimental section of three diverging compound channel. Longitudinal bed slope of the channel was maintained at 0.0014, satisfying subcritical flow conditions. The roughness of the floodplain and main channel were alike and the Manning's n found out as 0.011 from the in-bank experimental runs in the channel. In order to compare the results of experiments in non-prismatic compound channels with different divergence angles (θ) for each selected discharge, the downstream water level was adjusted using the tailgate. It was done in such a way that the backwater profile reached a given depth in the central section of diverging reach at x = 14.5 m, x = 15.5 m and x = 16 m for 5 m, 3 m and 2 m diverging portions of the compound channels, respectively (Fig. 10.3). Water depths were measured

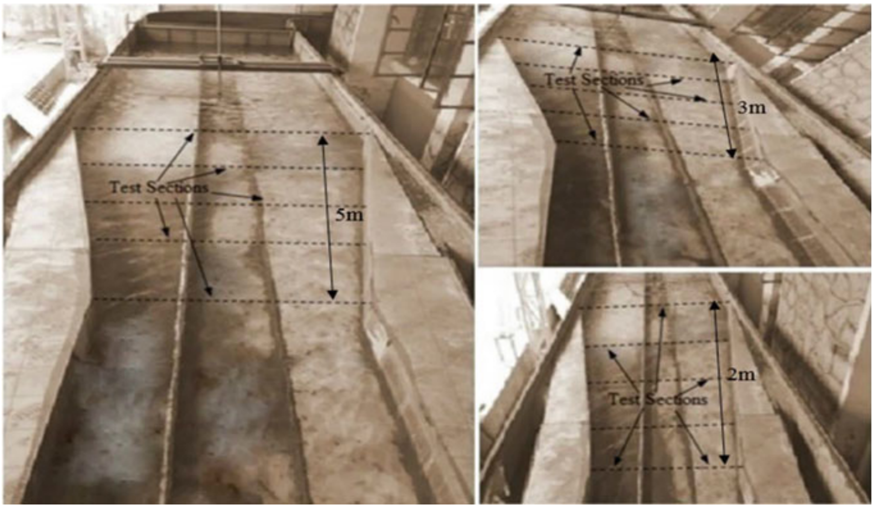

Fig. 10.2 Experimental sections of three different diverging compound channels (5.93°, 9.83°, and 14.57°)

directly with a point gauge located on an instrument carriage. A micro-Pitot tube of 4.77 mm external diameter in combination with suitable inclined manometers as well as 16-MHz Micro-ADV (Acoustic Doppler Velocimeter) were used to measure velocities. Details of experimental setup and procedures are available in Das and Khatua (2018a, b). Summary of experimental characteristics of present test channels is given in Table 10.1.

10.3 Discharge Distributions

10.3.1 Flow Percentage in Main Channel and Floodplains

The individual discharges carried by the main channel (Q_{mc}) and by the floodplain $\left(Q_{fp}\right)$ are estimated by summing the product of depth averaged velocity with the respective elementary cross-sectional area (ΔA) over the main channel (A_{mc}) and floodplain (A_{fp}) zone, respectively. The expressions are given as

$$Q_{mc} = \sum_{mc} U_d \Delta A \text{ and } Q_{fp} = \sum_{fp} U_d \Delta A \tag{10.1}$$

The mean velocities of the flow in the main channel (U_{mc}) and floodplain (U_{fp}) can be evaluated by

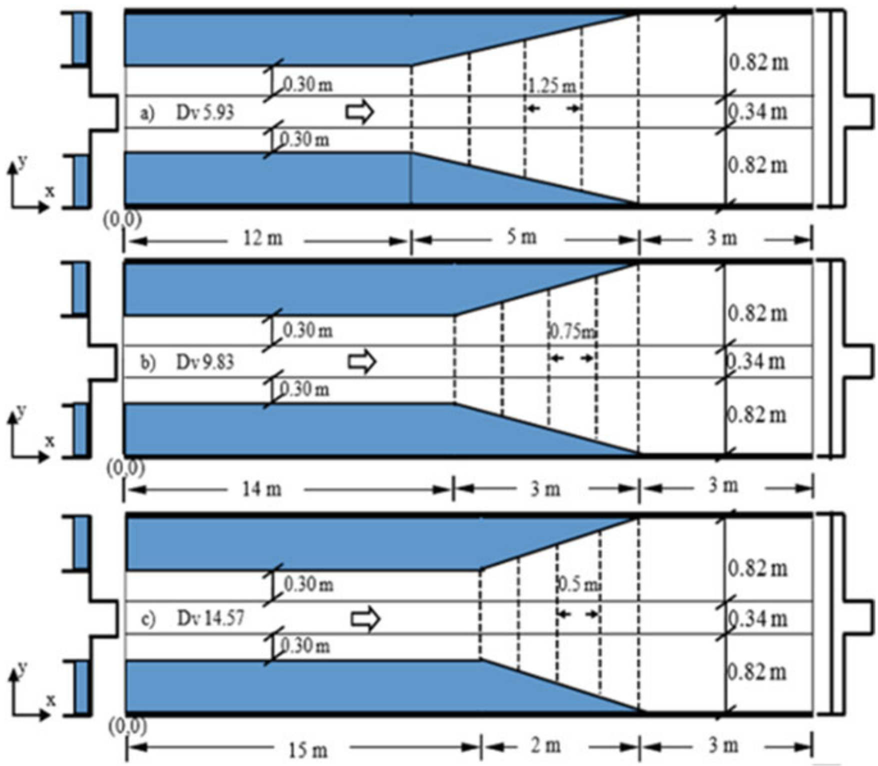

Fig. 10.3 Schematic view of compound channels with non-prismatic floodplains, diverging from 300 to 820 mm along a length of **a** 5 m (Dv 5.93), **b** 3 m (Dv 9.83) and **c** 2 m (Dv 14.57)

Table.10.1 Summary of experimental characteristics

Series	Geometry	Relative flow depth, Dr[(1)]	Discharge Q (m^3/s)	Fr	Re ($\times 10^5$)
Dv 5.93	Diverging angle = 5.93° (5 m diverging reach)	0.15,0.20,0.25 0.30,0.40,0.50	0.027, 0.032, 0.037, 0.043, 0.055, 0.067	0.211–0.581	0.471–1.949
Dv 9.83	Diverging angle = 9.83° (3 m diverging reach)	0.15,0.20,0.25 0.30,0.40,0.50	0.025, 0.029, 0.035, 0.041, 0.053, 0.065	0.192–0.544	0.440–1.862
Dv 14.57	Diverging angle = 14.57° (3 m diverging reach)	0.15,0.20,0.25 0.30,0.40,0.50	0.024, 0.028, 0.033, 0.040, 0.051, 0.062	0.189–0.517	0.426–1.801

[(1)] At x = 14.5 m, 15.5 m and 16 m for Dv5.93, Dv9.83, and Dv14.57, respectively,
Fr-Froude number, Re-Reynolds number

$$U_{mc} = \frac{Q_{mc}}{A_{mc}} \text{ and } U_{fp} = \frac{Q_{fp}}{A_{fp}} \tag{10.2}$$

where A_{mc} and A_{fp} denote the cross-sectional areas of the main channel and floodplain, respectively. The percentages of flow carried by both subareas are then obtained. Here, the total discharge is utilized as a divisor for calculating percentage discharge using Eq. 10.3.

$$\frac{Q_{mc}}{Q} \times 100 = \%Q_{mc} \text{ and } \frac{Q_{fp}}{Q} \times 100 = \%Q_{fp} \tag{10.3}$$

The percentages of flow carried by the floodplain ($\%Q_{fp}$) are plotted versus longitudinal distance for three diverging compound channels in Fig. 10.4.

$$\%\frac{Q_{mc}}{Q} = 100 - \%\frac{Q_{fp}}{Q} \tag{10.5}$$

10.3.2 Results on Flow Distribution

In order to compare the evolution of the discharge distribution along the compound channels with non-prismatic floodplains diverging from 300 to 820 mm along 5 m, 3 m and 2 m lengths, the percentage of discharge in the floodplains were plotted (Fig. 10.4) against the longitudinal distance of diverging portion. Figure 10.4 indicates that for the same relative depth β as the divergence angle increases from $\theta = 5.93°$ to $\theta = 14.57°$, the proportion of flow on floodplains decreases.

10.4 Sources of Data

For the development of the model, data has been collected from the present experimental channels and the data from University Catholic de Louvain diverging experimental channel (Bousmar et al. 2006) and from University of Tehran (Yonesi et al. 2013) on smooth diverging compound channel data. The geometric and hydraulic parameters of all the diverging compound channels are presented in Tables 10.2 and 10.3.

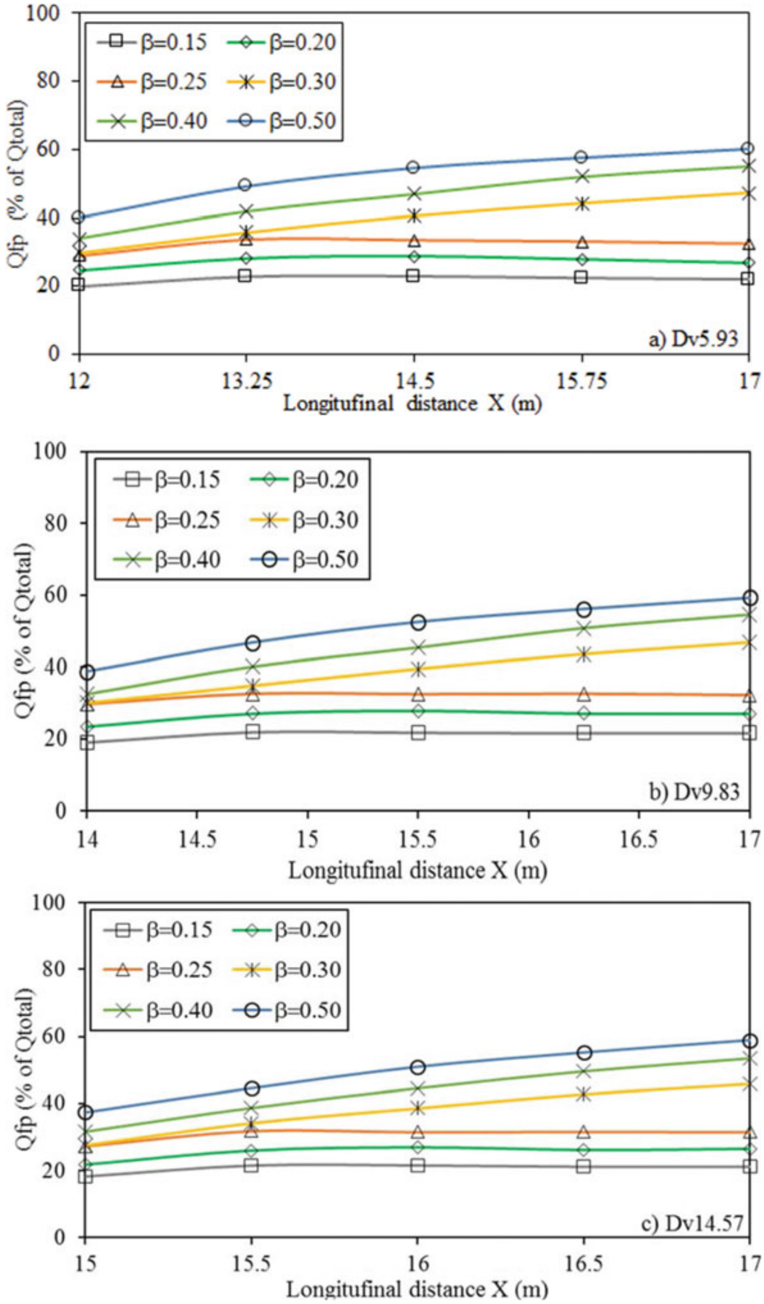

Fig. 10.4 In steam-wise direction for the diverging portion, percentage of flow at floodplain computed from the total flow **a** Dv5.93 series, **b** Dv9.83 series and **c** Dv14.57 series

Table.10.2 Details of geometric parameters collected from experimental work and published data for diverging compound channel

Verified test channel	S_0	b in (m)	h in (m)	θ in (°)	α	δ
1	2	3	4	6	5	7
NITR data -Dv5.93	0.0014	0.34	0.113	5.93	5.82–2.76	3.01
NITR data -Dv9.83	0.0014	0.34	0.113	9.83	5.82–2.76	3.01
NITR data -Dv14.57	0.0014	0.34	0.113	14.57	5.82–2.76	3.01
B et al. -Dv3.81	0.00099	0.40	0.05	3.81	3.0–1.0	8.00
B et al.-Dv5.71	0.00099	0.40	0.05	5.71	3.0–1.0	8.00
Y-Dv3.81	0.00088	0.40	0.18	3.81	3.0–1.0	2.22
Y-Dv5.71	0.00088	0.40	0.18	5.71	3.0–1.0	2.22
Y-Dv11.31	0.00088	0.40	0.18	11.31	3.0–1.0	2.22

B et al.- Bousmar et al. (2006, Y-Yonesi et al. (2013), Longitudinal slope-S_0, Main channel width in metre- *b*, Main channel depth in metre -*h*, Diverging angle in degree - θ, Width ratio- α, Aspect ratio- $\delta = b/h$

Table.10.3 Details of hydraulic and surface parameters for diverging compound channel collected from experimental work and

Verified Test channel	Q in (m^3/s)	n	β	Re in ($\times 10^5$)	Fr
1	2	3	5	6	7
NITR data -Dv5.93	0.026–0.067	0.0095–0.0161	0.146–0.51	0.49–1.58	0.42–0.68
NITR data -Dv9.83	0.025–0.065	0.0093–0.015	0.144–0.52	0.53–1.61	0.44–0.70
NITR data -Dv14.57	0.024–0.062	0.0087–0.0136	0.142–0.51	0.58–1.93	0.51–0.82
B et al. -Dv3.81	0.012–0.020	0.0053–0.025	0.218–0.51	0.34–1.39	0.38–0.86
B et al.-Dv5.71	0.012–0.020	0.0076–0.027	0.253–0.54	0.34–1.30	0.25–0.66
Y-Dv3.81	0.037–0.0615	0.0121–0.0211	0.142–0.36	1.43–1.93	0.24–0.33
Y-Dv5.71	0.037–0.0615	0.0129–0.0207	0.142–0.35	1.35–1.85	0.26–0.362
Y-Dv11.31	0.037–0.0615	0.0122–0.0223	0.143–0.35	1.28–1.74	0.28–0.38

10.5 Model Development

In this research, for the development of the mathematical expression for flow distributions in DCC, multivariable regression analysis (MRA) has been adopted. Along with present experimental dataset, other researchers' dataset on DCC are considered for development of the model. 75% of the total data sets are randomly selected and utilized for the development of the model and the rest 25% of the total data sets are kept independently for the validation purpose. From the experimental results analyses, the percentage of flow in FP was found to be a function of four non-dimensional parameters as such as width ratio, relative flow depth, relative longitudinal distance and flow aspect ratio , where the non-dimensional parameters are defined as follows:

1. Width ratio (α) = *B/b*, where *B*—total width of the channel, *b*—width of the main channel
2. Relative flow depth (β) = (*H–h*)/*H*, where *H*—height of water at a particular section and, *h*—bank full depth
3. Flow aspect ratio (δ*) = *b/H* and
4. Relative longitudinal distance (*Xr*) from a reference or origin, i.e., the ratio of the distance (*l*) of the arbitrary reach or section in the longitudinal direction of the channel to the total length (*L*) of the non-prismatic channel and can be expressed as *Xr* = *l/L*

Thus, the percentage flow in the main channel can be written as follows:

$$\%Qmc = f(\alpha, \beta, \delta^*, Xr) \tag{10.6}$$

10.5.1 Single Regression Analysis

Single regression analysis (SRA) is performed to get the best relationship between the dependent parameter (%Qmc) and each individual independent parameter (α, β, δ*, *Xr*). In this method, the functional relationship between the variable has been fixed. The plot between the dependent and independent parameters shown in Fig. 10.5a–d. It has been observed from Fig. 10.5a, b, d that the %Qmc decreases linearly, logarithmically and exponentially with increase in width ratio, relative flow depth and relative longitudinal distance, respectively, for diverging compound channels. Figure 10.5c depicts that with an increase in flow aspect ratio, the %Qmc increases in the diverging compound channel by a power function.

10.5.2 Multivariable Regression Analysis

After getting the best relationship between the dependent and independent variables by SRA, multivariable regression analysis has been performed. In this method, the coefficients of each functional parameter have been generated and by multiplying these factors with each individual parameter, the equation for %Qmc has been developed as follows:

$$\%Q_{mc} = 78.5 - 7.1\alpha - 23ln\beta + 8.71\delta^{*0.55} - 31.3e^{-0.39X_r} \tag{10.7}$$

10.5.3 Validation of the Model

The developed model is validated by the 25% data which was kept separately before the development of the regression model from the present experimental channel data series and data of Bousmar et al. (2006) and Yonesi et al. (2013) data on the diverging compound channels. Figure 10.6 shows the comparison of actual %Qmc and the %Qmc computed by the developed multivariable regression model. It is clearly seen in Fig. 10.6 that the predicted values for percentage flow in the main channel lie close to the best fit line which indicates the accuracy of the present model. Further, error analysis has been performed for different diverging compound channels in the next section.

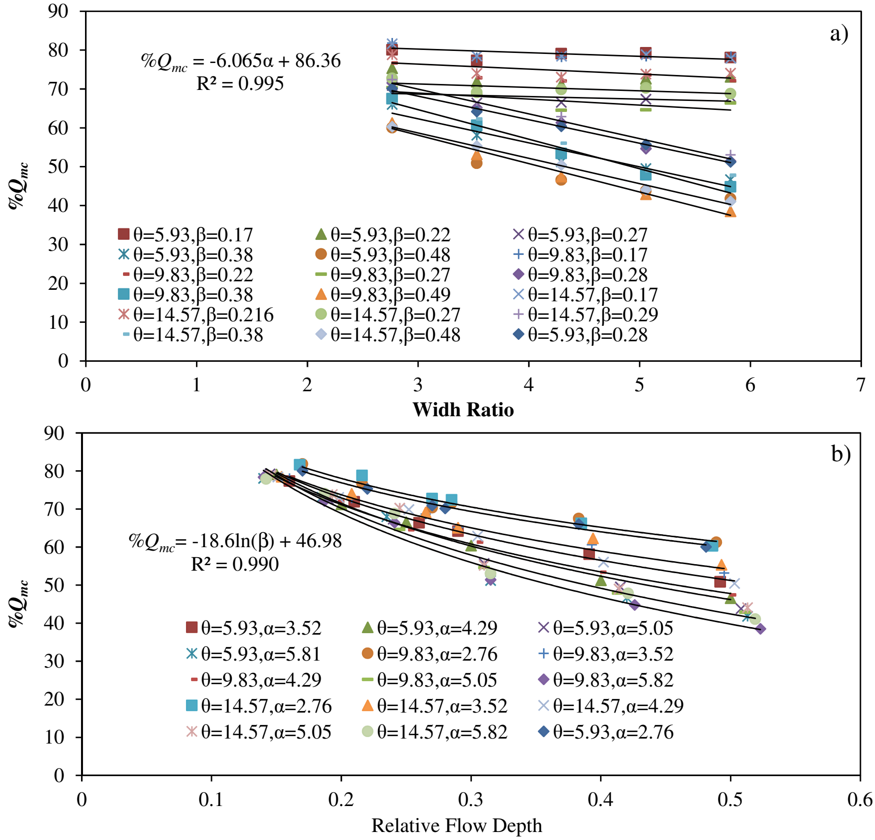

Fig. 10.5 Variation of %Qmc with different independent non-dimensional parameters **a** width ratio, **b** relative flow depth, **c** flow aspect ratio and **d** relative longitudinal distance

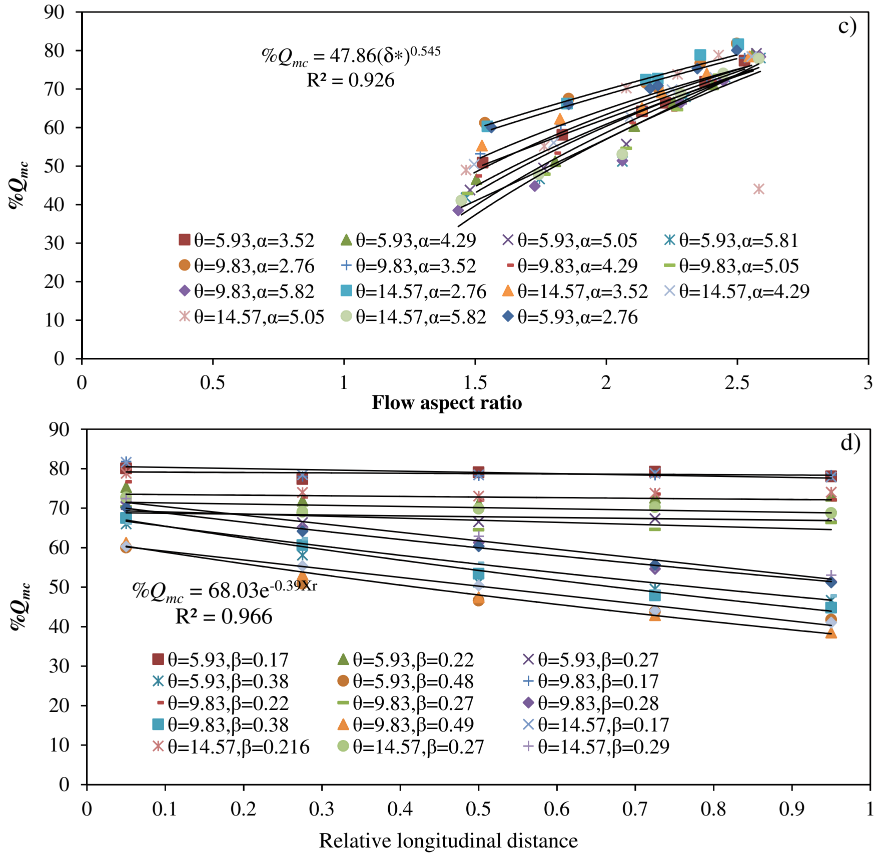

Fig. 10.5 (continued)

Fig. 10.6 Comparison of actual %Qmc and predicted %Qmc for different diverging compound channels

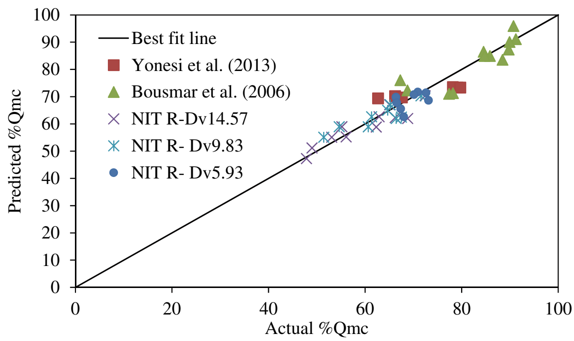

Table.10.4 Error in the computation of %Qmc by the present approach in different diverging compound channels

Test channels	MPE	MAPE	RMSE	I_d	E
NITR Dv5.93	-3.62	2.78	0.0071	0.86	0.90
NITR Dv9.83	-4.81	3.12	0.0085	0.93	0.96
NIT R Dv14.57	3.76	3.22	0.0076	0.88	0.91
Bousmar et al. (2006)	4.63	4.35	0.0092	0.84	0.86
Yonesi et al. (2013)	−2.81	2.58	0.0065	0.89	0.92

10.6 Error Analysis

To check the strength of the present model, the error analysis is performed in terms of statistical parameters such as mean percentage error (MPE), mean absolute percentage error (MAPE), root mean square error (RMSE), index of agreement (I_d) and Nash–Sutcliffe coefficient (E). The detail definition of different error analysis term may be found in Das and Khatua (2018c) and Devi et al. (2016). Table 10.4 shows the error analysis results for the different diverging compound channel. The MPE values lie between -5% to + 5% and MAPE values are less than 5% for all diverging compound channels. From Table 10.4, it also can be seen that the I_d and E value are greater than 0.85 for all diverging channel cases which depict the accuracy of the developed model.

10.7 Conclusions

In the diverging compound channel, the percentage flow in the main channel found to increase linearly, logarithmically and exponentially with increase in width ratio, relative flow depth, and relative longitudinal distance. But with the increase in flow aspect ratio the percentage flow in the main channel found to decrease by a power function. The developed multivariable regression model found to provide good results with the present experimental channel data and other researchers' data on diverging compound channels. In order to check the strength of the present model, error analysis has been performed in terms of mean percentage error (MPE), mean absolute percentage error (MAPE), root mean square error (RMSE), index of agreement and Nash-Sutcliff coefficient (E). The MAPE value found to be less than 5%, and RMSE value less than 0.0095 and I_d value greater than 0.85, which indicates the good strength of present model for prediction of flow distributions in the diverging compound channels.

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