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Evaluation of separate channel methods for discharge computation in asymmetric compound channels

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ABSTRACT

Some experimental results from the Fluid Mechanics Water Channel Facility at Birzeit University, Birzeit, Palestine, were used for computing discharge using separate channel methods in asymmetrical compound channels with varying floodplain widths and step heights. Three assumed interface planes (vertical, horizontal and diagonal) between the main channel and the floodplain subsections were considered. Then discharge values in the subsections and in the whole cross-section were evaluated. None of the separate channel methods used estimated the measured discharges accurately for the total range of the floodplain to main channel depths ratio (Y_f/Y_{mc}) investigated. The best discharge prediction methods with validity ranges of Y_f/Y_{mc} ratios are presented.

1. Introduction

One of the common tasks of a hydraulic engineer is to estimate flow rate through river channels based on a recorded, estimated, or simulated water level. This is an important issue to ensure adequate water supply during normal conditions and flood mitigation and flood forecasting during overbank flow or extreme water level. A compound open-channel is a channel consisting of a main channel flanked by one or two-side floodplains and usually used for measuring the discharge in sediment-laden rivers, streams and wadis. It is called asymmetric compound channel when the main channel is flanked by one flood plain. In dry seasons or in low flows, normally the main channel conveys these flows. Floodplains are used mainly to pass the major flows during the floods [1].

Open-channels of simple cross-sectional shape, such as rectangular or trapezoidal, have been extensively studied and satisfactory equations have been derived for their analysis and design. It is possible to calculate the discharge in a simple geometrical shape by using the uniform flow formulas such as Chezzy or Manning. Even for simple geometrical shapes, the satisfactory application of the uniform flow equation requires some knowledge of the flow resistance in the form of friction factor or resistance coefficient. In a compound open-channel, the flow is much more complex than in a simple geometry due to the presence of secondary flows and vortices occurring over the vertical axis which develops along the main channel–floodplain interface [2]. The cause of these vortices is that, in the case of rivers with floodplains there may be a sudden change of depth at the transmission between the main channel and the floodplain. Moreover, the hydraulic roughness of the floodplain is very often greater than that of the main channel. The combined effects of the greater depth of the flow and smaller hydraulic roughness of the main channel can lead to significantly higher velocities than those occurring in the floodplains. There is therefore a lateral transfer of momentum from the fast flowing main channel to the floodplain at their interface [3–5]. Due to this interaction, additional longitudinal shear stresses and a bank of vortices will arise in the interface and consequently the discharge capacity of the compound section will be reduced [6]. The reduced hydraulic radius of the floodplain and the often higher hydraulic roughness result in lower velocities on the floodplains than in the main channel. These differences referred to as "turbulence phenomenon" [7]. There is therefore a lateral transfer of momentum that results in apparent shear stress.

A great deal of experimental work has been presented in order to study the structure of turbulent flows in compound channels [8–13]. Many researchers [14–16] elaborated on the complexity of hydraulic structure of compound channels. Furthermore, others [17,18] had further investigations in this regard by considering the velocity profile distribution and the prominent effect of roughness coefficient on the discharge distribution in compound channels. In compound channels, a large exchange of momentum may occur between generally the faster flow in the main river and

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Nomenclature

A	Total cross sectional area of flow
B	Bottom width of the approach channel
B_f	Floodplain channel width
B_0	Bottom width of the upstream channel
n	Manning roughness coefficient
P	Wetted perimeter of the total cross-section
Q	Total discharge (m^3)
$R = A/P$	Hydraulic radius of the total cross-section
S_0	Channel bottom slope
Y_f	Floodplain water depth
Y_{mc}	Main channel water depth
Y_r	Relative depth which is equal to the Y_f/Y_{mc} ratio
Z	Step height
$\beta;\theta$	Entrance angles.

the slower flow in the flood plain. This produces a transverse shear layer influencing the flow in both the river and flood plain section.

Separate channel methods are developed to estimate the discharge capacity in straight, compound open channels. The momentum transfer mechanism is taken into account as a product of the apparent shear stress. Comparisons with other models indicate that separate channel methods are simple in manipulation and have a reasonable accuracy for engineering purposes.

The aim of this study is to evaluate the separate channel methods for discharge computation in asymmetric rectangular compound channels for nine different models.

2. Theoretical considerations

In this study, an asymmetric compound channel is divided into a main channel and a floodplain along some imaginary interface (V, H and D) as suggested by Wormleaton et al. [19,20]. Six methods using the vertical, horizontal and diagonal division planes were used for the estimation of discharge capacity. The methods of subdivision have been suggested in the literature [21,22]. These methods differ, however in the assumptions they make regarding the location and nature of the imaginary interface plane between the main channel and floodplain. The most commonly used subdivisions for an asymmetric rectangular compound channel are shown in Fig. 1, where B_0 is the upstream channel width, B is the main channel width, B_f is the floodplain channel width, h is the main channel water depth and Z is the main channel step height.

The Manning equation is widely used to compute the discharge in open-channel flows. The Manning equation is

$$Q = \frac{A}{n} R^{\frac{2}{3}} \sqrt{S_0} \tag{1}$$

where Q is the total discharge (m^3), A is the total cross sectional area of flow, R ($=A/P$) is the hydraulic radius of the total cross-section, P is the wetted perimeter of the total cross-section, S_0 is the channel bottom slope and n is the Manning roughness coefficient that can be obtained from Chow [23].

When over bank flow occurs, using the Manning equation for discharge computation in compound channels and considering the whole cross section as one unit this classical formula either overestimate or underestimate the discharge. Thus, the carrying capacity of the whole cross section is underestimated because the single channel method suffers from a sudden reduction in hydraulic radius as the main channel discharge inundates to flood plains [24].

The Manning equation has been applied to compound channels. However, the prediction of discharge through a compound channel

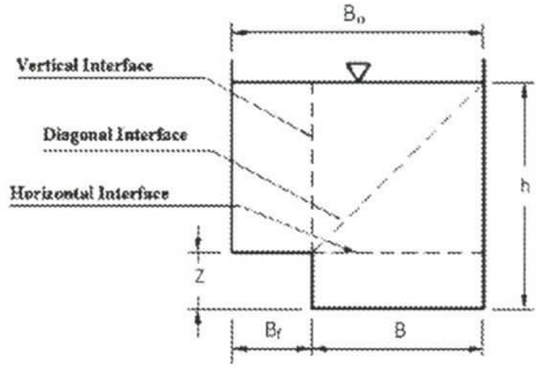


Fig. 1. Channel subdivision lines for asymmetric compound channels.

depends directly upon an accurate prediction of the roughness coefficient. The cross section is usually divided in such a way as to insure hydraulic homogeneity in flow computations.

In these subdivisions, the interface plane is assumed to pass through the junction between the main channel and floodplain where disparities in roughness and flow depth occur.

Whichever the subdivision is used, the method to compute the discharge in compound channels is based on the assumption that, the total discharge in the compound section is the summation of the discharges in the subsections, that is: by assuming that the Manning equation is applicable to each subsection separately, then the total discharge, Q, is given as

$$Q = \sum_{i=1}^{N} Q_i \tag{2}$$

where N is the total number of subdivisions, and Q_i is the discharge obtained from Eq. (1).

2.1. Separate channel methods

Separate channel methods (SCMs) are the standard discharge calculation methods in which the compound channel is simply divided by vertical or horizontal or diagonal interfaces as shown in Fig. 1.

Then the discharge in each subsection is calculated by using the Manning equation. In all separate channel methods, the interface plane is never considered in the wetted perimeter of the floodplains, but the difference in methods of computation arises from the fact that the interface is either included to or excluded from the wetted perimeter of the main channel. Once the individual discharges in the main channel and floodplain subsections for any assumed interface are computed, they are summed to obtain the total discharge of the compound channel. In the analysis to be performed, six different discharge calculation methods will be used as follows: SC–SEV, SC–SEH, SC–SED, SC–SIV, SC–SIH, SC–SID.

In naming and using the short-hand notation, SC stands for separate channel, S stands for standard computation methods, E, if the interface is excluded from the wetted perimeter of the main channel and I, if the interface is included to the wetted perimeter of the main channel. On the other hand, V, H and D stand for vertical, horizontal and diagonal interfaces, respectively.

In an asymmetric compound channel, the N value in Eq. (2) is 2 and Q is calculated as follows:

For an asymmetric compound channel,

$$Q = Q_{mc} + Q_f \tag{3}$$

$$Q_{mc} = \frac{A_{mc}}{n} R_{mc}^{\frac{2}{3}} \sqrt{S_0} \tag{4}$$

Table 1
Geometrical properties of the asymmetric compound channel models.

Types of models	B (cm)	Z (cm)	B_f (cm)	B_0 (cm)	Θ (°)	β (°)	B_0/B_f (−)	B_0/Z (−)	B_0/B (−)	B_f/Z (−)	B_f/B (−)	B/Z (−)
$B_{10}Z_2$	10	2	20	30	26.57	153.43	1.50	15.00	3.00	10.00	2.00	5.00
$B_{10}Z_4$	10	4	20	30	26.57	153.43	1.50	7.50	3.00	5.00	2.00	2.50
$B_{10}Z_6$	10	6	20	30	26.57	153.43	1.50	5.00	3.00	3.33	2.00	1.67
$B_{15}Z_2$	15	2	15	30	26.57	153.43	2.00	15.00	2.00	7.50	1.00	7.5
$B_{15}Z_4$	15	4	15	30	26.57	153.43	2.00	7.50	2.00	3.75	1.00	3.75
$B_{15}Z_6$	15	6	15	30	26.57	153.43	2.00	5.00	2.00	2.50	1.00	2.5
$B_{20}Z_2$	20	2	10	30	26.57	153.43	3.00	15.00	1.50	5.00	0.50	10.00
$B_{20}Z_4$	20	4	10	30	26.57	153.43	3.00	7.50	1.50	2.50	0.50	5.00
$B_{20}Z_6$	20	6	10	30	26.57	153.43	3.00	5.00	1.50	1.67	0.50	3.33

$$Q_f = \frac{A_f}{n} R^{\frac{2}{3}} \sqrt{S_0} \qquad (5)$$

where $R_{mc} = A_{mc}/P_{mc}$, and $R_f = A_f/P_f$ which are the hydraulic radius of the main channel and floodplain, respectively, A_{mc} and A_f are the main channel and floodplain areas, respectively, P_{mc} and P_f are the wetted perimeters of the main channel and floodplain, respectively, $Y_f = h - Z$ and $h = Y_{mc}$, for SC–SEV, $A_{mc} = Bh$, $A_f = B_f Y_f$, $P_{mc} = (h + B + Z)$, $P_f = B_f + Y_f$; for SC–SEH, $A_{mc} = BZ$, $A_f = B_O Y_f$, $P_{mc} = (B + 2Z)$, $P_f = B_f + 2Y_f$; for SC–SED, $A_{mc} = B(Z + h)/2$, $A_f = Y_f(B_f + B)/2$, $P_{mc} = (h + B + Z)$, $P_f = B_f + Y_f$; for SC–SIV, $A_{mc} = Bh$, $A_f = B_f Y_f$, $P_{mc} = (2h + B)$, $P_f = B_f + Y_f$; for SC–SIH, $A_{mc} = BZ$, $A_f = B_O Y_f$, $P_{mc} = (2B + 2Z)$, $P_f = B_f + 2Y_f$; for SC–SID, $A_{mc} = B(Z + h)/2$, $A_f = Y_f(B_f + B)/2$, $P_{mc} = (h + B + Z + \sqrt{B^2 + {Y_f}^2})$, $P_f = B_f + Y_f$.

For example, some experimental results from the SERC Flood Channel Facility at Hydraulic Research, Wallingford, UK, were used for computing the discharge and shear stress in symmetrical compound channels with varying floodplain widths. Three assumed interface planes (horizontal, vertical, and diagonal) between the floodplain subsections and the main channel were considered. The apparent shear stresses across those interfaces were computed and the ratios of these stresses to the average main channel shear stresses were determined. Then the discharge values in the subsections and in the whole cross-section were evaluated. The results showed that the performance of these computation methods depends on their ability to accurately predict apparent shear stress. Diagonal and horizontal division methods provided better results than the vertical division method, with the diagonal method giving the most satisfactory results [22].

Using the experimental observations and the data from a natural compound river channel, Myers et al. [25] showed that the SCM significantly underestimates the compound discharge for low flow depths, but becomes more accurate at greater depths for the smooth boundary laboratory data and the river data. They also found that the DCM exhibits reasonable accuracy when applied to laboratory data with a smooth floodplain, but shows significant errors of up to 35% for rough floodplain data, and up to 27% for river data [22].

Mohaghegh and Kouchakzadeh [26] presented experimental results that were compared with the computed results obtained from the nine most well-known methods for computation of discharge in a rectangular symmetric compound channel. The results demonstrate a high accuracy of the divided channel method with the horizontal division lines, while the length of the division line is included within the calculation of the wetted perimeter. Furthermore, the results show the effects of the maximum momentum transfer on the horizontal interface between flood plains and the main channel.

3. Experimental apparatus and procedure

The experiments were carried out in a glass-walled horizontal laboratory flume 7.5 m long, 0.30 m wide and 0.3 m deep with a bottom slope of 0.0025 at the fluid mechanics laboratory, Mechanical Engineering Department, Birzeit University. Discharge was measured volumetrically with a flow meter with 0.1 l accuracy. A point gauge was used along the centerline of the flume for head measurements. All depth measurements were done with respect to the bottom of the flume.

Models of asymmetric rectangular compound cross sections were fabricated from Plexiglas and placed at about mid length of the laboratory flume. Fig. 2 shows the plan view, longitudinal profile and cross section of the models with symbols designating important dimensions of the model elements. The dimensions of the models used in the experiments and all of the related dimensionless parameters are given in Table 1. In this study, model types tested are denoted by B_iZ_j ($i = 10, 15, 20$; $j = 2, 4, 6$). Here B and Z are the width and the step height of the main channel of the asymmetric compound cross section, respectively.

The required experiments first were conducted in the models of smallest $B(=10$ cm) with varying Z values (=2 cm, 4 cm and 6 cm) and then B was increased to 15 cm at the required amount of Z (=2 cm, 4 cm and 6 cm), and finally for $B = 20$ cm with the same three values of Z. The entrance angles, θ and β, were 26.565° and 153.35°, respectively. The transition length was twice of the floodplain width, B_f. The discharge values, Q, and the flow depths, h, tested in this study varied between 0.0039 m^3/s–0.0144 m^3/s, and 0.047 m and 0.136 m, respectively.

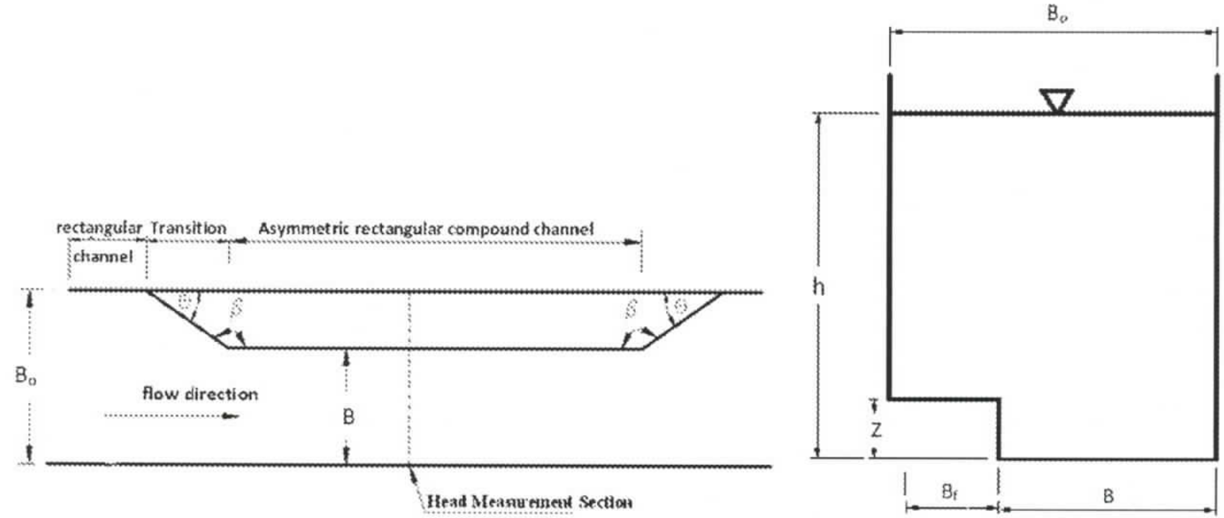
4. Results and discussions

In the subsequent sections, the variations of measured and calculated discharges with each other are graphically presented in Figs. 3–11. In each figure, the ranges of B/Z, B_f/B, Y_f/B_f and Y_f/Y_{mc} ratios are shown.

4.1. Analysis of the data of model $B_{10}Z_2$ as a sample

Fig. 3 presents the comparison of separate channel methods applied to model $B_{10}Z_2$ with $0.145 \le Y_f/B_f \le 0.450$ and $0.592 \le Y_f/Y_{mc} \le 0.818$. At high floodplain depths that is for small and high Y_f/B_f values, the method SC–SIV estimates the discharge better than the others. As the depth of the flow increases the momentum transfer and hence the apparent shear stresses decrease over the vertical interface for a given step height. This is the reason why SC–SIV gives quite good results at low floodplain depths.

In all the interface included methods, it is assumed that the interface acts like a solid boundary and the apparent shear stress along the interface is equated to the shear stress along the boundary [19]. Thus, this assumption results in an overestimation of discharge especially at high floodplain depths. Although the results of Wormleaton et al. [19] show that at low floodplain depths, the apparent shear stresses across the vertical interface planes for symmetrical compound sections were shown to be much higher than the main channel boundary shear stresses, at high floodplain depths the physical magnitude of the apparent shear stresses cannot be as high as the boundary shear. Since the



(a) Plan view.

(b) Cross section of the asymmetric rectangular compound channel.

Fig. 2. Definition sketch of the flume used in the experiments.

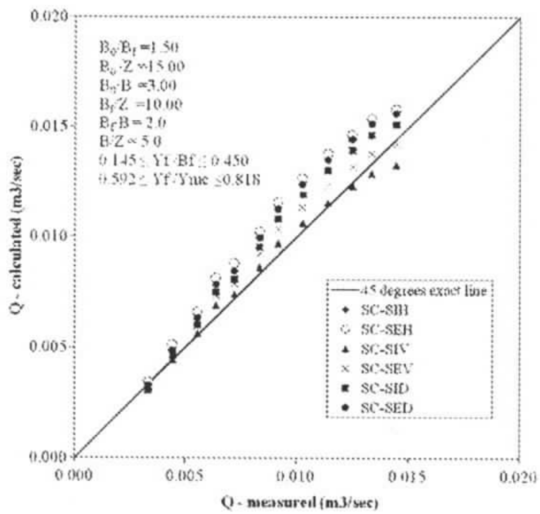


Fig. 3. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{10}Z_2$.

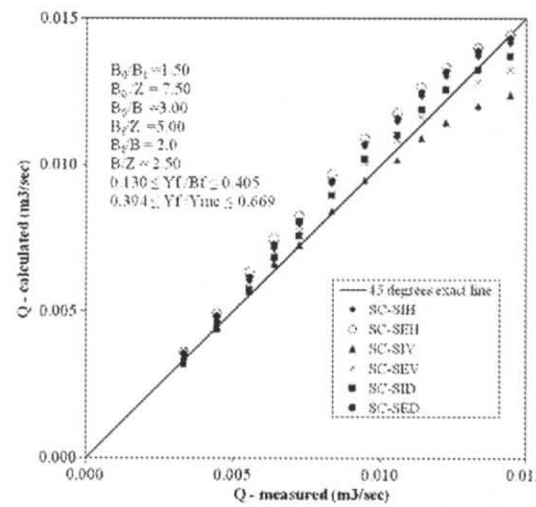


Fig. 4. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{10}Z_4$.

diagonal interface plain gives the longest boundary compared to the vertical and horizontal cases, to include the interface as a solid boundary increases the overestimation. On the other hand, the investigations by Tominaga and Nezu [27] show that the least apparent shear stresses are on an inclined plane passing through the junction between the floodplain and the main channel.

Numerical example

Following is a numerical example for model $B_{10}Z_2$ where $B = 0.10$ m, $Z = 0.02$ m and $n = 0.015$. In Table 2 in a row, the main channel depth and the measured discharge are presented in addition to the calculated discharges using the different separate channel methods by utilizing Eqs. (3)–(5) and the definition of each separate channel method described in Section 2.1.

4.2. Analysis of the data of other models

From the inspection of Figs. 3–11, one can state that almost all of the methods applied overestimate the discharge for the channels of $Z = 2$ cm. As the Z value of the channel increases to first 4 cm and then 6 cm, the locations of the calculated discharge data on the related figures fall downward and approach to the best fit line. Especially in the channels of $Z = 6$ cm at high floodplain depths almost all of the methods underestimate the discharge.

Another important result that can be stated from the above mentioned figures is that the methods in which the interface excluded from the wetted perimeter of the main channel give always larger discharges than the same method of including the interface as expected from the Manning equation.

The SC–SEH method overestimates the discharge for all models with Z values equal to 2 and 4 cm, while it almost estimates exactly the discharge for models with Z equal to 6 cm. This means that as the step height increases, the SC–SEH model estimates the discharge more accurately than the other models. This result agreed with the experimental results presented by De Marchis and Napoli [28] that were compared with the computed results obtained from the nine most well-known methods for

Table 2
Numerical example for $B_{10}Z_2$ model.

h (m)	Q-measured (m^3/s)	Q-calculated (m^3/s)					
		SC–SEV	SC–SEH	SC–SED	SC–SIV	SC–SIH	SC–SID
0.110	0.0144	0.0142	0.0158	0.0157	0.0133	0.0157	0.0151
0.108	0.0133	0.0138	0.0154	0.0152	0.0129	0.0153	0.0147
0.105	0.0125	0.0132	0.0147	0.0145	0.0123	0.0146	0.0140
0.101	0.0114	0.0124	0.0138	0.0135	0.0116	0.0137	0.0130
0.096	0.0103	0.0113	0.0127	0.0124	0.0106	0.0125	0.0119
0.091	0.0092	0.0104	0.0115	0.0112	0.0097	0.0114	0.0108
0.085	0.0083	0.0092	0.0103	0.0099	0.0086	0.0101	0.0095
0.078	0.0072	0.0079	0.0088	0.0085	0.0074	0.0087	0.0081
0.075	0.0064	0.0074	0.0082	0.0079	0.0069	0.0081	0.0075
0.067	0.0056	0.0060	0.0066	0.0063	0.0056	0.0065	0.0060
0.059	0.0044	0.0047	0.0051	0.0049	0.0044	0.0050	0.0046
0.049	0.0033	0.0032	0.0034	0.0033	0.0031	0.0033	0.0030

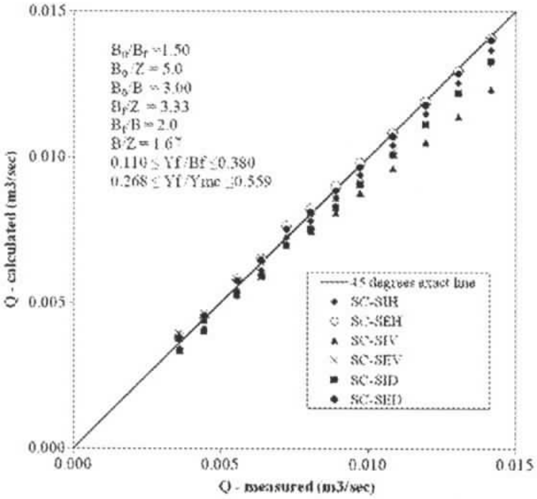


Fig. 5. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{10}Z_6$.

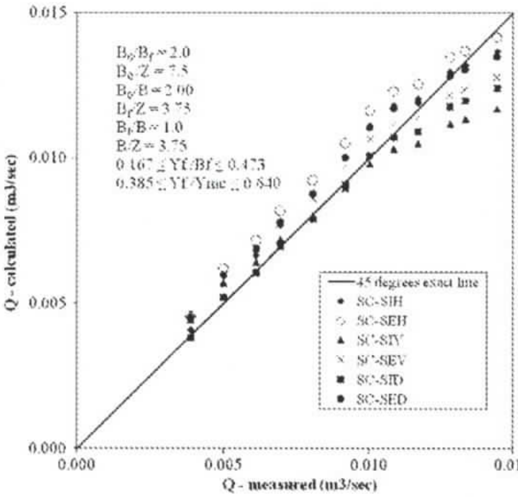


Fig. 7. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{15}Z_4$.

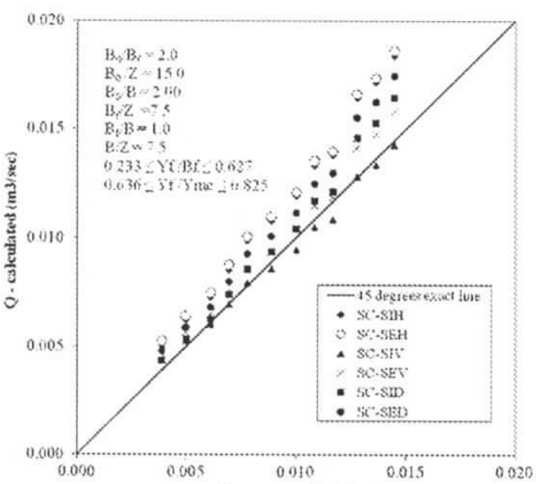


Fig. 6. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{15}Z_2$.

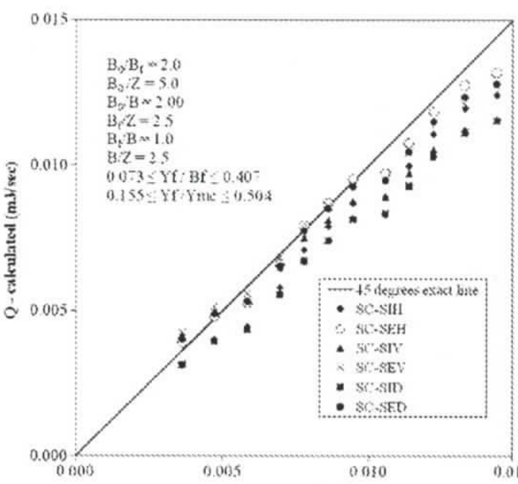


Fig. 8. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{15}Z_6$.

computation of discharge in a compound channel. Their results demonstrated a high accuracy of the divided channel method with the horizontal division lines. Furthermore, the results show the effects of the maximum momentum transfer on the horizontal interface between the main channel and flood plains, while further angular distance from the horizontal interface toward the vertical interface between main channel and flood plains causes gradual decrease of momentum transfer effects.

Table 3
Suitable and best discharge computation methods for models tested.

Model type	$B_f/B\,(-)$	$B/Z\,(-)$	Range of Y_f/Y_{mc}	Range of Y_f/B_f	Suitable methods	The best prediction method
$B_{10}Z_2$	2.00	5.00	0.661–0.815	0.195–0.44	SIV, SEV, SID	SIV
$B_{10}Z_4$	2.00	2.50	0.394–0.545	0.13–0.24	SID, SIV, SIH	SID
			0.545–0.633	0.24–0.345	SIV, SID, SEV	SIV
			0.633–0.664	0.345–0.395	SEV, SID, SIV	SEV
$B_{10}Z_6$	2.00	1.67	0.268–0.394	0.11–0.195	SIV, SED, SEH	SIV
			0.394–0.483	0.195–0.280	SED, SEH,	SED
			0.483–0.559	0.280–0.380	SEH, SED, SIH	SEH
$B_{15}Z_2$	1.00	7.5	0.636–0.756	0.233–0.413	SIV, SID, SEV	SIV
			0.756–0.785	0.413–0.487	SEV, SIV, SID	SEV
			0.785–0.825	0.487–0.627	SIV, SEV, SID	SIV
$B_{15}Z_4$	1.00	3.75	0.385–0.615	0.167–0.427	SID, SIV, SIH	SID
			0.615–0.640	0.427–0.473	SED, SIH, SEV	SED
$B_{15}Z_6$	1.00	2.5	0.155–0.259	0.073–0.140	SEH, SED	SEH
			0.259–0.400	0.140–0.260	SEV, SEH, SED	SEV
			0.400–0.504	0.260–0.407	SEH, SED, SEV	SEH
$B_{20}Z_2$	0.50	10.00	0.574–0.706	0.270–0.48	SID, SIV	SID
			0.706–0.821	0.48–0.920	SIV, SID, SEV	SIV
$B_{20}Z_4$	0.50	5.00	0.286–0.452	0.16–0.33	SEH, SIV, SED	SEH
			0.452–0.649	0.33–0.74	SIV, SID	SIV
$B_{20}Z_6$	0.50	3.33	0.167–0.362	0.12–0.34	SEH, SED,	SEH
			0.362–0.400	0.34–0.40	SIH, SIV	SIH
			0.400–0.512	0.40–0.63	SIV, SID, SED	SIV

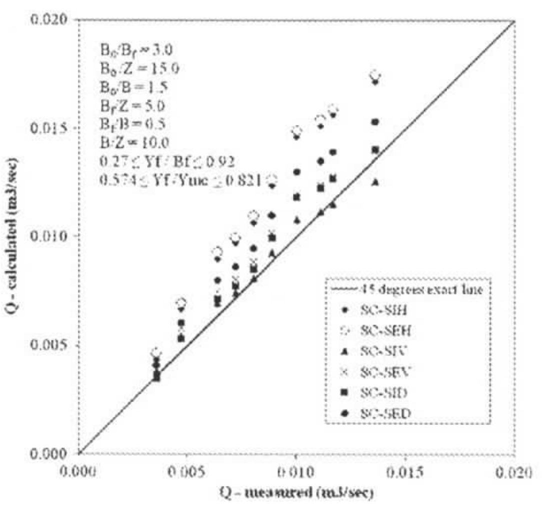


Fig. 9. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{20}Z_2$.

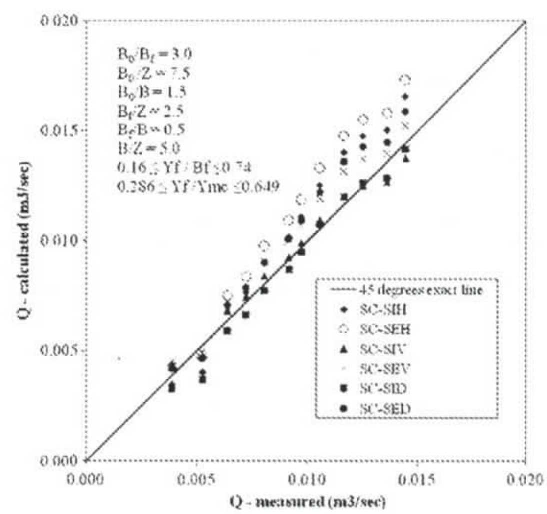


Fig. 10. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{20}Z_4$.

However, SC–SIV estimates the discharge consistently better than the other methods for Z values equal to 2 and 4 cm respectively supersedes all the methods as far as accuracy is concerned mainly for lower and intermediate values of floodplain to main channel depth ratio (relative depth, Y_r). Other models either overestimates the discharge for Z values equal to 2 and 4 cm respectively, or underestimate the discharge for $Z = 6$ cm. It is clearly noticed that there is no clear relationship among the main channel width, B, and the accuracy of the discharge computation methods for the different ranges of Y_r.

The calculated discharges are not compatible with the measured discharges in Figs. 7–10. The reason of this is, as the step height of the channel, Z, increases and B_f value gets smaller, the effect of the flow in the floodplain section on the total discharge decreases due to the decreased area of the floodplain. Therefore, the method including or excluding the interface from the wetted perimeter of the main channel has major effect on the calculated total discharge.

An overall evaluation of all the data presented in this paper reveals that the separate channel methods for discharge computation procedures in asymmetric compound channels depend on four basic factors:

(i) the ratio of the floodplain width to main channel width, B_f/B, (ii) the ratio of the main channel width to the step height, B/Z, (iii) the relative floodplain depth, Y_f/Y_{mc}, and (iv) the ratio of the flow depth in the floodplain to the width of the floodplain, Y_f/B_f.

To summarize the suitable and best discharge prediction methods for each model type Table 3 is prepared considering the calculated data which best fit the measured data given in the related figures. From this table one can select the proposed best discharge prediction method to estimate the flow discharge in a compound asymmetric channel of known dimensions considering the values of B_f/B, B/Z, Y_f/Y_{mc} and Y_f/B_f listed in Table 3.

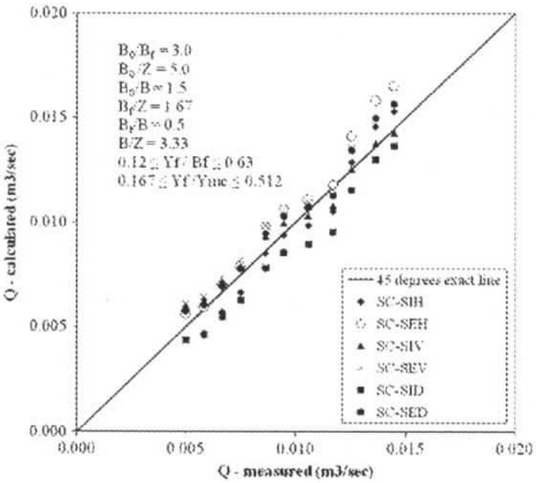


Fig. 11. Comparison of measured discharges with calculated discharges obtained from the discharge computation methods for the model $B_{20}Z_6$.

5. Conclusions

In this study, a series of laboratory experiments were conducted in nine models of asymmetrical rectangular compound cross section having different dimensions to investigate the separate channel methods for discharge computation. For this reason, flow patterns in each model were observed for a wide range of discharge. From the analysis of the experimental results, it was observed that, none of the separate channel methods used estimated the measured discharges accurately for the total range of Y_f/Y_{mc} investigated. The best calculation methods with the validity ranges of Y_f/Y_{mc} ratios are given in Table 3.

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