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# Evaluating Methods for Discharge Prediction of Straight Asymmetric Compound Channels

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**Abstract:** Accurate prediction of flow discharge in a compound channel is increasingly important in river flood risk management. This paper evaluates four most recently developed 1-D methods for discharge prediction. The four methods, which have considered the impact of momentum exchange, are Interacting Divided Channel Method (IDCM), Momentum-Transfer Divided Channel Method (MTDCM), Modified Divided Channel Method (MDCM) and Apparent Shear Stress Method (ASSM). The four methods are compared with 20 experimental datasets from the author and the literature. These datasets include both homogeneous (8 datasets) and heterogeneous (12 datasets) asymmetric compound channels, which have various width ratios ($B/b$) of 1.5 ~ 5 [channel total width $B$ at bankfull / main channel bottom $b$] and bed slopes of $2.65\times10^{-4}$ to $1.3\times10^{-2}$. This study shows that the four methods performed reasonably well (in averaged errors < 6.5%) against all the datasets except in a very steep channel with high width ratio (e.g. $B/b \geq 5$ in $S_o = 0.013$), particularly with improved discharge predictions of main channels compared with conventional divided channel method (DCM). It appears that the MDCM shows the best overall performance for homogeneous channels whereas all four methods perform similarly for heterogeneous compound channels. Close examination reveals that the error percentage by all four methods increases as increasing width ratio ($B/b$) for roughened floodplain channels, but it seems in reverse for homogeneous channels. Finally, all four methods have shown improved flow predictions of main channels compared with the DCM.

**Key words:** Overbank flow, compound channel, asymmetric compound channel, open channel, momentum exchange.

## 1. Introduction

Many rivers have a deep main channel adjoined with one or two shallow floodplains, which becomes a compound channel, or called a two-stage channel. In certain cases, e.g. in urban river landscape design, compound channels are deliberately constructed in order to increase channel flow capacity in times of floods, or to create environmental friendly space in the floodplain. The existence of floodplain enlarges the dimension of river, thus increasing the transport capacity of flow; meanwhile, the wetting soil of floodplain can provide wealthy nutrients that contribute to the reproduction and diversity of species.

Compound channels have drawn much attention from researchers and river engineers. The accurate prediction of flow in a compound channel is a prerequisite to the flood risk and environmental management of river to eliminate or mitigate environmental impact, economic or human losses.

Traditional one-dimensional (1-D) channel divisional methods, namely the Divided Channel Method (DCM), and the Single Channel Method (SCM), are still widely used in practice because of their simplicity. However, it is well-known that these methods either over-estimate or under-estimate channel discharge, particularly for zonal discharge (i.e. discharge in main channel and its floodplain) [1-7]. When a floodplain is inundated, the velocity differences between the main channel and floodplain result in a mixing shear layer due to lateral momentum exchange. Early research [1, 2, 4, 6, 8-10] indicated the importance of considering the main channel/floodplain interaction effects. Most recently, Hamidifar et al. [11] compared SCM and various DCMs with their experimental data and concluded that these methods are less accurate compared with the Coherence Method (COHM) by Ackers [12] and quasi-2D analytical

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method (called SKM) by Shiono and Knight [13].

Despite the availability of quasi-2D approach, e.g. SKM [13], and 3-D approaches that take into account the interaction between the main channel and floodplain, e.g. Refs. [14-16], they are usually complex and require more information and turbulence parameters, which are often not available. Therefore, 1-D approach has still been developing even since due to its simplicity and practical significance.

In the river management and eco-environmental design, it is required precisely to predict not only the overall discharge but also zonal discharge (the discharge in the main channel and floodplain, respectively) in a compound river channel. Recently some new developed 1-D methods have been proposed, for example, the Interacting Divided Channel Method (IDCM) by Huthoff et al. [17], the Momentum-Transfer Divided Channel Method (MTDCM) by Yang et al. [18], the Modified Divided Channel Method (MDCM) in Refs. [19-21], and the Apparent Shear Stress Method (ASSM) that was based on the force balance with the apparent shear stress proposed by Moreta and Martin-Vide et al. [22]. These methods have taken into account the effect of the lateral interaction of momentum in different forms, and they were developed and validated based on their own limit data. These methods were proposed mainly based on the data from symmetric compound channels. Most recently, Tang [23] compared these methods (except MTDCM) against a large set of data in homogenous symmetric compound channels and concluded that they can predict the total discharge reasonably well within an average error of 5%. It is worth noting that heterogeneously roughened compound channels widely exist in natural rivers, some of which exist in asymmetric form, i.e. a main channel adjoined with only one floodplain. It is important to understand how well the above-mentioned methods are compared with each other for a wide range of data in an asymmetric compound in both homogeneous and heterogeneously roughened channels, particularly for zonal discharge.

In the present paper, we compared four most recently developed 1-D methods, which are capable to predict both total and zonal discharge, namely the IDCM, MTDCM, MDCM, and the ASSM that was based on the force balance with the apparent shear stress given in [22], against a wide range of our experimental data and the data available in the literature. The 20 datasets used include both homogeneous and heterogeneously roughened asymmetric compound channel for comparison of the methods. These datasets cover different bed slopes ($2.65\times10^{-4}$~$1.3\times10^{-2}$) and a wide range of roughness ratio between floodplain and main channel, i.e. $n_f$(roughness of floodplain)/$n_c$ (roughness of main channel) = 1.0~2.0. The datasets also cover various shapes of channel cross-sections (rectangular or trapezoidal).

## 2. Method

For better reference in the subsequent sections, the cross-section of an asymmetric compound channel is illustrated in Fig. 1. $H$, $h$ and $h_f$ are the flow depths of main channel, bankfull and floodplain (subscript f), respectively. $b$ and $b_f$ denote the widths of the main channel bottom and floodplain, respectively; $S_c$ and $S_f$ represent the side slopes of the main channel and floodplain, respectively.

The four methods in this study are described as follows.

### *2.1 Interacting Divided Channel Method (IDCM)*

As proposed in [17], the zonal velocities were evaluated by considering the impact of apparent shear stress ($\tau_a$) at the interface between main channel and its floodplain, as expressed by

$$\tau_a = \frac{1}{2}\rho\alpha_m(U_c^2 - U_f^2) \tag{1}$$

Based on the force balance of each part of channels per unit length (i.e. main channel and floodplain), it follows,

$$\rho g A_c S_o = \rho f_c U_c^2 P_c + N_f \tau_a h_f \tag{2}$$

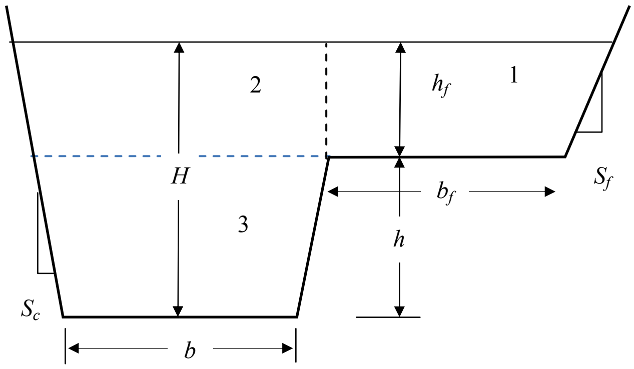


**Fig. 1 The sketched cross-section of asymmetric compound channel.**

$$\rho g A_f S_o = \rho f_f U_f^2 P_f - \tau_a h_f \quad (3)$$

Then, the zonal velocities are

$$U_c^2 = U_{c,0}^2 - \frac{\frac{1}{2}\alpha_m N_f \epsilon_c (U_{c,0}^2 - U_{f,0}^2)}{1+\frac{1}{2}\alpha_m (N_f \epsilon_c + \epsilon_f)} \quad (4)$$

$$U_f^2 = U_{f,0}^2 + \frac{\frac{1}{2}\alpha_m \epsilon_f (U_{c,0}^2 - U_{f,0}^2)}{1+\frac{1}{2}\alpha_m (N_f \epsilon_c + \epsilon_f)} \quad (5)$$

With their coefficients:

$$\epsilon_c = h_f / f_c P_c \ ; \ \epsilon_f = h_f / f_f P_f \quad (6)$$

where $U$ is the cross-sectional velocity, $A$ is the cross-sectional area, $\rho$ is the density of fluid, $S_o$ is the bed slope of channel, $\alpha_m$ is the interface coefficient, $h_f$ is the flow depth of floodplain, $P$ is the wetted perimeter, $f$ is the frictional factor, $N_f$ is the number of floodplain, the subscripts *c* & *f* denote the main channel and floodplain respectively, and the subscript (,0) represents the values calculated by the DCM with vertical interface exclusive.

Huthoff et al. [17] validated their method using 11 laboratory datasets in homogeneous channels (only two datasets of asymmetric compound channels) and recommended a constant for the interface coefficient ($\alpha_m$ = 0.02). However, Huthoff et al. did not extensively analyze the efficiency of the method for predicting zonal discharges in homogeneous channels and discharge in a heterogeneously compound channel with roughened floodplain.

### *2.2 Modified Divided Channel Method (MDCM)*

Khatua et al. [20] proposed a modified divided channel method (MDCM) based on a modified representation of the boundary shear stress on the interface between the main channel and its adjacent floodplain. By considering the net force on the main channel, which should be affected by the flow of floodplain, the wetted perimeter of main channel should be enlarged. On the other hand, the wetted perimeter of floodplain should be reduced by taking consideration of the accelerating force from the flow of main channel on floodplain. Therefore, from the force balance of each part of channels per unit length (i.e. main channel and floodplain), it follows,

$$P_c \tau_c + X_c \tau_c = \rho g A_c S_o \quad (7)$$

$$\mathrm{P}_f \tau_f + X_f \tau_f = \rho g A_f S_o \quad (8)$$

where $\tau$ is the averaged boundary shear stress, and $X$ is the interacting length at the interface, which is calculated by,

$$X_c = \frac{100 P_c}{(100 - \%S_f)[1+(\alpha-1)\beta]} - P_c \quad (9)$$

$$X_f = P_f - \frac{100(\alpha-1)\beta}{\%S_f[1+(\alpha-1)\beta]} P_f \quad (10)$$

where the geometrical parameters of $\alpha$ and $\beta$ are $B/b$ and $(H\text{-}h)/H$, respectively; $\%S_f$ is the percentage of boundary shear force of the floodplain. Through the data analysis, Khatua et al. [20] found $\%S_f$ can be calculated by,

$$\%S_f = 4.1045\ (\%A_f)^{0.6917} \quad (11)$$

Thus, the zonal discharges can be obtained by,

$$Q_c = \frac{\sqrt{S_o}}{n_c} A_c^{5/3} (P_c + X_c)^{-2/3} \quad (12)$$

$$Q_f = \frac{\sqrt{S_o}}{n_f} A_f^{5/3} (P_f - X_f)^{-2/3} \quad (13)$$

where $\%A_f$ is the percentage of the floodplain area, $n$

is the Manning coefficient, and $Q$ is the discharge. It should be noted that Eq. (11) was obtained based on experimental data that have the width ratio (α) up to 6.67 for smooth, straight symmetric compound channels.

Considering the impact of roughness of floodplain, Mohanty & Khatua [21] extended Eq. (11) for symmetric compound channels as follows:

$$\%S_f = 3.3254(\%A_f)^{0.7467}[1 + 1.02\sqrt{\beta}\log_{10}(\gamma)] \quad (14)$$

where γ is the ratio of Manning coefficients between the main channel and floodplain (= $n_f/n_c$).

Most recently, Devi et al. [19] proposed a similar equation to Eq. (11) for asymmetric compound channels as follows:

$$\%S_f = 3.576(\%A_f)^{0.717} \quad (15)$$

Eq. (15) was used in the present paper.

### *2.3 Momentum-Transfer Divided Channel Method (MTDCM)*

Based on a similar concept of evaluating apparent shear stress in [17], Yang et al. [18] introduced a momentum transfer coefficient to the calculation of apparent shear stress on the vertical and horizontal interfaces (i.e. the interface between zones 1 & 2 and between zones 2 & 3 as referred in Fig. 1, respectively), given by

$$\tau_{a12} = \frac{1}{2}\rho\alpha_{12}(U_2^2 - U_1^2) \quad (16)$$

$$\tau_{a23} = \frac{1}{2}\rho\alpha_{23}(U_2^2 - U_3^2) \quad (17)$$

where $\tau_{\alpha 12}$ and $\tau_{\alpha 23}$ are the apparent shear stress at the vertical and horizontal interfaces, respectively, and $\alpha_{12}$ and $\alpha_{23}$ are their corresponding coefficients of moment transfer. $U$ is the average velocity of sub-section, and subscripts (1, 2, 3) denote the sub-sections as shown in Fig. 1.

Based on the force balance of each sub-section (1, 2 and 3), we can obtain the averaged velocity of each sub-section, consequently giving the zonal velocity of both main channel and floodplain as follows:

$$U_f = U_1;\ U_c = (U_2A_2 + U_3A_3)/A_c \quad (18)$$

where the velocities of sub-section are

$$U_1^2 = \frac{U_{1,0}^2 + \varepsilon_f U_2^2}{1+\varepsilon_f}\ ;\ U_3^2 = \frac{U_{3,0}^2 + \varepsilon_c U_2^2}{1+\varepsilon_c} \quad (19)$$

$$U_2^2 = \frac{gA_2S_o(1+\varepsilon_c)(1+\varepsilon_f) + m_c(1+\varepsilon_f)U_{3,0}^2 + m_f(1+\varepsilon_c)U_{1,0}^2}{m_c(1+\varepsilon_f) + m_f(1+\varepsilon_c)} \quad (20)$$

with the coefficients:

$$m_c = \frac{1}{2}\alpha_{23}B_c\ ;\ m_f = \frac{1}{2}\alpha_{12}h_f \quad (21)$$

$$\varepsilon_c = m_c/f_3P_3\ ;\ \varepsilon_f = m_f/f_1P_1 \quad (22)$$

where $U$ is the cross-sectional velocity, $\rho$ is the density of fluid, $B_c$ is the width of main channel at bankfull, $f$ is the frictional factor, the subscripts 1, 2 & 3 denote sub-sections, and the subscript (,0) denotes the values based on the DCM with vertical interface excluded.

Yang et al. [18] validated their method mainly based on experimental data in homogeneous symmetrical channels and recommended an approximate constant for the interface coefficient ($\alpha_{12} \approx \alpha_{23} = 0.04$). However, they did not undertake the analysis on the efficiency of the method for predicting discharges in a wide range of asymmetric compound channels and heterogeneously compound channels with roughened floodplain.

### *2.4 Apparent Shear Stress Method (ASSM)*

The apparent shear stress ($\tau_a$) at the interface is supposed to relate to the velocity difference between the main channel and floodplain. Unlike the expression of Eq. (1), $\tau_a$ is directly related to the difference of velocity square, given by,

$$\tau_a = \frac{1}{2}\rho\alpha_d(U_c^2 - U_f^2) \quad (23)$$

where $\alpha_d$ is the apparent shear coefficient at the vertical interface. Based on the force balance of main channel and floodplain, like Eqs. (2) and (3), we can have,

$$U_c^2 = U_{c,0}^2 - \frac{8\,N_f\,h_f\,\tau_a}{\rho\,f_c\,P_c} \quad (24)$$

$$U_f^2 = U_{f,0}^2 + \frac{8\,h_f \tau_a}{\rho f_f P_f} \quad (25)$$

Various formulae have been proposed to evaluate the coefficient ($\alpha_d$) in Eq. (23). In this paper, Moreta and Martin-Vide et al. [22]'s formula for $\alpha_d$ was used because their formula was proposed based on a relatively wide range of data and demonstrated to have better performance against other methods for homogeneous compound channels [23]. They related $\alpha_d$ to the geometric parameters and relative roughness, given by,

$$\alpha_d = K_1 \frac{B}{B_c}\left(\frac{h}{B_c} Dr\right)^{-\frac{1}{3}} - K_2 Dr^{\frac{1}{3}}\left(\frac{n_f}{n_c} - 1\right)^{-\delta} \quad (26)$$

where Dr = ($H$-$h$)/$H$, the same as $\beta$ in the MDCM method. Moreta and Martin-Vide et al. [22] suggested that for symmetric channels: $K_1$ = 0.004, $K_2$ = 0.018, $\delta$ = 0.2 for small-scale flumes; $K_1$ = 0.003, $K_2$ = 0.002, $\delta$ = 2 for large-scale flumes. However, for asymmetric channels, the corresponding values of $K_1$ are 0.005 (small-scale flumes) and 0.004 (large-scale flumes), although there is not any clear criterion for the classification of flume scale. It is also worth noting that Eq. (26) is not validated by rough asymmetric compound channels and limited to $B/b$ < 6.7

## 3. Data Used in This Study

To compare the four methods in Section 2, the author used a wide range of experimental data of asymmetric compound channels including both homogenous and heterogeneously roughened floodplains. These data are from www.flowdata.bham.ac.uk (built by the author) and the literature available. Twenty datasets used cover 8 datasets of homogenous compound channel and 12 datasets of heterogeneous compound channel, with $B/b$ from 1.5 to 5.0 and $S_o$ being $2.65\times10^{-4}$~$1.3\times10^{-2}$. The datasets also cover different types of cross-sections (rectangular or trapezoidal). The details are shown in Table 1, where $N$ is the number of experiment runs, and other notations are seen in Fig. 1.

## 4. Results and Discussion

To evaluate the errors of each method against the experimental data, the absolute error percentage of predicted discharge was used as a criterion for the purpose of method evaluation. The percentage of error in predicted discharge of each flow depth is calculated by,

$$\%E_{Q,i} = \frac{|Q_{cal,i} - Q_{exp,i}|}{Q_{exp,i}} \times 100\% \quad (27)$$

where $\%E_{Q,i}$ is the error percentage of predicted discharge, and $Q_{cal,i}$ and $Q_{exp,i}$ are the predicted and observed discharge at $i$th flow depth, respectively. Therefore, the mean absolute percentage error (MAPE) of each method for an experiment is obtained by

$$\%E_Q = \frac{1}{N}\sum_{i=1}^{N}(\%E_{Q,i}) \quad (28)$$

where $N$ is the total number of runs in an experiment.

In subsequent figures, subscripts (t, c, f) denote the values for the total channel, main channel and floodplain, respectively. Fig. 2 shows the average percentage errors of predicted discharge by the four methods for all 20 datasets. The averaged percentage errors of discharge predictions for both smooth (homogeneous) and rough (heterogeneously roughened floodplain) cases are given in Fig. 3.

As shown in Fig. 2, compared with the DCM, all four methods, which have considered the effect of momentum transfer in their calculation, generally improve prediction of total discharge ($Q_t$), particularly for a steep channel with roughened floodplain, e.g. JS9, JS66 and JS46. Among the four methods, the MDCM appears to show slightly better overall prediction of $Q_t$. Furthermore, Fig. 3a demonstrates that all four methods have the combined average percentage error less than 6.5%, with the prediction of discharge being slightly better for channels of roughened floodplain than those of smooth floodplain. For channels of much roughened floodplain (e.g. $\gamma \geq 2$), all four methods show significant improvement (Fig. 3b). In such case, the strong momentum exchange occurs due to larger difference in velocity between the main channel and floodplain. Without taking into account the effect of momentum transfer, the DCM will lead to a large error,as demonstrated in Fig. 3b.

**Table 1 Summary of experimental datasets of asymmetric compound channels used.**

| Series | $N$ | $n_c$ | $n_f/n_c$ | $b_f$ (m) | $b$ (m) | $B/b$ | $S_c$ | $S_f$ | $Q_t$ (m$^3$/s) | $D_r$ |
|---|---|---|---|---|---|---|---|---|---|---|
| FCF data [24], $S_o$ = 0.001027, $h$ = 0.15 m | | | | | | | | | | |
| FCF6 | 8 | 0.01 | 1.0 | 2.25 | 1.50 | 2.70 | 1 | 1 | 0.2240-0.9290 | 0.052-0.503 |
| Joo and Seng [25], $S_o$ = 0.013, $h$ = 0.05 m | | | | | | | | | | |
| JSS | 7 | 0.008 | 1.0 | 0.20 | 0.05 | 5.00 | 0 | 0 | 0.0035-0.0058 | 0.184-0.261 |
| JS9 | 8 | 0.008 | 2.0 | 0.20 | 0.05 | 5.00 | 0 | 0 | 0.0030-0.0061 | 0.207-0.342 |
| JS66 | 7 | 0.008 | 2.0 | 0.14 | 0.05 | 3.80 | 0 | 0 | 0.0035-0.0060 | 0.235-0.365 |
| JS46 | 8 | 0.008 | 2.0 | 0.09 | 0.05 | 2.80 | 0 | 0 | 0.0034-0.0060 | 0.247-0.400 |
| University of Birmingham [24], $S_o$=0.002024, $h$ = 0.05 m | | | | | | | | | | |
| BUA | 13 | 0.0091 | 1.0 | 0.4073 | 0.398 | 2.02 | 0 | 0 | 0.0150-0.0499 | 0.184-0.529 |
| Al-Khatib et al. [26], $S_o$ = 0.0025, $h$ = 0.02, 0.04, 0.06 m | | | | | | | | | | |
| AK10-2 | 12 | 0.015 | 1.0 | 0.20 | 0.10 | 3.0 | 0 | 0 | 0.0033-0.0143 | 0.592-0.818 |
| AK15-4 | 12 | 0.015 | 1.0 | 0.15 | 0.15 | 2.0 | 0 | 0 | 0.0039-0.0144 | 0.385-0.640 |
| AK20-6 | 7 | 0.015 | 1.0 | 0.10 | 0.20 | 1.5 | 0 | 0 | 0.0058-0.0144 | 0.189-0.51210 |
| AK10-6 | 10 | 0.015 | 1.0 | 0.20 | 0.10 | 3.0 | 0 | 0 | 0.0036-0.0117 | 0.268-0.559 |
| Myers [27], $S_o$ = 0.000265, $h$ = 0.102 m | | | | | | | | | | |
| Myers | 10 | 0.0105 | 1.0 | 0.356 | 0.254 | 2.4 | 0 | 0 | 0.0063-0.0182 | 0.086-0.394 |
| James & Brown [28], $S_o$ = 0.001, $h$ = 0.0508 m | | | | | | | | | | |
| JB51 | 14 | 0.01 | 1.2 | 0.192 | 0.178 | 2.64 | 1 | 1 | 0.0041-0.0138 | 0.025-0.444 |
| JB61 | 15 | 0.01 | 1.2 | 0.368 | 0.178 | 3.64 | 1 | 1 | 0.0051-0.0142 | 0.026-0.413 |
| JB71 | 12 | 0.01 | 1.2 | 0.572 | 0.178 | 4.79 | 1 | 1 | 0.0046-0.0143 | 0.058-0.378 |
| James & Brown [28], $S_o$ = 0.002, $h$ = 0.0508 m | | | | | | | | | | |
| JB52 | 11 | 0.011 | 1.1 | 0.192 | 0.178 | 2.64 | 1 | 1 | 0.0054-0.0142 | 0.042-0.389 |
| JB62 | 14 | 0.011 | 1.1 | 0.368 | 0.178 | 3.64 | 1 | 1 | 0.0061-0.0142 | 0.079-0.351 |
| JB72 | 9 | 0.011 | 1.1 | 0.572 | 0.178 | 4.79 | 1 | 1 | 0.0057-0.0137 | 0.025-0.291 |
| James & Brown [28], $S_o$ = 0.003, $h$ = 0.0508 m | | | | | | | | | | |
| JB53 | 11 | 0.011 | 1.1 | 0.192 | 0.178 | 2.64 | 1 | 1 | 0.0061-0.0157 | 0.002-0.369 |
| JB63 | 14 | 0.011 | 1.1 | 0.368 | 0.178 | 3.64 | 1 | 1 | 0.0067-0.0144 | 0.048-0.311 |
| JB73 | 8 | 0.011 | 1.1 | 0.572 | 0.178 | 4.79 | 1 | 1 | 0.0065-0.0148 | 0.008-0.282 |

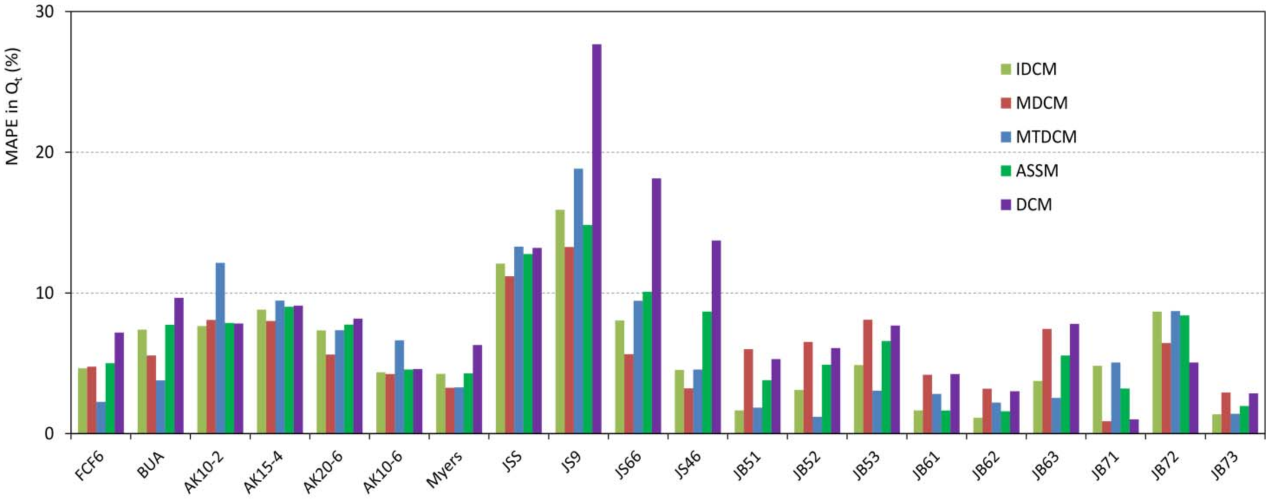


**Fig. 2 The sketched cross-section of asymmetric compound channel.**

Further analysis of zonal discharge shows that the four methods have similar and significant improvement of $Q_c$ compared with the DCM (Fig. 4a), particularly for the channels with roughened floodplain (Fig. 4b), but they have relatively high errors of $Q_f$ prediction (Fig. 4c).

Fig. 5 reveals the impact of $B/b$ on the prediction of $Q_t$ for two examples (one for mild channel, another for a steep channel). The errors of predicted discharge decrease as increasing $B/b$ for homogeneous channels (Fig. 5a), but they increase as increasing $B/b$ for heterogeneous channels, i.e. roughened floodplain (Fig. 5b). Regarding the influence of channel bed slope ($S_o$) as shown in Fig. 6, all methods have relatively smaller errors as decreasing channel slopes when $B/b$ is small (< 2.64) (Fig. 6a); however, this does not hold true for channels with large $B/b$ (Fig. 6b). Figs. 5 & 6 also show that among all the methods, the MDCM is relatively less sensitive to both $B/b$ and $S_o$.

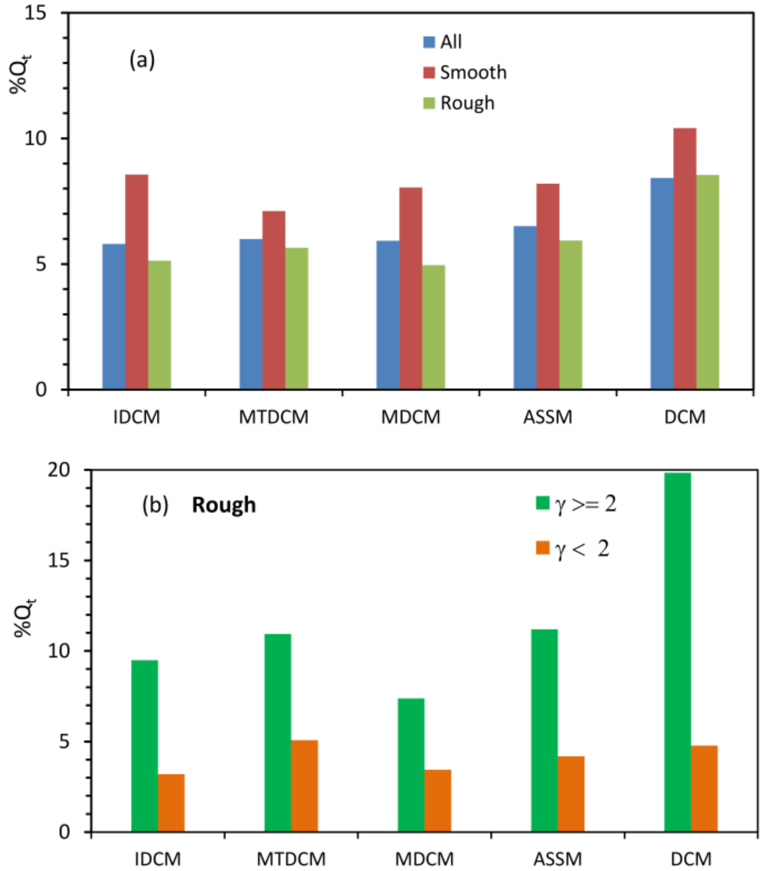


**Fig. 3 The mean absolute percentage error of $Q_t$.**

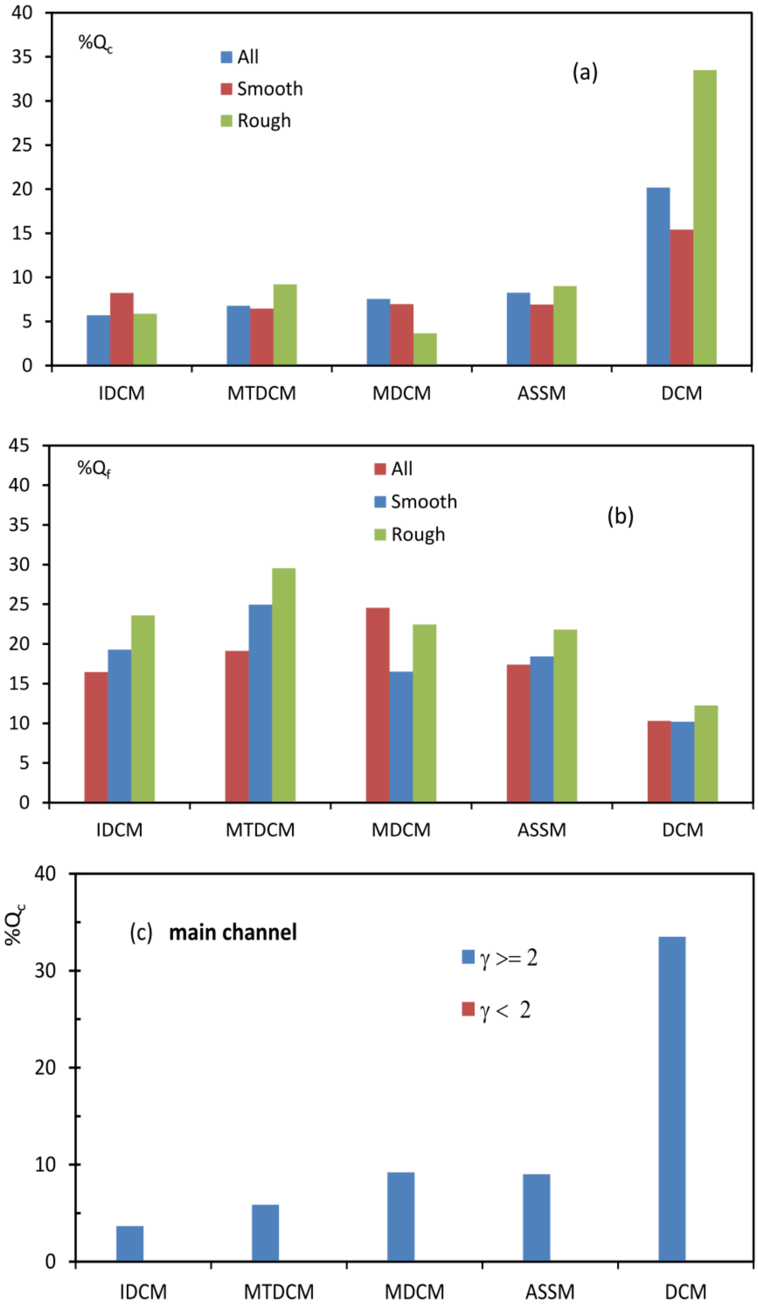


**Fig. 4 The mean error of zonal discharges ($Q_c$, $Q_f$).**

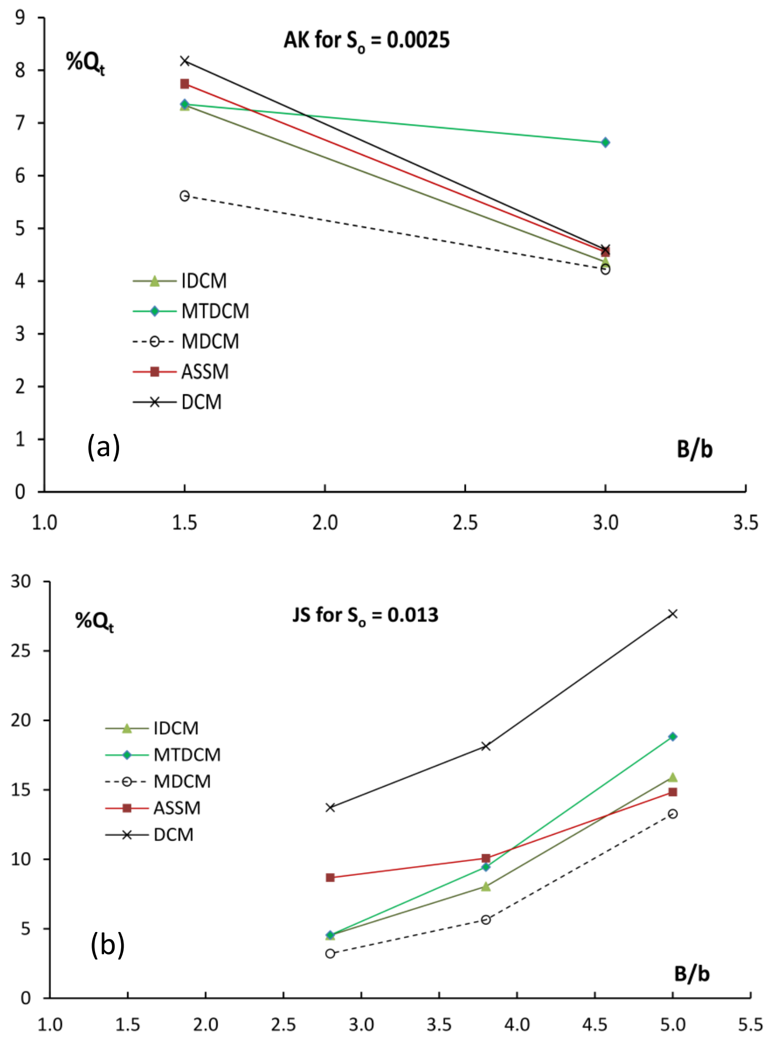


**Fig. 5 Effect of *B*/*b* on the prediction of discharge.**

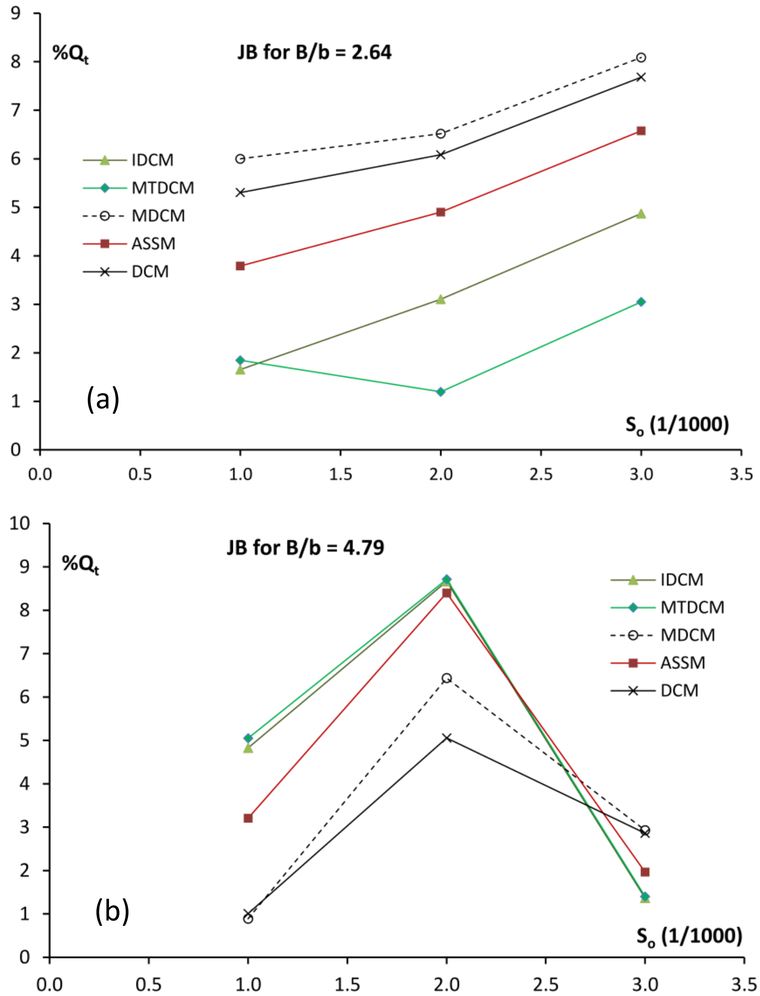


**Fig. 6 Effect of $S_o$ on the prediction of discharge.**

## 5. Conclusions

Through the comparison against a wide range of data in asymmetric compound channels, the recently developed four methods that have taken into account the effect of momentum transfer show that:

• Compared with the DCM, all four methods can be used to predict the overall discharge ($Q_t$) with the average errors about 6.5%, and the MDCM performs best overall. The four methods improve the prediction of $Q_t$ slightly better for channels of roughened floodplain than for smooth floodplain.

• The four methods can also improve the prediction of main channel discharge within the averaged error less than 12% for both homogenous and heterogeneous asymmetric channels, with the results for homogeneous channels being slightly better except the MTDCM. However, the DCM performs well for the prediction of zonal discharge in floodplain.

• The prediction error by all four methods appears to decrease as increasing $B/b$ for homogeneous channels but increases with increasing $B/b$ for heterogeneous channels. The errors of all methods can be large if the channel is very steep and has a large $B/b$ (Fig. 5b). Generally, among all five methods, the MDCM appears relatively less sensitive to both $B/b$ and $S_o$. To establish the finding above, further study may need using more datasets in the future.

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