A Method for Improving Stage Discharge Prediction in Asymmetric Compound Channels

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Abstract: *In nature, asymmetric compound channels widely exist. Accurate prediction of stage-discharge in an asymmetric compound channel becomes increasingly important in flood risk management and river environmental engineering. To predict discharge precisely, momentum exchange between the main-channel and its floodplains needs to be considered. Currently, Interacting Divided Channel Method (IDCM) has considered such exchange, but has certain errors for asymmetric compound channels, particularly for roughened floodplains. In this paper, the author proposes a new parameter of IDCM to improve flow discharge prediction. The proposed method is evaluated by a range of experimental data from the literature. 20 datasets studied include both homogeneous asymmetric compound channels (8 datasets) and heterogeneously roughened channels (12 datasets), which have different aspect ratios [the ratio of total width (B) of channel at bankfull to main-channel bottom (b) =1.5 ~ 5] and bed slopes (So = $2.65\text{x}10^{-4}$~ $1.3\text{x}10^{-2}$). This study shows that the method of using the new parameter performs well (in average errors less than 6.5%) against all the datasets except in a very steep channel with high aspect ratio (e.g. B/b $\geqslant$ 5 in S_o = 0.013). Close analysis shows that the proposed method can predict the zonal discharge ratio well for both homogeneous and heterogeneous compound channels. Finally, this method has also shown improved stage-discharge predictions of main channels over the conventional divided channel method (DCM).*

Keywords: *overbank flow, compound channel, asymmetric compound channel, stage discharge, momentum exchange*

1 Introduction

Many natural rivers and engineering channels have a cross-section with deep main-channel adjoined by one or two shallow floodplains, which forms a compound cross-sectional channel, or called a two-stage channel. In some circumstances, e.g. in urban river landscape design or river restoration, compound channels are deliberately constructed for increasing channel flow capacity in times of floods, or creating hydro- or eco-environmentally friendly space on the floodplain. Therefore, the existence of floodplain can enlarge the dimension of river, thus increasing the channel capacity of flow. Furthermore, the wetting soil of floodplain can provide wealthy nutrients for the reproduction and diversity of species. Recently, studying compound channel flow has drawn much attention from researchers and river environmental engineers.

In practice, traditional one-dimensional (1-D) channel divided methods are still widely used because of their simplicity, e.g. the Single Channel Method (SCM), and the Divided Channel Method (DCM). However, these conventional methods are well-known to either under-predict or over-predict channel discharge, particularly for zonal discharge, i.e. discharge in main-channel and its floodplains [1-4]. When a floodplain is inundated, lateral exchange of momentum occurs between the main-channel and floodplains due to their velocity differences, which will produce a mixing shear layer. Previous research indicated the importance of considering the main channel/floodplain interaction effects [1, 3, 5-8]. More recently, Hamidifar et al. [9] compared various DCMs and SCM with their experimental data. They pointed out that these methods are less accurate than the COHM (Coherence Method) by Ackers [10] and the quasi-2D analytical method, such as SKM by Shiono & Knight [11].

Although quasi-2D and 3D approaches are available, e.g. 2D by SKM by Shiono & Knight [11], 3D by [12-14], these approaches are often complicated and need lots of input information and turbulence parameters, which are often difficult to obtain. Therefore, 1-D method has been developing ever since because of its simplicity in use and practical value.

In the river engineering and hydro-environmental design and management, precise prediction of stage-discharge is required. This prediction includes both the total discharge and zonal discharge (i.e. the discharge in the main-channel and its floodplains, respectively) in a compound river channel. Recently there are some new 1-D methods to be proposed. For example, the Interacting-Divided-Channel Method (IDCM) by Huthoff et al. [15], the Momentum-Transfer-Divided-Channel Method (MTDCM) by Yang et al. [16], the Modified-Divided-Channel Method (MDCM) by [17-19], and the Energy Concept-based Method (ECM) by Yang et al. [20] and Tang [21]. These methods have all considered the influence of the lateral exchange of momentum in different forms, but they were developed and evaluated using their own certain limited data. Moreover, these methods were proposed mainly based on the data from symmetric compound channels. Most recently, Tang [22] compared the above methods (except MTDCM) against a wide range of data in homogenous symmetric compound channels, and he concluded that these methods can predict the total discharge well with a mean error of 5%. However, these methods seem to have relatively large errors for asymmetrical compound channels. Since asymmetric compound channels exist widely in many natural rivers, i.e. a main channel adjoined with only one floodplain, it is important to understand how to improve the prediction of discharge (including total and zonal discharge) in an asymmetric compound in both homogeneous and heterogeneously roughened channels, particularly for zonal discharge.

Under the consideration of apparent shear stress arising from the velocity difference between the main-channel and its floodplains, the IDCM method can predict both total and zonal discharge, and this method has shown to work reasonably well with homogeneous symmetric channels. However, the IDCM has not yet validated in a wide range of asymmetric compound channels. The preliminary study by the author shows that the IDCM appears to have some large errors for a channel with a large aspect ratio (B/b) or roughened floodplains; this may be due to a single constant used in the method. In this paper, the author extended the IDCM method by introducing a new parameter (α_m) to improve the prediction precision for asymmetrical compound channels. This new parameter is related to the aspect ratio of channel (B/b). The IDCM method based on the new parameter is tested by a wide range of data available in the literature, which include author's experimental data. The comparison includes twenty datasets, which include both homogeneous and heterogeneously roughened asymmetric compound channels. The datasets used in this study also include various bed slopes ranging from $2.65\text{x}10^{-4}$ to $1.3\text{x}10^{-2}$, and a range of roughness ratio of floodplain to main-channel, i.e. n_f (roughness of floodplain) /n_c (roughness of main-channel) = 1.0 ~ 2.0. Meanwhile, the datasets cover both rectangular and trapezoidal channel cross-sections.

2 Method

For better reference in the following sub-sections, the cross-section of an asymmetric compound channel is sketched in Figure 1, where H and h are the flow depth of main-channel and bankfull, respectively, and h_f is the flow depth of floodplain (subscript f). S_c and S_f are the side slopes of the main-channel and floodplain, respectively. b and b_f are the bottom widths of the main-channel and floodplain, respectively.

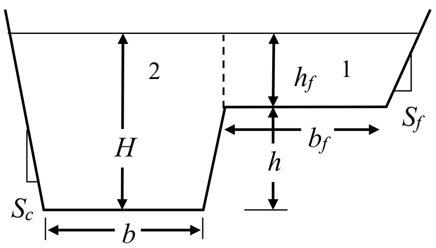

Figure 1. The sketched cross-section of asymmetric compound channel

2.1 Interacting-Divided-Channel Method (IDCM)

Huthoff et al. [15] in 2008 proposed that the apparent shear stress (τ_a) on the interface plane between the main-channel and its floodplain is evaluated by the zonal velocities, which is expressed as

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

According to the balance of force in each zone of channels per unit length, i.e. main-channel (2) and floodplain (1), it follows,

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

$$\rho g A_f S_o = \rho f_f U_f^2 P_f - \tau_a h_f \tag{3}$$

Then, the zonal velocities become

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

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

with the coefficients:

$$\epsilon_c = h_f / f_c P_c \ ; \qquad \epsilon_f = h_f / f_f P_f \tag{6}$$

where U is the cross-sectional velocity, ρ is the density of fluid, and S_o is the bed slope of channel. α_m is the interface coefficient, and h_f is the depth of flow at the interface (i.e. the flow depth of floodplain). A is the area of cross-section, P is the wetted perimeter, f is the frictional factor, and N_f is the number of floodplain. The subscripts c & f denote the main-channel and floodplain, respectively, while the subscript (,0) represents the values based on the DCM with vertical interface exclusive.

Huthoff et al. [15] validated their method using 11 experimental datasets of homogeneous channels (only limited two datasets of asymmetric compound channels) and recommended a constant for the interface coefficient (α_m = 0.02). However, they did not undertake the in-depth analysis of the method for predicting zonal discharges in homogeneous asymmetric channels and heterogeneously compound channels with roughened floodplain.

2.2 A New Parameter for Interacting Divided Channel Method (IDCM)

As can be seen from Equation (1), the apparent shear stress (τ_a) increases as increasing velocity difference between the main-channel and floodplain. This indicates that the aspect ratio (B/b) could have certain impact on the velocity difference, consequently affecting the apparent shear stress (τ_a). Meanwhile, through comparison, Huthoff et al. [15] found that the interacting coefficient (α_m) is actually not a constant, which appears to relate with the aspect ratio (B/b). In this study, the author proposed the coefficient (α_m) is linearly related with B/b, as described by the following expression:

$$\alpha_m = k\ \left(\frac{B}{b}\right) \tag{7}$$

where k is a constant, which was found to be 0.01 in this study. This method using Eq. (7) is then named as IDCM-new in the subsequent sections.

3 Data Used for Comparison

To test the IDCM-new method based on Eq. (7) in Section 2 above, the author used a wide range of experimental data of asymmetric compound channels, which include both homogenous and heterogeneously roughened floodplains. These data are from the literature available and www.flowdata.bham.ac.uk (created by the author). A total of 20 datasets used for comparison cover 8 datasets of homogenous compound channels and 12 datasets of heterogeneously compound channels, which have the aspect ratio (B/b) from 1.5 to 5.0 and the bed slope (S_o) from 2.65x10^{-4} to 1.3x10^{-2}. These datasets also cover different cross-sections of channel (e.g. rectangular and trapezoidal channels). The details of datasets are given in Table 1, where D_r = (H-h)/H, N denotes the number of experiment tests, and other notations see Figure 1.

Table 1 Summary of experimental data 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 [23], 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 [24], 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 [23], 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. [25], 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	0.189-0.5121
AK10-6	10	0.015	1.0	0.20	0.10	3.0	0	0	0.0036-0.0117	0.268-0.559
Myers [26], 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 [27], 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 [27], 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 [27], 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

4 Results and Discussions

4.1 Methods for Error Evaluation

To evaluate the errors of the proposed method, the absolute value of relative error percentage of predicted discharge was adopted as a precision criterion for the method evaluation. The error percentage for predicted discharge at a flow depth is calculated by

$$\%E_{Q,i} = \frac{|Q_{cal,i} - Q_{exp,i}|}{Q_{exp,i}} \times 100\% \tag{8}$$

where $\%E_{Q,i}$ is the error percentage of predicted discharge; $Q_{\mathrm{exp,i}}$ and $Q_{\mathrm{cal,i}}$ are the measured and predicted discharge at i-th flow depth, respectively. Meanwhile, the averaged error by the proposed method for an experiment is evaluated by

$$\%E_Q = \frac{1}{N}\sum_{i=1}^{N}(\%E_{Q,i}) \tag{9}$$

where N is the total number of tests in an experiment.

In subsequent figures, subscripts (t, c, f) represent the values for the whole channel, main-channel and floodplain, respectively.

4.2 Results and Discussion

Figure 2 illustrates the averaged percentage errors of total discharge (Q_t) by the new proposed method for all 20 datasets, along with the IDCM and DCM methods for comparison. It shows that both IDCM and the new proposed method, namely IDCM-new here, generally improve the prediction of discharge compared with the DCM for all datasets, particularly for the cases with much roughened floodplain, such as JS66 and JS46.

To closely evaluate the proposed method, the averaged percentage errors of discharge predictions for both smooth (homogeneous) and rough (heterogeneously roughened floodplain) cases are given in Figure 3.

As shown in Figure 3(a), compared with the DCM, the new proposed method (IDCM-new), which considers the effect of the momentum exchange of flow between the main-channel and floodplain, shows an overall improved prediction of total discharge (Q_t) for both smooth and rough floodplain cases, particularly for the channels with roughened floodplains. Meanwhile, Figure 3(a) demonstrates that the IDCM-new has the combined (mean) average error percentage less than 6.5%, with the predicted discharge being slightly better for asymmetric compound channels of roughened floodplain than for those of smooth floodplain. In the channels with roughened floodplain (Figure 3b), the IDCM-new shows much better prediction for relatively low roughness ratios of γ (=n_f/n_c) < 2 than for high ratios of $\gamma \geq 2$. In this study, the averaged errors for $\gamma < 2$ and $\gamma \geq 2$ are about 2.5% and 12.9% respectively, while the corresponding prediction errors by the DCM are 4.8% and 20% respectively.

For zonal discharge, the predictive percentage errors by the IDCM-new are shown in Figure 4. The proposed method shows an improved discharge prediction of main channel (Q_c) for both smooth and rough floodplain cases (Figure 4a), with the error being less than 10%, while the DCM has relatively large errors, particular in the cases of roughened floodplain. In terms of Q_f prediction, the IDCM-new appears not to show any improvement (Figure 4b), in which it is always difficult for flow measurement due to relatively low flow depth in the floodplain. However, the IDCM-new shows a good prediction of zonal discharge distribution (both Q_c/Q_t and Q_f/Q_t), as demonstrated in Figure 5. For a similar aspect ratio (B/b $\approx$ 2.8), the IDCM-new gives good percentage of zonal discharge for both smooth and roughened cases (Figures 5a & 5b), so does it for a wide respect ratio (B/b = 5) as shown in Figure 5(c). However, as seen in Figure 5 as an example, the DCM over-estimates the discharge percentage of main channel (Q_c/Q_t), but under-estimates the discharge percentage of floodplain (Q_f/Q_t), particularly in larger relative flow depths of floodplain.

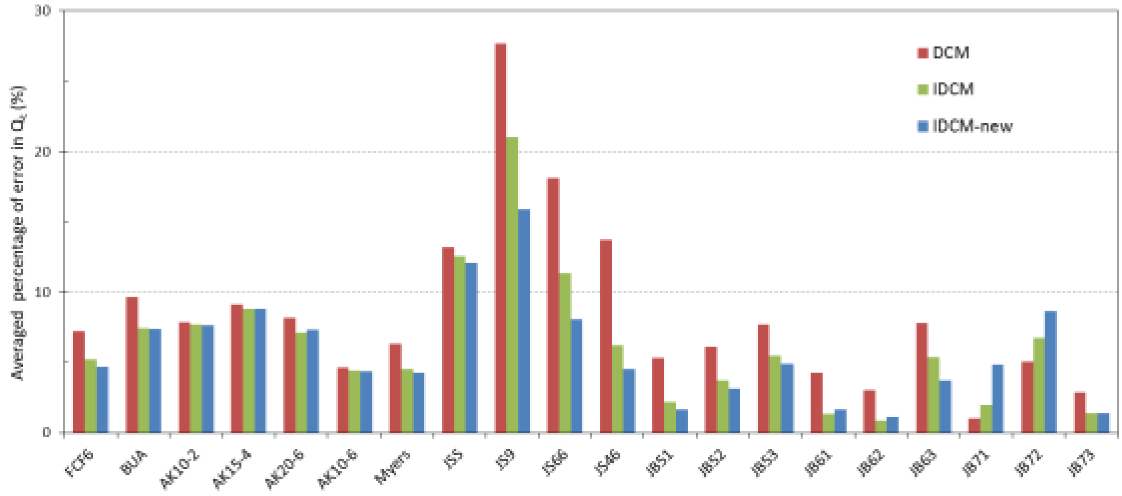

Figure 2 Averaged percentage error of total discharge (%Q_t) by the proposed method

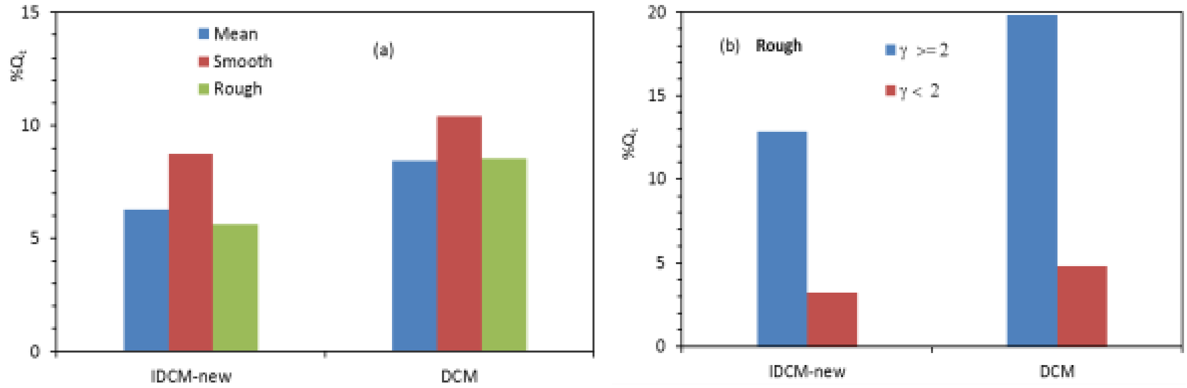

Figure 3 Averaged percentage error of Q_t

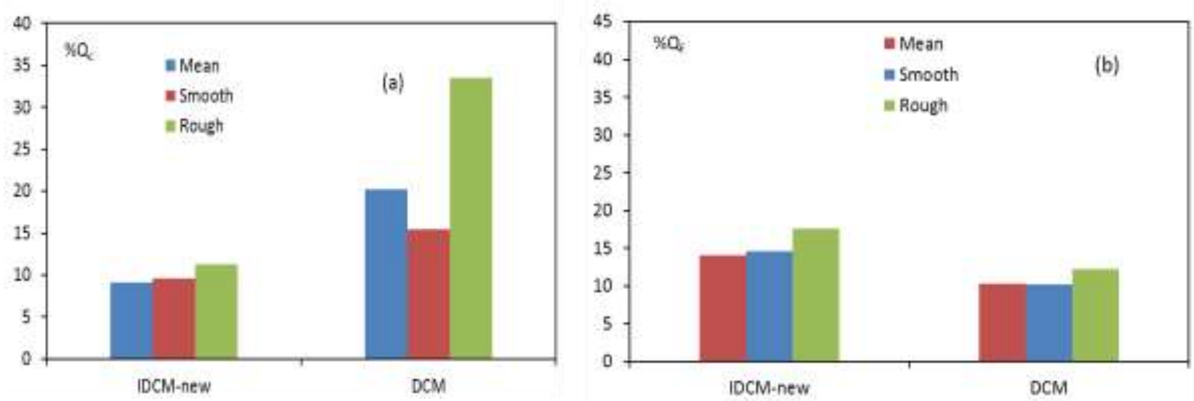

Figure 4 Averaged error percentage of zonal discharges (Q_c, Q_f)

Finally, the predicted discharge by the new proposed method agrees well with the measured discharge for all the datasets, see Figure 6. This demonstrates that the proposed method based on Eq. (7) can improve the stage-discharge prediction of asymmetrical compound channels.

5 Conclusions

Based on the evaluation of apparent shear stress on the vertical plane between the main-channel and floodplain, the zonal velocities can be described by Eqs. (4) and (5), where the interacting parameter α_m is proposed to be related to the aspect ratio of B/b, as described by Eq. (7), rather than an constant originally given by Huthoff et al. [15]. The proposed new method based on Eq. (7), namely IDCM-new in this study, has comprehensively been tested with a wide range of experimental data of asymmetric compound channels. The following points may be drawn:

- Compared with the DCM, the proposed IDCM-new method predicts the Q_t (total discharge) well with a mean error of 6.5% for both smooth and rough channels, and the new method also shows a good prediction of zonal discharge distribution (Q_c/Q_t and Q_f/Q_t).
- The IDCM-new method can also improve the prediction of main channel discharge in an averaged error of less than 12% for both homogenous and heterogeneous asymmetric channels, in which the results of roughed floodplain channels are slightly better. However, the DCM performs reasonably well for the prediction of zonal discharge in floodplain from the limited datasets of zonal discharge measured, which needs a further study in the future.
- In the channels with roughened floodplain (Figure 3b), the IDCM-new shows much improved prediction for relatively low roughness ratios of $\gamma < 2$ than for high ratios of $\gamma \geq 2$.
- Overall, the IDCM-new shows improved discharge prediction (Figure 6). This method can be used to predict both the total discharge and the zonal discharge in an asymmetric compound channel.

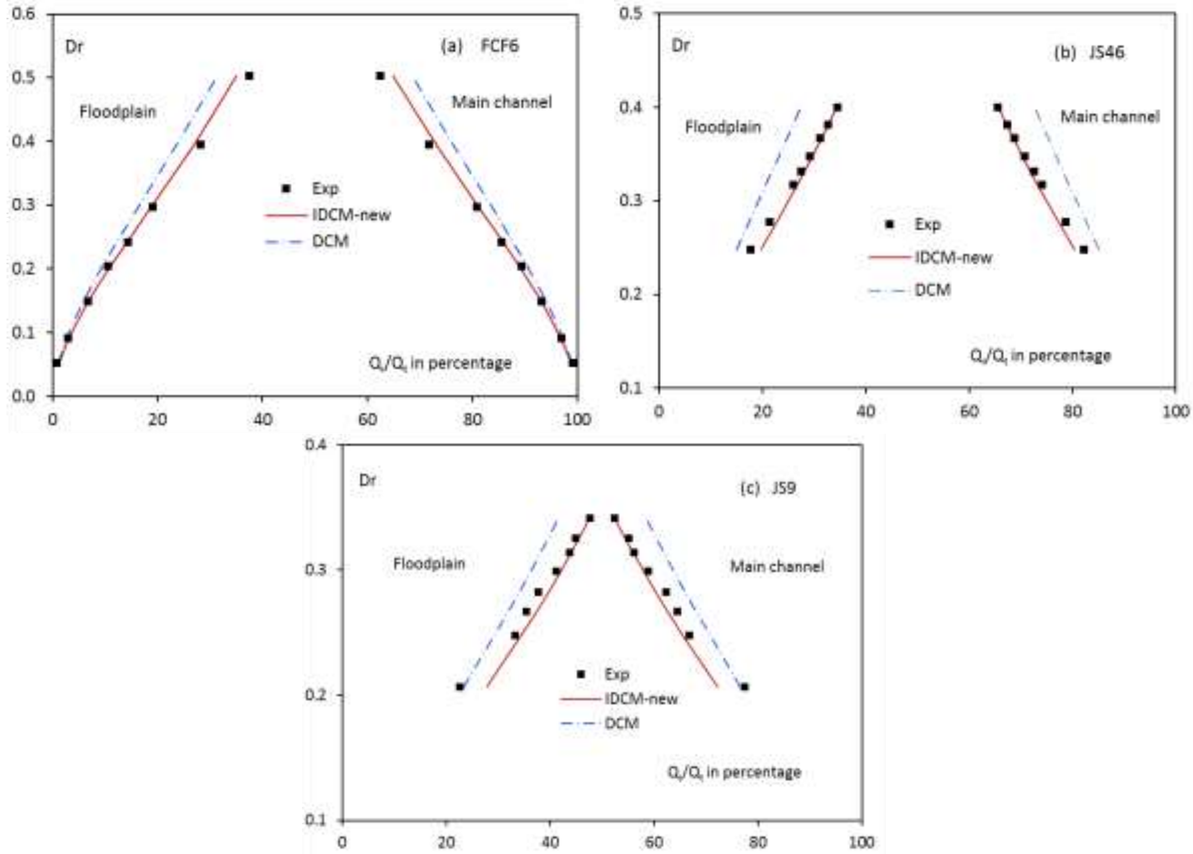

Figure 5 Effect of aspect ratio (*B*/*b*) on the prediction of discharge: (a) B/b =2.7, (b) (a) B/b =2.8, (c) B/b =5

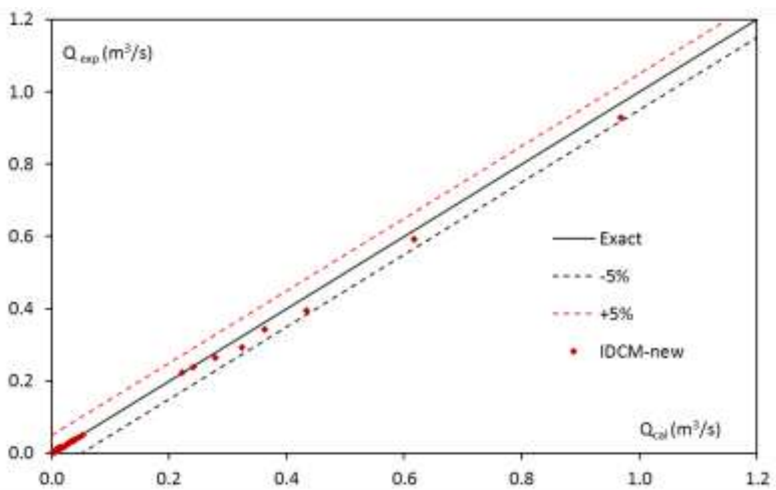

Figure 6 Comparison on the prediction of total discharge for all datasets

6 Acknowledgments

The author is grateful to the financial support by the National Natural Science Foundation of China (No. 11772270).

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