Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

COMPARISON OF DIFFERENT METHODS FOR PREDICTING ZONAL DISCHARGE OF STRAIGHT HETEROGENOUSLY ROUGHENED COMPOUND CHANNELS

XIAONAN TANG[(1)]

[(1)]Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China
xiao.tang@xjtlu.edu.cn

ABSTRACT

Accurate prediction of flow discharge in different parts of a compound river channel is increasingly important in river management, such as flood mitigation, eco-environment design, restoration and sediment transport. This paper compares four most recently developed 1-D methods, namely Interacting Divided Channel Method (IDCM), Energy Concept Method (ECM), Modified Divided Channel Method (MDCM) and Apparent Shear Stress Method (ASSM), against a wide range experimental data in this study and the data available in the literature. The 32 datasets used include heterogeneously roughened symmetric channels (22 datasets) and asymmetric channels (10 datasets) with various aspect ratios [channel total width (*B*) at bankfull / main channel bottom (*b*) =2.6 ~ 15.8], bed slopes (S_o = 4.3x10^{-4} ~1.3x10^{-2}), and ratios of Manning's roughness between floodplain and main channel (1.1 ~ 3.9). It is found that none of the methods performed well against all the datasets. Compared with the traditional Divided Channel Method (DCM), all above methods, in general, predict both the total discharge and main channel discharge reasonably well within 12%, but they have relatively large errors for the prediction of the zonal discharge, particularly for floodplain with large roughness. The ASSM has shown the best overall performance on both the total and zonal discharge prediction.

Keywords: Overbank flow; compound channel flow; heterogeneous compound channel; zonal discharge.

1 INTRODUCTION

Compound channels (or two-stage channels) with roughened floodplains widely exist in most natural rivers; in certain cases compound channels are deliberately constructed in order to increase conveyance capacity in times of floods, or create environmentally friendly space in the floodplain. 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 these methods either overestimate or underestimate channel discharge, particularly for zonal discharge (i.e. discharge in main channel and its floodplain) (Wormleaton et al.,1982; Knight et al.,1984; Tang & Knight, 2007; Yang et al., 2007). 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 (Wormleaton et al., 1982; Knight & Demetriou, 1983; Knight & Hamed, 1984; Prinos & Townsend, 1984; Christodoulou, 1992) indicated the importance of considering the main channel / floodplain interaction effects.

Despite the availability of 2-D or 3-D approaches that take into account the interaction between the main channel and floodplain, e.g. Krishnappan and Lau (1986), Shiono and Knight (1991), Cater and Williams (2008), Marjang and Merkley (2009), they are usually complex and require more information and turbulence parameters, which are not available. 1-D approach has still been developing even since due to its simplicity and practical significance.

In river management and water environmental design, it is required precisely to predict not only the overall discharge but also zonal discharge (main channel and floodplain discharge, respectively) in a compound river channel. Recently many newly developed 1-D methods have emerged, for example, the Interacting Divided Channel Method (IDCM) by Huthoff et al. (2008), the Energy Concept Method (ECM) by Yang et al. (2012), and the Modified Divided Channel Method (MDCM) by Khatua et al. (2012), Mohanty & Khatua (2014) and Devi et al. (2016). These methods had taken into account the effect of the lateral momentum exchange in different forms, and they were developed and validated based on their own limited data. Most recently, Tang (2016) compared these methods against a large set of data in homogenous compound channels and concluded that they can predict the total discharge reasonably well within an average error of 5% for symmetric compound channels, but do not for asymmetric channels, particularly in the prediction of zonal discharge. It is worth noting that heterogeneously roughened compound channels widely exist in natural rivers, so it is important to understand how good the above-mentioned methods are compared with each other for a wide range of data in heterogeneously roughened channels, particularly for zonal discharge.

In this paper, we compare four recently developed 1-D methods, namely the IDCM, ECM, MDCM, and the Apparent Shear Stress Method (ASSM) that are based on the force balance with the apparent shear stress proposed by Moreta and Martin-Vide et al. (2010), against a wide range of experimental data in this study and the data available in the literature. 32 datasets of heterogeneously roughened compound channel are used for comparison of the methods. These datasets include cases in both symmetric and asymmetric compound channels with different bed slope and a wide range of roughness ratio between floodplain to main channel. The datasets also cover various channel cross-sections (rectangular or trapezoidal).

2 METHOD

For the convenience of reference in the subsequent context, the sketched cross-sections of symmetric and asymmetric compound channels are shown in Figure 1, where *H*, *h* and h_f are the flow depth of main channel, bankfull, and floodplain (subscript *f*), respectively. *b* and b_f are the widths of the main channel bottom and floodplain, respectively; S_c and S_f are the side slopes of the main channel and floodplain, respectively.

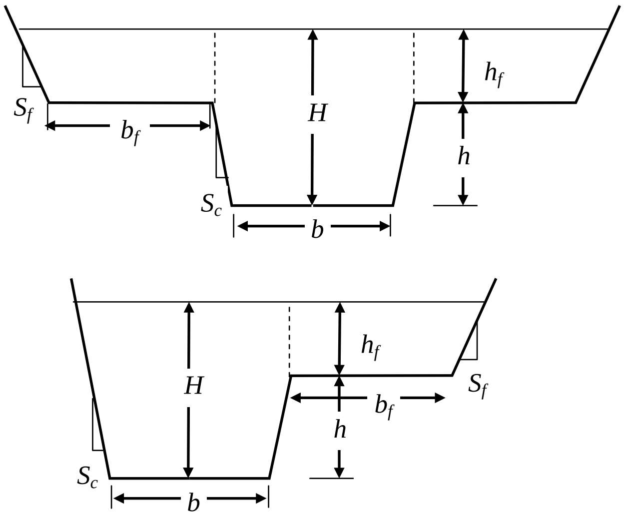

Figure 1. Sketched cross-sections of compound channels: (a) - symmetric cross-section, (b) - asymmetric cross-section.

In this study, the four methods that take into account the momentum transfer of flow between the main channel and the floodplain are summarized as follows:

2.1 Interacting divided channel method (IDCM)

As proposed by Huthoff et al. (2008), the zonal velocities were evaluated by considering the impact of apparent shear stress (τ_a) at the interface between main channel and its floodplain, as expressed by

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

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

$$\rho g A_c S_o = \rho f_c U_c^2 P_c + N_f \tau_a h_f \quad [2]$$

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

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 the coefficients:

$$\epsilon_c = h_f/f_c P_c \qquad [6a]$$

$$\epsilon_f = h_f/f_f P_f \qquad [6b]$$

Where U is the cross-sectional velocity, A is the cross-sectional area, ρ is the density of fluid, S_o is the bed slope of channel, α_m is the interface coefficient, h_f is the depth of flow at the interface (i.e. 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) denotes the values based on DCM with vertical interface excluded.

Huthoff et al. (2008) validated their method using 11 sets of laboratory data in homogeneous channels and recommended a constant for the interface coefficient (α_m =0.02). However, the efficiency of the method for predicting zonal discharges was not undertaken by Huthoff et al.

2.2 Modified divided channel method (MDCM)

Many modified division channel methods have been developed to improve the prediction of stage-discharge. Here described is the one recently proposed by Khatua et al. (2012), who quantified the boundary shear stress distribution in a compound channel based on a new parameterization of the interface shear stress between the main channel and floodplain.

$$P_c\tau_c + X_c\tau_c = \rho g A_c S_o \qquad [7a]$$

$$P_f\tau_f + X_f\tau_f = \rho g A_f S_o \qquad [7b]$$

Where τ is the averaged boundary shear stress, S_o is the bed slope of channel, A is the cross-sectional area, and X is the interacting length, which is calculated by,

$$X_c = \frac{100P_c}{(100-\%S_f)[1+(\alpha-1)\beta]} - P_c \qquad [8a]$$

$$X_f = P_f - \frac{100(\alpha-1)\beta}{\%S_f[1+(\alpha-1)\beta]} P_f \qquad [8b]$$

Where the geometrical parameters α and β are B/b and $(H-h)/H$, respectively; $\%S_f$ is the percentage of boundary shear force of the floodplain. Through the data analysis, Khatua et al. (2012) found $\%S_f$ can be calculated by,

$$\%S_f = 4.1045\ (\%A_f)^{0.6917} \qquad [9]$$

Thus, the zonal discharges are

$$Q_c = \frac{\sqrt{S_o}}{n_c} A_c^{5/3} (P_c + X_c)^{-2/3} \qquad [10a]$$

$$Q_f = \frac{\sqrt{S_o}}{n_f} A_f^{5/3} (P_f - X_f)^{-2/3} \qquad [10b]$$

Where $\%A_f$ is the percentage of the floodplain area, n is the Manning coefficient, and Q is the discharge. It is worth noting that Eq. [9] was obtained based on experimental data, which have the width ratio (α) up to 6.67 for smooth, straight and symmetric compound channels. Considering the impact of roughness of floodplain, Mohanty & Khatua (2014) extended Eq.[9] for symmetric compound channels as follows:

$$\%S_f = 3.3254(\%A_f)^{0.7467} \times (1 + 1.02\sqrt{\beta}\log_{10}(\gamma) \qquad [11]$$

Where γ is the ratio of Manning coefficient between main channel and floodplain (=n_f/n_c).
Most recently, Devi et al. (2016) developed anequation similar to Eq.[9] for asymmetric compound channels as follows:

$$\%S_f = 3.576(\%A_f)^{0.717} \qquad [12]$$

2.3 Apparent shear stress method (ASSM)

Due to the velocity difference between the main channel and floodplain, the momentum transfer exists. This can be evaluated by the apparent shear stress (τ_a) at the interface. Unlike the expression of Eq.[1], (τ_a) is directly related to the velocity difference, given by,

$$\tau_a = \frac{1}{2}\rho\alpha_d(U_{c,0} - U_{f,0})^2 \qquad [13]$$

where α_d is the interface coefficient. Based on the force balance similar to Eqs. [2] and [3], we can obtain,

$$U_c^2 = U_{c,0}^2 - \frac{8\,N_f\,h_f\,\tau_a}{\rho\,f_c\,P_c} \qquad [14a]$$

$$U_f^2 = U_{f,0}^2 + \frac{8\,h_f\tau_a}{\rho f_f P_f} \qquad [14b]$$

Various formulae had been proposed to evaluate the coefficient (α_d) in Eq. [13]. In this study, Moreta and Martin-Vide (2010)'s formula was used because their formula was proposed based on a wide range of data, and demonstrated to have better performance against other methods for homogeneous compound channels (Tang, 2016). They related α_d to the geometric parameters and relative roughness, given by

$$\alpha_d = K_1\frac{B}{B_c}\left(\frac{h}{B_c}Dr\right)^{-1/3} - K_2 Dr^{\frac{1}{3}}\left(\frac{n_f}{n_c} - 1\right)^{-\delta} \qquad [15]$$

Where $Dr = (H\text{-}h)/H$, the same as β in the MDCM method by Khatua et al. (2012), and B_c is the width of main channel at bankfull. Moreta and Martin-Vide (2010) suggested that for symmetric channels: K_1 = 0.004, K_2 = 0.018, δ = 0.2 for small-scale flumes; K_1 = 0.003, K_2 = 0.002, δ = 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.[15] is not validated by rough asymmetric compound channels and limited to B/b< 6.7.

2.4 Energy Concept Method (ECM)

Based on the energy loss and the transition mechanics of fluid in open channels, Yang et al. (2012) proposed a method for estimating the discharge in straight, symmetrical compound channels, as expressed by the following equation,

$$Q_t = Q_{c,0} + Q_{f,0} - \frac{\tau_a\,(H+h_f)(U_{c,0}-U_{f,0})}{4\rho g S_o} \qquad [16]$$

Where g is the gravitational acceleration and the subscript (,0) denotes the values using DCM. Yang et al. evaluated Eq. [16] by examining various formulae of the apparent shear stress term (τ_a), including Eqs. [1] and [13]. They recommended Eq. [13] to be used with α_d= 0.01B/b, which is proposed by Christodoulou (1992) due to its simplicity and accuracy in the calculation. Noting that the α_d proposed by Christodoulou was valued only by homogeneous compound channels, so the α_d given by Eq.[15] for the ECM method was used in this study. Furthermore, this method cannot predict the zonal discharge but the total discharge. Therefore, this method was not included in the comparison of zonal discharge.

3 DATA FOR ANALYSIS

To compare the four methods in Section 2, a wide range of different experimental data was used in heterogeneously roughened compound channels. These data were from www.flowdata.bham.ac.uk (created by the author) and the literature. A total of 32 datasets used included 22 datasets of symmetric compound channel and 10 datasets of asymmetric compound channel, with the aspect ratio (*B/b*) being 2.6 ~ 15.8 and the bed slope being S_o = 4.3x10^{-4} ~1.3x10^{-2}. The datasets also covered various channel cross-sections (rectangular or trapezoidal) either symmetric (sym) or asymmetric (asym). The details are shown in Table 1, where N_f is the number of floodplain, N is the number of experiment runs, and other notations can be referred to Figure 1. It is worth noting that Manning's coefficient (n_f) of floodplain was the averaged value for the experiments where large elements were used to roughen the floodplain.

Table 1. Details of experimental datasets of heterogeneously roughened compound channels.

Series	N_f	N	n_c	n_f/n_c	b_f(m)	b (m)	B/b	S_c	S_f	Q_t (m^3/s)	Dr
FCF data (1992), S_o= 0.001027, h =0.15 m											
FCF7	2	8	0.01	1.04-3.78	2.25	1.50	4.20	1	1	0.2160-0.5434	0.038-0.504
FCF11	2	7	0.01	1.36-3.78	2.25	1.50	4.40	2	1	0.2601-0.6066	0.096-0.505
University of Birmingham (2001), S_o=0.002024, h=0.05 m											
UB05	2	9	0.0091	1.59-5.51	0.4073	0.398	3.05	0	0	0.0148-0.0501	0.234-0.702
UB01	2	7	0.0091	1.77-2.67	0.4073	0.398	3.05	0	0	0.0149-0.0343	0.197-0.521
Knight and Hamed (1984), S_o=0.000966, h=0.076 m											
DWK4	2	6	0.0097	1.11-1.17	0.229	0.152	4.01	0	0	0.0052-0.0297	0.104-0.511
DWK6	2	6	0.0097	1.38-1.63	0.229	0.152	4.01	0	0	0.0054-0.0264	0.113-0.515
DWK7	2	6	0.0097	1.74-2.41	0.229	0.152	4.01	0	0	0.0051-0.0211	0.113-0.502
DWK9	2	6	0.0097	2.51-4.78	0.229	0.152	4.01	0	0	0.0043-0.0158	0.137-0.505
Prinos and Townsend (1984), S_o=0.0003, h=0.102 m											
PT03	2	5	0.011	1.27	0.381	0.203	5.26	0.5	0	0.0061-0.0180	0.089-0.329
PT04	2	5	0.011	1.64	0.381	0.203	5.26	0.5	0	0.0055-0.0161	0.089-0.329
PT05	2	5	0.011	2.00	0.381	0.203	5.26	0.5	0	0.0048-0.0140	0.089-0.329
PT06	2	5	0.011	1.27	0.381	0.305	3.83	0.5	0	0.0096-0.0245	0.089-0.329
PT07	2	5	0.011	1.64	0.381	0.305	3.83	0.5	0	0.0087-0.0225	0.089-0.329
PT08	2	5	0.011	2.00	0.381	0.305	3.83	0.5	0	0.0082-0.0204	0.089-0.329
Wormleatonet al. (1982), S_o=0.00043, h=0.12 m											
W-B	2	6	0.01	1.40	0.46	0.29	4.17	0	0	0.0170-0.0480	0.205-0.429
W-C	2	8	0.01	1.70	0.46	0.29	4.17	0	0	0.0115-0.0430	0.143-0.429
W-D	2	8	0.01	2.10	0.46	0.29	4.17	0	0	0.0090-0.0380	0.143-0.429
Patra et al. (2012), S_o=0.000311,h=0.08m											
Patra	2	6	0.0098	1.12	0.805	0.12	15.75	1	0	0.0475-0.0908	0.281-0.408
Hu et al. (2010), S_o=0.001, h=0.06 m											
Hu	2	7	0.011	1.18	0.35	0.30	3.33	0	0	0.0091-0.0388	0.134-0.535
Joo et al. (2007), S_o=0.013, h=0.05m											
JS	1	8	0.011	2.00	0.20	0.05	5.00	0	0	0.0030-0.0061	0.207-0.342
James and Brown (1977), S_o=0.001, h=0.069m(sym), 0.508 m (asym)											
JB131	2	7	0.01	1.60	0.502	0.243	5.71	1	1	0.0115-0.0328	0.097-0.385
JB51	1	14	0.01	1.20	0.191	0.178	2.64	1	1	0.0041-0.0138	0.025-0.444
JB61	1	15	0.01	1.20	0.368	0.243	3.64	1	1	0.0041-0.0142	0.123-0.413
JB71	1	12	0.01	1.20	0.572	0.243	4.79	1	1	0.0046-0.0143	0.058-0.378
James and Brown (1977), S_o=0.002, h=0.069 m(sym), 0.508 m (asym)											
JB132	2	6	0.01	1.60	0.502	0.243	5.71	1	1	0.0141-0.0330	0.048-0.337
JB52	1	11	0.011	1.09	0.191	0.178	2.64	1	1	0.0054-0.0142	0.042-0.389
JB62	1	14	0.011	1.09	0.368	0.243	3.64	1	1	0.0061-0.0142	0.079-0.351
JB72	1	9	0.011	1.09	0.572	0.243	4.79	1	1	0.0057-0.0137	0.025-0.291
James and Brown (1977), S_o=0.003, h=0.069 m(sym), 0.508 m (asym)											
JB133	2	5	0.01	1.60	0.502	0.243	5.71	1	1	0.0162-0.0340	0.044-0.296
JB53	1	11	0.011	1.09	0.191	0.178	2.64	1	1	0.0061-0.0157	0.002-0.369
JB63	1	14	0.011	1.09	0.368	0.243	3.64	1	1	0.0060-0.0144	0.048-0.311
JB73	1	8	0.011	1.09	0.572	0.243	4.79	1	1	0.0065-0.0148	0.008-0.282

4 RESULTS AND DISCUSSION

To evaluate the error of each method against the experimental data, the percentage of error in predictive 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:

$$\%E_{Q,i} = \frac{|Q_{cal,i} - Q_{exp,i}|}{Q_{exp,i}} \times 100\% \qquad [17]$$

Where $\%E_{Q,i}$ is the percentage error 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 average error of each method for an experiment is obtained by

$$\%E_Q = \frac{1}{N}\sum_{i=1}^{N}(\%E_{Q,i}) \qquad [18]$$

Where N is the total number of runs.

Table 2 shows the average percentage errors of predicted discharge by the four methods for all 32 datasets, where subscriptst, c, f denote the values for the total channel, main channel, and floodplain, respectively. For comparison, the results using the DCM are also given in Table 2. The corresponding results of $\%Q_t$ are given in Figure 2. For convenience, in the subsequent figures, Sym = symmetric channels, Asym=asymmetric channels, Mean = the average for all channels.

Table 2. Summary of averaged percentage errors of methods for predicting discharges.

Series	ECM	IDCM			MDCM			ASSM			DCM		
	$\%Q_t$	$\%Q_c$	$\%Q_f$	$\%Q_t$	$\%Q_c$	$\%Q_f$	$\%Q_t$	$\%Q_c$	$\%Q_f$	$\%Q_t$	$\%Q_c$	$\%Q_f$	$\%Q_t$
FCF7	21.62	15.79	37.48	18.97	2.58	39.84	10.08	4.35	35.18	8.82	33.21	32.30	29.78
FCF11	20.76	16.73	79.18	25.42	2.68	85.01	14.00	3.06	73.93	13.13	38.71	54.92	39.91
BU05	31.38	27.70	34.40	28.21	46.56	49.46	18.07	19.05	32.77	14.61	88.15	24.93	65.28
BU01	20.68	16.31	20.33	17.95	2.43	34.81	7.08	15.36	14.67	14.92	44.26	11.45	34.29
DWK4	5.66	2.56	8.63	2.72	5.02	10.47	2.45	10.79	9.83	4.06	16.49	12.91	6.65
DWK6	4.93	5.23	10.19	4.92	12.61	9.52	7.24	4.37	16.90	3.81	16.09	21.96	3.34
DWK7	6.43	3.24	19.73	5.62	13.30	13.12	10.57	1.50	26.12	7.01	26.84	32.94	6.83
DWK9	3.03	15.00	26.84	8.58	25.34	16.89	17.36	13.28	30.77	12.87	56.42	39.90	24.93
Hu	4.46	22.46	43.79	2.54	28.25	54.30	4.92	15.47	31.36	3.33	11.37	27.10	3.58
JS	5.37	18.23	27.75	21.05	6.92	41.51	13.27	3.91	35.99	14.84	36.36	15.55	27.67
PT03	9.00			11.21			14.46			11.96			19.47
PT04	13.24			18.74			21.34			17.65			30.54
PT05	16.67			26.07			27.18			22.68			40.68
PT06	8.89			10.26			11.22			11.36			17.30
PT07	9.33			13.00			13.46			12.93			22.45
PT08	11.22			15.67			16.16			15.75			28.47
W-B	7.28			5.90			5.42			5.68			14.23
W-C	12.95			17.34			13.81			13.35			30.93
W-D	19.85			24.53			20.60			18.48			43.14
Patra	1.89			2.99			8.02			2.81			6.61
JB131	4.97			3.32			4.15			3.13			10.77
JB132	12.37			8.31			9.25			5.59			17.30
JB133	11.71			9.46			10.01			4.79			17.70
JB51	5.33			2.23			6.00			3.92			5.30
JB52	5.01			3.80			6.51			5.05			6.08
JB53	13.57			5.45			8.09			6.61			7.68
JB61	1.52			1.52			4.18			1.94			4.23
JB62	3.29			0.94			3.19			1.60			3.01
JB63	6.32			5.43			7.44			5.76			7.80
JB71	10.57			2.01			0.89			2.88			1.01
JB72	24.75			6.67			6.44			8.07			5.06
JB73	25.29			1.36			2.93			1.75			2.86

As shown in Table 2, compared with the DCM, all four methods, which take into account the momentum transfer of flow between the main channel and floodplain, show an overall improved prediction of total discharge (Q_t), although the ECM does not performance well for asymmetric channels. This is not surprising because the ECM method was based on symmetric channels, and not validated by compound channels with roughened floodplain. Figure 3 demonstrates that all four methods have the combined average percentage of error less than 12%, whereas the DCM overestimates the discharge with the combined averaged percentage of error larger than 20%. Further analysis in Figure 4 shows that the roughness of floodplain affects the precision of prediction, i.e. all four methods give a better prediction of total discharge for the relative lower ratio of roughness ($\gamma = n_f/n_c < 2$) than that for the higher ratio of roughness (γ>2).

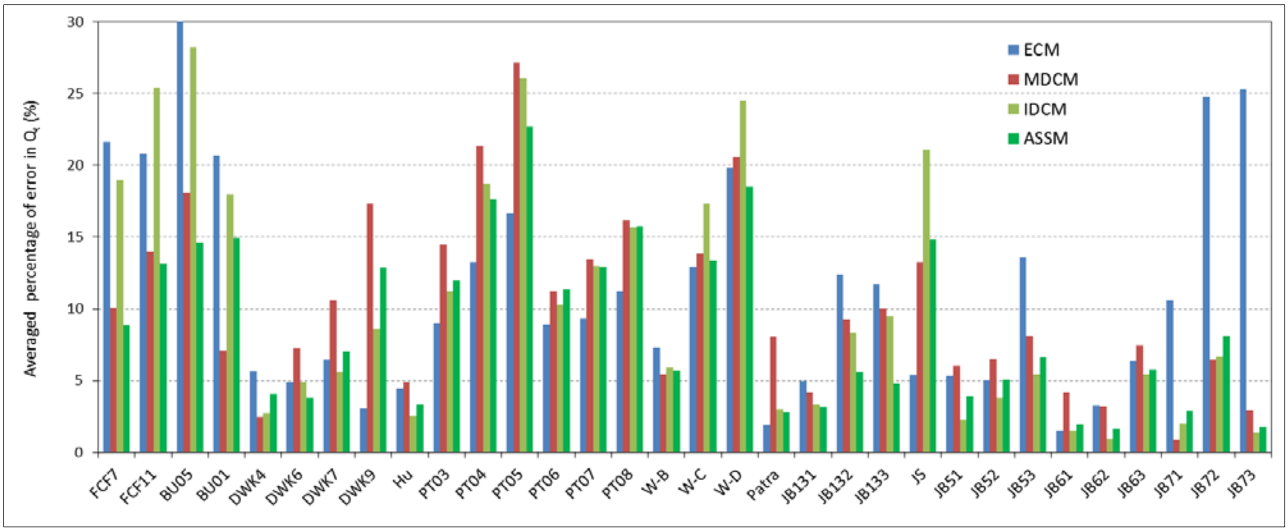

Figure 2. Averaged percentage error of total discharge (*%*Q_t) by four methods in heterogeneous channels.

This is true for both symmetric and asymmetric channels. Among the four methods, the ASSM gives the best results in the prediction of overall discharges (Q_t), and the other three methods (ECM, MDCM and IDCM) have a similar prediction precision of total discharge. This is not surprising because the ASSM takes various geometric parameters into account, namely the interface coefficient (α_d) of apparent shear stress (τ_a) for predicting the discharge.

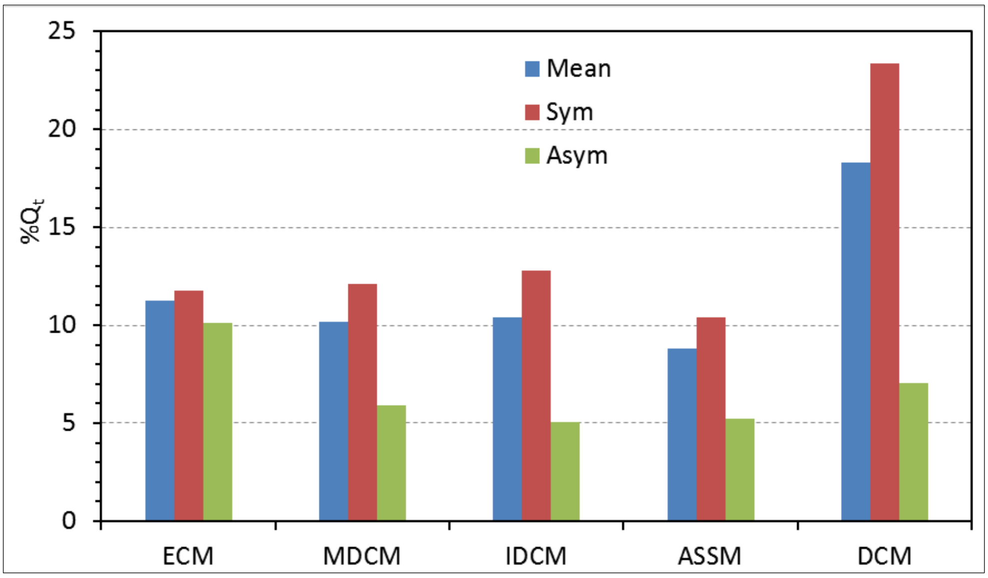

Figure 3. Averaged percentage errors of Q_t.

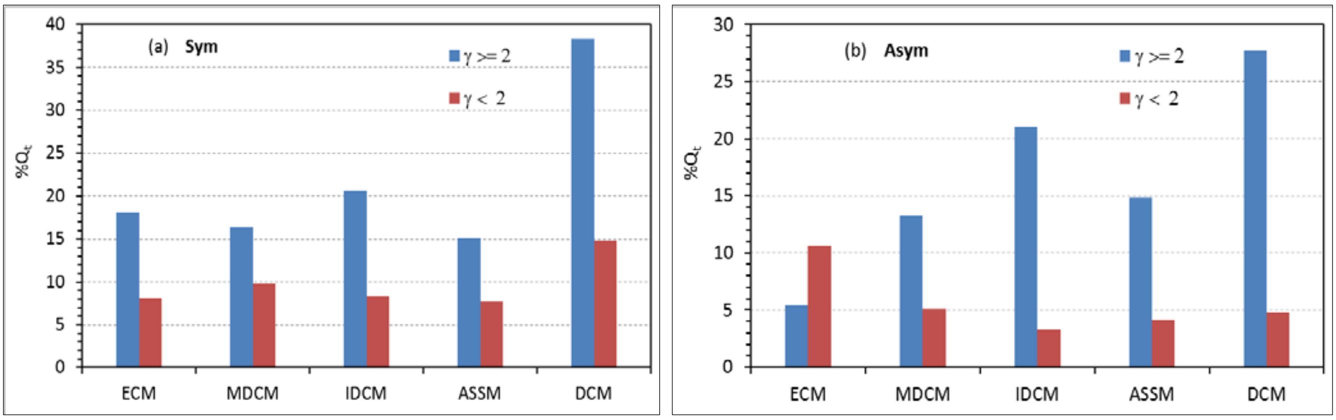

Figure 4. Averaged percentage errors of Q_t for (a)symmetric and (b) asymmetric channels.

For zonal discharge, the ECM is excluded in the analysis due to its incapability. As shown in Figure 5, all the methods significantly improve the prediction of main channel discharge within an averaged error below 15%, particularly the ASSM within an error less than 10%; however, they do not have any improvement for the prediction of floodplain discharge compared with the DCM. Although the ASSM isn't significantly different from the MDCM and IDCM in zonal discharge prediction, the ASSM shows good prediction of zonal discharge percentage (both Q_c/Q_t and Q_f/Q_t). This can be seen in Figure 6 as an example, where both the MDCM and IDCM underestimate the discharge percentage of main channel, but overestimate the discharge percentage of floodplain, particularly in higher relative flow depths of floodplain.

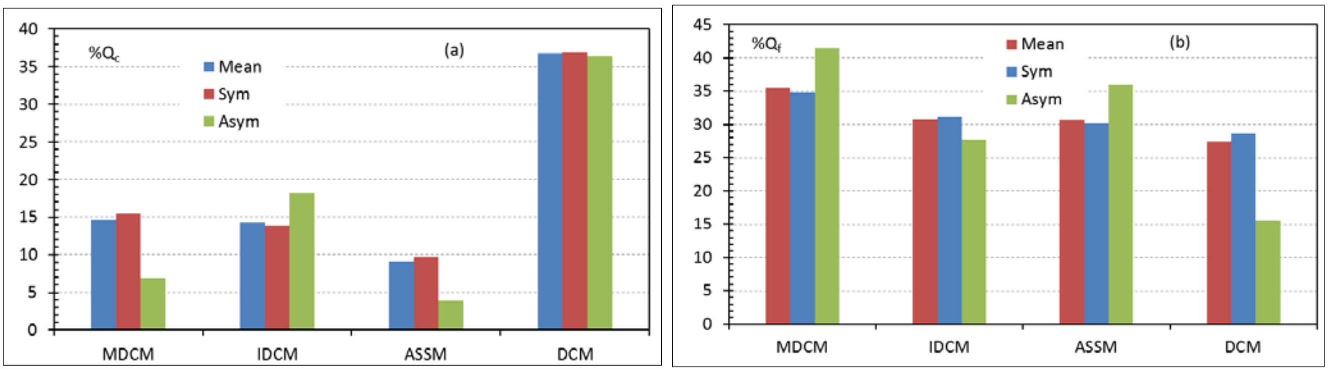

Figure 5. Averaged percentage errors: (a)%Q_c; (b) %Q_f.

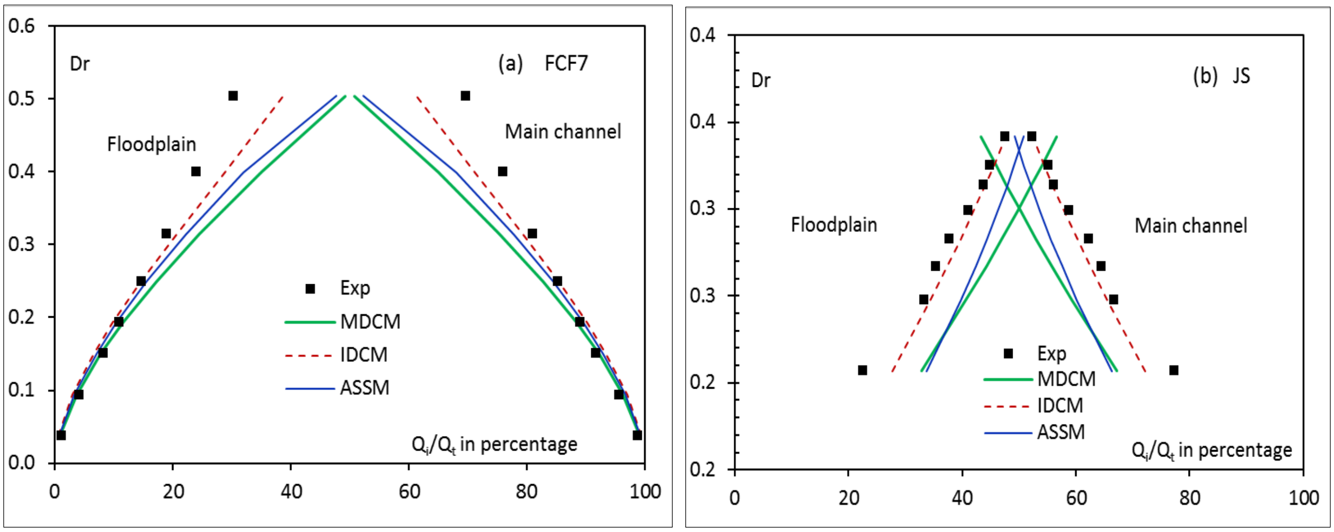

Figure 6. Comparison of zonal discharge percentage for: (a) FCF7, (b) JS.

Finally, it is worth noting that in all four methods except the IDCM, the roughness of floodplain had been taken into account in the prediction of discharge, while a single value of parameter α_m (=0.02) was used in the IDCM for channels with various roughened floodplains. Therefore, it is not surprising that the IDCM has shown relatively higher errors in the prediction of total discharge (see Figure 4).

5 CONCLUSIONS

Through comparison against a wide range of data in heterogeneously roughened compound channels, the four recently developed methods that take into account the impact of momentum transfer between the main channel and floodplain show that:

- Compared with DCM, all four methods improve the prediction of total discharge with the precision within 12% for roughened compound channels and the ASSM gives the best overall results, whereas the DCM has an averaged error over 20%. The four methods improve the prediction of total discharge significantly as the ratio of roughness between floodplain and main channel reduces; for example, the percentage of error in discharge reduces almost half when γ (=n_f/n_c) changes from above 2 to below 2.
- The four methods can also improve the prediction of main channel discharge within an averaged error less than 15% for symmetric channels, but they do not perform well for the prediction of floodplain discharge. Furthermore, except the ASSM, the other methods do not predict zonal discharge percentage well. Typically, they overestimate the discharge percentage of floodplain but underestimate the discharge percentage of main channel, particularly for the higher relative flow depth of floodplain.
- In general, the ASSM can be used to predict total discharge within an average error less than 10%, which can be further improved with decreasing ratio of roughness (γ). However, for zonal discharge prediction, none of these methods predicts well, so further study is needed, especially for asymmetric roughened floodplain compound channels.

NOTATION

$\%A_f$= area percentage of floodplain
$\%S_f$= shear force percentage of floodplain
B= width of main channel at bankfull
b= width of main channel bottom
D_r= relative depth of floodplain,= $(H-h)/H$
f= friction factor
g= acceleration of gravity
h= bankfull height
H= main channel depth
h_f= flow depth of floodplain
n= Manning's coefficient
N_f= number of floodplain
Q= discharge of cross-section
S_o= bed slope of channel
U= mean velocity of cross-section
X= interaction length
α= aspect ratio, = B/b
α_m= interface coefficient (also α_d)
ρ= density of water
γ= ratio of Manning coefficients between main channel and floodplain, =n_f/n_c
τ= averaged shear stress of boundary
τ_a= apparent shear stress at the interface

Subscripts:
,0= reference values based on DCM
c= main channel
f= floodplain
t= total

REFERENCES

Al-Khatib, I.A., Dweik, A.A. & Gogus, M. (2012). Evaluation of Separate Channel Methods for Discharge Computation in Asymmetric Compound Channels. *Flow Measurement and Instrumentation*, 24, 19-25.

Cater, J.E. & Williams, J.J.R. (2008). Large Eddy Simulation of a long Asymmetric Compound Open Channel. *Journal of Hydraulic Research*, 46(4), 445-453.

Christodoulou,G.C.(1992). Apparent Shear Stress in Smooth Compound Channels. *Water Resources Management*, 6(3), 235-247.

Devi,K., Khatua, K.K. & Das,B.S. (2016). *Apparent Shear in an Asymmetric Compound Channel*, *River Flow 2016*,Constantinescu, Garcia & Hanes (Eds), 48-56; July 12-15, St. Louis, USA.

Hu, C., Ju, Z. & Guo,Q. (2010). Flow Movement and Sediment Transport in Compound Channels. *Journal of Hydraulic Research*, 48(1), 23–32.

Huthoff,F., Roos,P.C., Augustijn,D.C.M. & Hulscher,S.J.M.H. (2008). Interacting Divided Channel Method for Compound Channel Flow. *Journal of Hydraulic Engineering*, 134(8), 1158-1165.

James, M. & Brown, B.J. (1977). *Geometric Parameters That Influence Food Plain Flow*. *Research report H-77-I*, U.S. Army. Vicksburg, Missouri, U.S.A: Hydraulic Laboratory.141pp.

Jazizadeh, F. & Zarrati,A.R. (2008). Development of a Three-Dimensional Numerical Model to Solve Shallow-Water Equations in Compound Channels. *Journal of Civil Engineering*, 35(9), 963-974.

Joo, C.B.H. & Seng,D.M.Y. (2007). Study of Flow in a Non-Symmetrical Compound Channel with Rough Flood Plain. *The Institution of Engineers Journal*, 69(2), 18-26.

Khatua, K.K. Patra, K.C. & Mohanty, P.K. (2012). Stage-Discharge Prediction for Straight and Smooth Compound Channels with Wide Flood Plains. *Journal of Hydraulic Engineering*, 138 (1), 93–99.

Knight, D.W. & Demetrious,J.D. (1983). Flood Plain and Main Channel Flow Interaction. *Journal of Hydraulic Division (ASCE)*, 109 (8), 1073-1092.

Knight, D.W. & Hamed, M.E. (1984). Boundary Shear in Symmetrical Compound Channels. *Journal of Hydraulic Engineering*, 110(10), 1412-1430.

Krishnappan, B.G. & Lau, Y.L. (1986). Turbulence Modeling of Flood Plain Flows. *Journal of Hydraulic Engineering*, 112(4), 251-266.

Marjang, N. & Merkley, G.P. (2009). Velocity Profile Modelling in Rectangular and Compound Open-Channel Cross Sections. *Irrigation Science*, 27(6), 471–484.

Mohanty,P.K. & Khatua, K.K. (2014). Estimation of Discharge and its Distribution in Compound Channels. *Journal of Hydrodynamics*, 26(1), 144-154.

Moreta, P.J.M. & Martin-Vid, J.P. (2010). Apparent Friction Coefficient in Straight Compound Channels. *Journal of Hydraulic Research*, 48(2), 169–177.

Myers, W., Knight, D.W., Lyness, J.F., Cassells, J.B. & Brown, F. (1999). Resistance Coefficients for Inbank and Overbank Flows. *Proceeding of Institution of Civil Engineers Water, Maritime & Energy*, 136, 105-115.

Noutsopoulos, G. & Hadjipanos, P. (1983). Discharge Computations in Compound Channels. *Proceeding of 20th IAHR Congress*, Moscow, 5, 173-180.

Patra, K.C, Sahoo, N. & Khatua, K.K. (2012). Distribution of Boundary Shear in Compound Channel with Roughness Flood Plain. *9th international conference on Advances in Fluid Mechanics*, June 28, University of Split,Croatia.

Prinos, P. & Townsend, R.D. (1984). Comparison of Methods for Predicting Discharge in Compound Open Channels. *Advanced Water Resource*s, 7, 180-187.

Shiono, K. & Knight,D.W. (1991). Turbulent Open Channel Flow with Variable Depth across the Channel. *Journal of Fluid Mechanics*, 222, 617-646.

Tang, X. (2016).*Critical Evaluation on Different Methods for Predicting Zonal Discharge of Straight Compound Channels.* River Flow 2016, Constantinescu, Garcia & Hanes (Eds), 57-64; July 12-15, St Louis, USA.

Tang, X. & Knight,D.W. (2007).An Improved Discharge Prediction Method for Overbank Flows. *Proceeding of 2nd Congress of IAHR*, July 1-6, Venice, Italy.

University of Birmingham (2001). *Flow database* [online]. Retrieved from: www.flowdata.bham.ac.uk.

Wormleaton, P.R., Allen, J. and Hadjipanos,P. (1982). Discharge assessment in compound channel flow. *Journal of Hydraulic Division (ASCE)*, 108 (9), 975-994.

Yang, K., Cao, S. & Liu,X. (2007). Flow Resistance and Its Prediction Methods in Compound Channels. *Acta Mechanica Sin*ica, 23(1), 23-31.

Yang, Z., Gao,W. & Huai, W. (2012). Estimation of Discharge in Compound Channels Based on Energy Concept. *Journal of Hydraulic Research*, 50(1), 105-113.