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ORIGINAL ARTICLE

Flow discharge estimation in compound open channel using theoretical approaches

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Abstract Estimating the value of discharge in water ways is an important factor in the flood controlling projects. Recently by advances in flood management, investigators have proposed to use the concept of compound section for modeling the flow characteristics in the natural waterways such as rivers. Several conceptual and theoretical approaches based on the idea of compound section have been proposed for estimating the discharge in rivers. In this study, the performances of the theoretical methods were assessed using performing series of experiments in straight prismatic compound open channel and also analyzing the published data in the literature. Analyzing the performance of theoretical methods shows that Divided Channel Method including vertical bounded line with the determination of coefficient (0.91) and root mean square error (0.02) is an accurate method through the theoretical approaches and only this method has suitable ability to apply for practical purposes.

Keywords Compound open channel · River discharge · Divided channel method · Flood management

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Introduction

Flow discharge is a basic parameter in developing the water resource projects such as hydro-power systems, irrigation and drainage networks (Chen 2015; Chow et al. 1988). Channels are the main structures which have been used for conveying the water or wastewater in the water engineering projects (Akan 2011; Subramanya 2009). Study on the flow discharge in the open channels has become an important subject in management of water resources; therefore, several researchers have attempted to propose approaches for measurement and estimation of discharge in the open channel (Haghiabi 2012; Heidarpour et al. 2008; Parsaie and Haghiabi 2015a, b, c; Parsaie et al. 2015a, b; Vatankhah 2012, 2013a, b). Calculating the flow discharge in conventional open channels usually is conducted by classical empirical formulas such as Manning and Chezy formulas (Parsaie 2016). These formulas have dependable performance for calculating the discharge in normal channel but when floods occur, surplus flow on the capacity of the normal channel flow in floodplains makes using the classical formulas for estimating the discharge of flow unsure. Using them may lead to errors (Ackers 1993; Al-Khatib et al. 2012, 2013; Azamathulla et al. 2016; Dehdar-behbahani and Parsaie 2016; Parsaie and Haghiabi 2014; Parsaie and Haghiabi 2015a, b, c). Several reasons have been reported for the lack reliability of these methods under flood conditions (Bousmar and Zech 1999). Investigators have tried to modify and improve the performance of these formulas and proposed the concept of compound sections as a novel approach for estimating the discharge of flow especially in natural streams (Hosseini 2004; Huthoff et al. 2008; Parsaie and Haghiabi 2015a, b, c). Figure 1 shows a sketch of the proposed compound section for use in the study on the natural streams. As seen from Fig. 1a
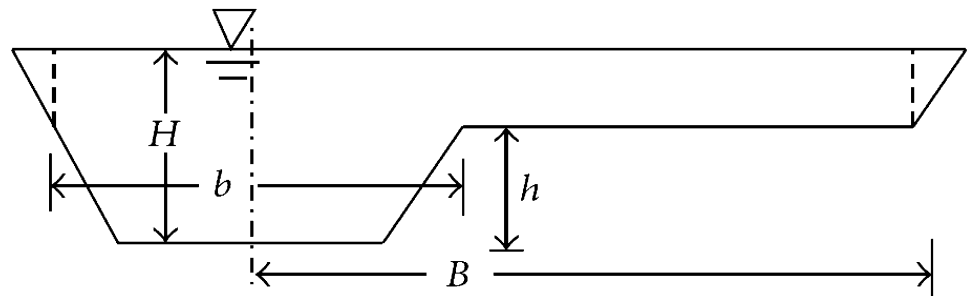
compound section includes a main channel and flood plains. Because of reduction of flow velocity in the flood-plains, this part of the cross section is usually covered by vegetation and is rougher than the main channel.

In the Fig. 1 the roughness of the main channel was defined with the n_{mc} and roughness of the floodplains were introduced by n_{fp}. Flow depth in the main channel characterized by H and main channel depth was defined by h. Several ways for theoretical methods and soft computing techniques have been proposed for calculating and predicting the flow discharge in compound open channel. In field of theoretical approaches Single Channel Method (SCM) and divided channel method (DCM) as proxy of theoretical methods can be stated (Atabay and Knight 2006; Knight and Demetriou 1983; Knight and Shamseldin 2005; Knight et al. 1984; Liao and Knight 2007; Tang et al. 1999; Unal et al. 2010). In the field of soft computing techniques using the Artificial Neural Networks (ANNs), M5 tree, Genetic Programming (GP), group method of data handling (GMDH) and Support Vector Machine (SVM) can be mentioned (Azamathulla and Zahiri 2012; Noori et al. 2009, 2016; Osooli et al. 2011; Parsaie et al. 2015a, b; Sahu et al. 2011; Unal et al. 2010; Zahiri and Azamathulla 2014). In this study to assess the performance of the most famous empirical approaches, a series of laboratory experiments were programmed and executed in the hydraulic laboratory of Tehran University (Iran). To compare the obtained results from the laboratory experiments with previous studies, 396 datasets related to discharge of flow in compound open channel published in the literature were retrieved and examined.

Materials and method

The experiments were carried out in a compound open channel in which properties were shown in Fig. 2. As indicated, the longitudinal slope is equal to 0.00088, the length of channel is about 15 m, bottom with of the main channel is 0.4 m and the main channel depth is 0.18 m, and with of floodplains are 0.4 m. The cross slope of floodplains are equal to zero. The range of discharge of flow was

measured between 0.35 and 0.75 (m^3/s). The discharge of flow was measured using a calibrated v-notch weir and the flow depth in the main channel and floodplains were recorded using the point gage.

Flow in the compound open channel is a complex phenomenon and there are many influencing parameters on the discharge capacity. The important parameters are given in Eq. (1) including the hydraulic and geometric characteristics:

$$Q_{cmp} = f\left(f_{fp}, f_{mc}, A_{fp}, A_{mc}, R_{fp}, R_{mc}, S, h, (H-h)\right), \quad (1)$$

where Q_{cmp} is the discharge of the flow in compound open channel, f_{fp} and f_{mc} are the roughness of main channel and floodplains, respectively. A_{fp} and A_{mc} are the areas of main channel and floodplains, R_{fp} and R_{mc} are the hydraulic radius of the main channel and floodplains, S is longitudinal slope of compound open channel, H and h are the depth of flow in the main channel and floodplains, respectively. Sahu et al. (2011) arranged these parameters in a group of dimensionless parameters (Eq. 2) and used them to develop an ANN for predicting the discharge of flow in compound open channel:

$$Q = f\, f_r, A_r, R_r, S, H_r. \quad (2)$$

In which that f_r is defined as $\frac{f_{mc}}{f_{fp}}$, A_r is defined as $\frac{A_{mc}}{A_{fp}}$, R_r is defined as $\frac{R_{mc}}{R_{fp}}$, and H_r is defined as $\frac{H-h}{H}$. As mentioned in the introduction section one of the main part of this study is a compression with the results of other researches. To this 396 data set related to the discharge of flow in compound open channel was collected and ranges of them are given in Table 1.

Single channel method (SCM)

The Single channel method (SCM) considered the cross section of the compound open channel as unique, and there is no difference between the normal and the compound channel. The main point of the SCM is calculating the equivalent roughness for the compound open channel by prevalent methods such as the Horton and the Einstein formulas (Eq. 3), and then the discharge is calculated by

Fig. 2 Sketch of laboratory model of compound open channel
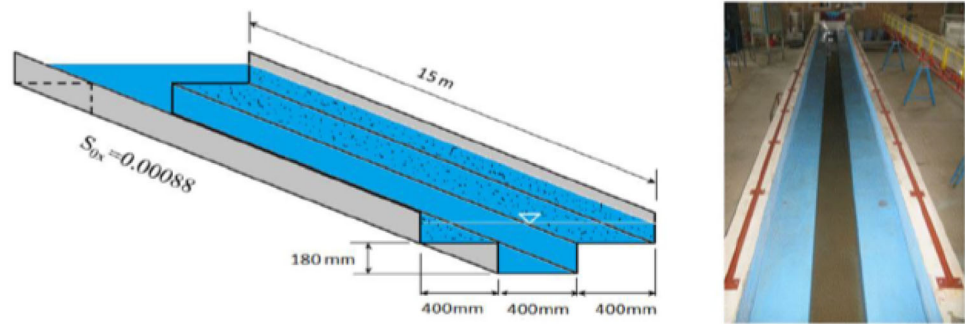
Table 1 Summary of collected data range related to discharge of flow in the compound channel

References	Range	H	h	$(H–h)$	B	b	n (fp)	n (mc)	S	Q (m)
Knight et al. (1984)	Min	0.085	0.08	0.009	0.15	0.08	0.0100	0.0100	0.0010	0.0049
	Max	0.154	0.08	0.078	0.31	0.08	0.0100	0.0100	0.0010	0.0294
	AVG	0.112	0.08	0.036	0.23	0.08	0.0100	0.0100	0.0010	0.0116
	STDEV	0.022	0.00	0.022	0.06	0.00	0.0000	0.0000	0.0000	0.0068
Wormleaton and Merrett (1990) (UK Flood Channel Facility)	Min	0.058	0.05	0.006	0.61	0.20	0.0091	0.0091	0.0001	0.0100
	Max	0.302	0.15	0.152	5.00	0.75	0.0910	0.0210	0.0020	1.1142
	AVG	0.169	0.12	0.050	2.40	0.58	0.0220	0.0113	0.0007	0.3230
	STDEV	0.066	0.05	0.040	1.47	0.26	0.0239	0.0030	0.0009	0.2946
Tang et al. (1999)	Min	0.056	0.05	0.006	0.61	0.20	0.0056	0.0079	0.0020	0.0130
	Max	0.220	0.05	0.170	0.61	0.20	0.0957	0.0390	0.0020	0.2180
	AVG	0.092	0.05	0.042	0.61	0.20	0.0346	0.0170	0.0020	0.0499
	STDEV	0.042	0.00	0.042	0.00	0.00	0.0228	0.0093	0.0000	0.0546
Atabay and Knight (2006)	Min	0.061	0.05	0.011	0.61	0.20	0.0063	0.0091	0.0020	0.0180
	Max	0.120	0.05	0.070	0.61	0.20	0.0112	0.0115	0.0020	0.1830
	AVG	0.072	0.05	0.022	0.61	0.20	0.0081	0.0098	0.0020	0.0474
	STDEV	0.014	0.00	0.014	0.00	0.00	0.0013	0.0006	0.0000	0.0391
Khatua et al. (2012)	Min	0.136	0.12	0.016	0.22	0.06	0.0100	0.0100	0.0019	0.0087
	Max	0.223	0.12	0.103	0.22	0.06	0.0100	0.0100	0.0019	0.0391
	AVG	0.174	0.12	0.054	0.22	0.06	0.0100	0.0100	0.0019	0.0212
	STDEV	0.031	0.00	0.031	0.00	0.00	0.0000	0.0000	0.0000	0.0111
Ikeda and McEwan (2009)	Min	0.207	0.20	0.007	0.81	0.28	0.0100	0.0100	0.0001	0.0260
	Max	0.278	0.20	0.078	0.81	0.28	0.0100	0.0100	0.0003	0.0730
	AVG	0.242	0.20	0.042	0.81	0.28	0.0100	0.0100	0.0002	0.0486
	STDEV	0.018	0.00	0.018	0.00	0.00	0.0000	0.0000	0.0001	0.0133
Mohanty and Khatua (2014)	Min	0.071	0.07	0.006	1.98	0.17	0.0100	0.0100	0.0011	0.0130
	Max	0.115	0.07	0.050	1.98	0.17	0.0100	0.0100	0.0011	0.1062
	AVG	0.091	0.07	0.026	1.98	0.17	0.0100	0.0100	0.0011	0.0467
	STDEV	0.016	0.00	0.016	0.00	0.00	0.0000	0.0000	0.0000	0.0326
Seckin (2004)	Min	0.060	0.05	0.010	0.61	0.20	0.0090	0.0090	0.0020	0.0148
	Max	0.168	0.05	0.118	0.61	0.20	0.0490	0.0090	0.0020	0.0553
	AVG	0.090	0.05	0.040	0.61	0.20	0.0288	0.0090	0.0020	0.0299
	STDEV	0.027	0.00	0.027	0.00	0.00	0.0177	0.0000	0.0000	0.0117
Wormleaton and Hadjipanos (1985)	Min	0.135	0.12	0.015	0.75	0.29	0.0110	0.0099	0.0004	0.0009
	Max	0.210	0.12	0.090	0.75	0.29	0.0210	0.0099	0.0018	0.4800
	AVG	0.167	0.12	0.047	0.75	0.29	0.0160	0.0099	0.0006	0.0372
	STDEV	0.023	0.00	0.023	0.00	0.00	0.0042	0.0000	0.0003	0.0735

Fig. 3 Types of separating boundary between main channel and floodplains. *a–b* Vertical, *a–c* diagonal, *a–a* horizontal
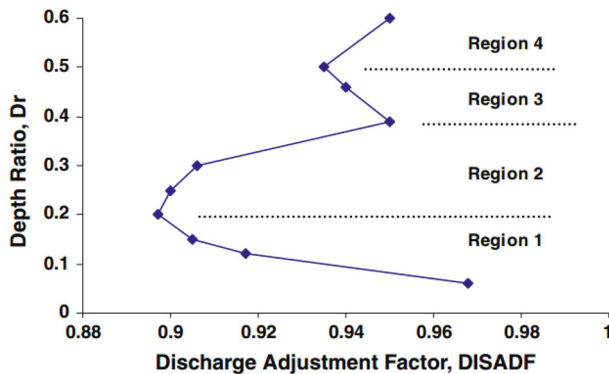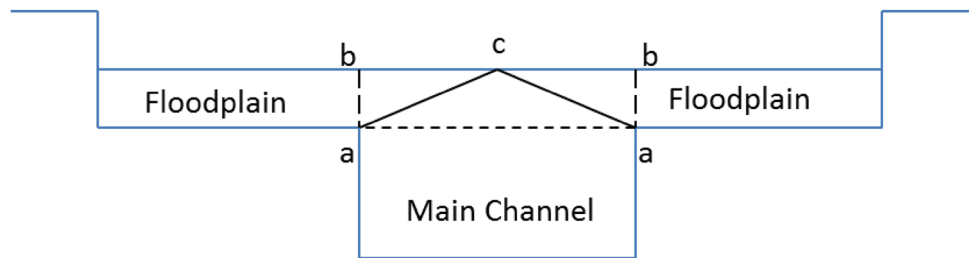

Fig. 4 The diagram of flow discharge adjustment parameter versus relative depth

Eq. (4). The weakness of the SCM is related to the calculation of the transport capacity, especially when the water level increases and the flow covers the floodplains, the wet perimeter increases in comparison with the wet area so the calculated transport capacity is less than the measured data, and at the end, the flow discharge, which is calculated by SCM is less than the actual values. By increasing the flow depth on the floodplains the accuracy of the SCM is improved.

$$n_e = \frac{\left[\sum_{i=1}^{N}\left(P_i n_i^{\frac{3}{2}}\right)\right]^{\frac{2}{3}}}{P^{\frac{2}{3}}}, \tag{3}$$

$$Q = \frac{1}{n_e}AR^{\frac{2}{3}}S^{\frac{1}{2}}, \tag{4}$$

in which the P_i is the perimeter of wetted area of the sub section, n_i is the Manning's roughness factor for the each sub sections, P is the perimeter of the total flow cross section and n_e is the equivalent roughness (Parsaie et al. 2015a, b).

Divided channel method (DCM)

The Divided channel method (DCM) divides the compound channel into subsections. The DCM is based on the uniform velocity in the area. In this method, the compound channel section is divided into the main channel and the floodplains, and then the total discharge is calculated by adding the discharge through the area. The discharge in the subsections is calculated by Eq. 5. The Manning formula is used for calculating the discharge and the subscription is related to the discharge in each subsections. The separation line between the main channel and the floodplains (Fig. 3) may be considered as vertical, diagonal, or horizontal.

Modifications have been carried out on the Divided Channel Method and in this regard the divided channel method with horizontal separated lines are excluded within the calculation of the wetted perimeter (DCM(h–e)). The Divided Channel Method with horizontal separated lines are included within the calculation of the wetted perimeter (DCM(h–i)). The Divided Channel Method with vertical separated lines is excluded within the calculation of the wetted perimeter (DCM(v–e)). The Divided Channel Method with vertical separated lines which are included within the calculation of the wetted perimeter (DCM(v–i)). The divided channel method with bisectional division lines is excluded within the calculation of wetted perimeter (DCM(b–e)), and the Divided Channel Method with bisectional division lines is included within the calculation of wetted perimeter(DCM(b–i). A number of commercial software such as HEC RAS, Mike 11 and ISIS have been developed based on the DCM (Atabay and Knight 2006).

$$Q_t = \left(\sum_{i=1}^{N}\frac{A_i R_i^{\frac{2}{3}}}{n_i}\right)S_0^{\frac{1}{2}}, \tag{5}$$

Table 2 Results of experiments regards to the Eq. (2)

Range	H	h	$(H–h)$	B	b	n (fp)	n (mc)	S	Q (m)
Min	0.195	0.18	0.015	0.60	0.20	0.0139	0.0139	0.0009	0.335
Max	0.333	0.18	0.153	0.60	0.20	0.0165	0.0139	0.0009	0.682
AVG	0.257	0.18	0.077	0.60	0.20	0.0154	0.0139	0.0009	0.511
STDEV	0.036	0.00	0.036	0.00	0.00	0.0011	0.0000	0.0000	0.098
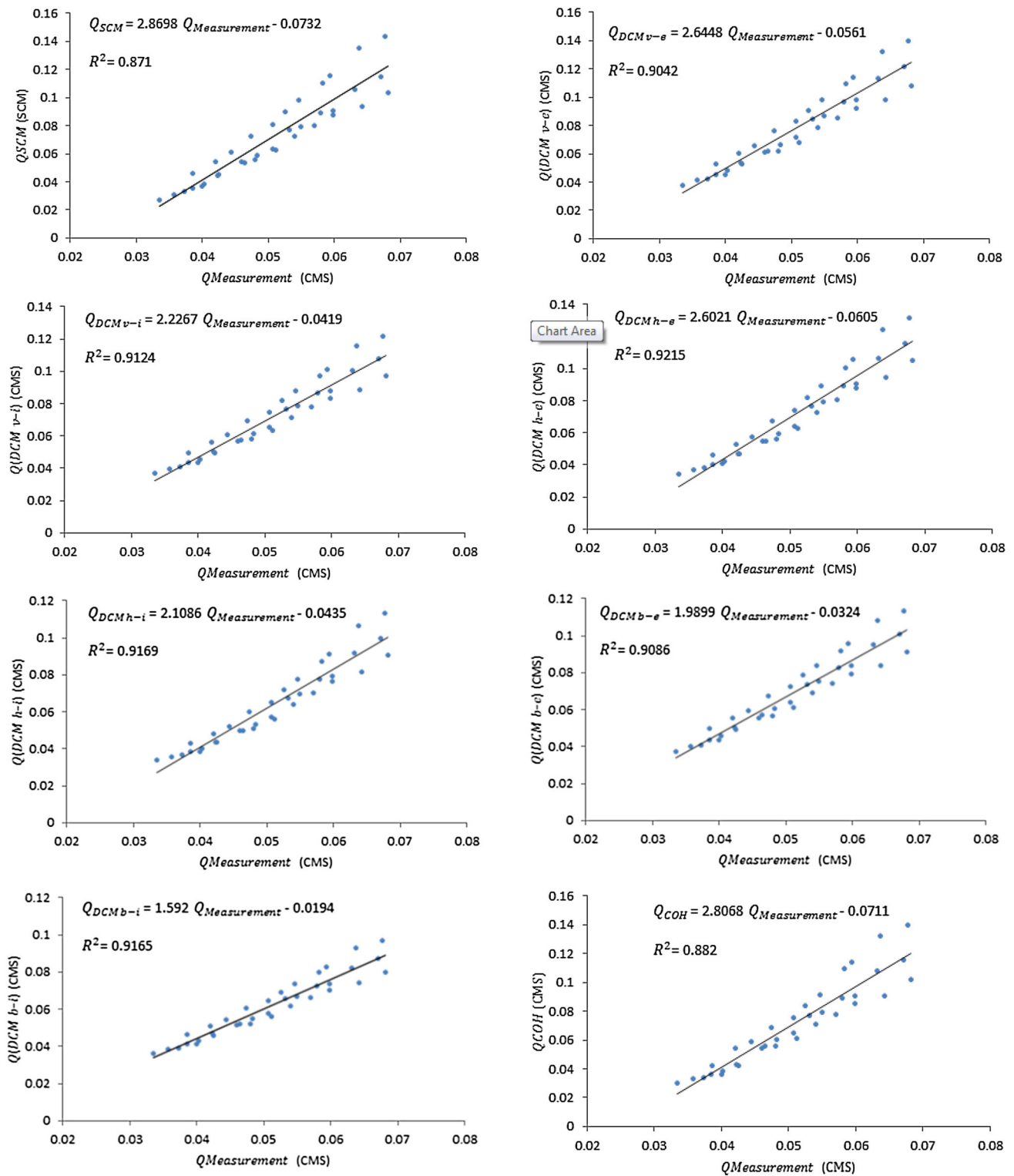
Fig. 5 Correlation between the results of theoretical methods versus the measured data

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Table 3 Performance of theoretical methods for the laboratory experiments

Errors	R^2	RMSE	APE	ER	MAE	MAPE
SCM	0.87	0.03	85.63	−0.11	0.02	133.16
DCM$_{v-e}$	0.90	0.03	109.10	0.13	0.03	145.51
DCM$_{v-i}$	0.91	0.02	105.06	0.09	0.02	132.43
DCM$_{h-e}$	0.92	0.03	98.00	0.02	0.02	132.33
DCM$_{h-i}$	0.92	0.02	94.31	−0.02	0.01	117.62
DCM$_{d-e}$	0.91	0.02	105.60	0.09	0.02	128.03
DCM$_{d-i}$	0.92	0.01	101.14	0.05	0.01	114.67
COHM	0.88	0.03	86.53	−0.10	0.02	131.27

where A_i is the area of each subsection, R_i is the hydraulic radius of each subsection and S_0 is the longitudinal slope of compound open channel.

Coherence method (COHM)

The Coherence method (COHM) is a one dimensional method that was proposed for rectification of the transport capacity parameter in the compound open channel. The COHM is based on the momentum and mass transferring between the main channel and the floodplains. Ackers (1993) proposed a parameter which named the Coherence parameter. As given in Eqs. (6, 7) the COH parameter is defined as a ratio of the transport capacity parameter of SCM to DCM. If the COH parameter was close to 1, the compound open channel has hydraulic behaviors similar to the normal channel.

$$\text{COH} = \frac{\dfrac{(1+A_{r-\text{COH}})^{\frac{3}{2}}}{\sqrt{1+\dfrac{P_{r-\text{COH}}^{\frac{4}{3}}n_{r-\text{COH}}^2}{A_{r-\text{COH}}^{\frac{1}{3}}}}}}{1+\dfrac{A_{r-\text{COH}}^{\frac{5}{3}}}{\left(n_{r-\text{COH}}P_{r-\text{COH}}^{\frac{2}{3}}\right)}} \tag{6}$$

$$A_{r-\text{COH}} = \frac{N_{\text{fp}}A_{\text{fp}}}{A_{\text{mc}}}, \quad P_{r-\text{COH}} = \frac{N_{\text{fp}}P_{\text{fp}}}{P_{\text{mc}}}, \quad n_{r-\text{COH}} = \frac{n_{\text{fp}}}{n_{\text{mc}}} \tag{7}$$

where N_{fp} is the number of the floodplains, A_{fp} is section area of floodplains, A_{mc} is section area of the main channel, P_{fp} and P_{mc} are the wetted perimeters of floodplains and main channel, respectively, fp and mc are the subscription related to the floodplains and the main channel. COH parameter gets a value between zeros to one. Whenever the

COH is becoming close to one, the compound channel has a behavior similar to normal channel. Ackers (1993) also proposed a coefficient that he named the Discharge Adjustment Factor (DISADF) used to edit the discharge capacity. The discharge should be corrected based on a value that is derived from Fig. 4 and Eqs. 8 and 9.

Region 1: $Q_{\text{COH}} = Q_{\text{DCM}} - \text{DISDEF}$, $\tag{8}$

Region 2, 3 and 4: $Q_{\text{COH}} = \text{DISADF} \times Q_{\text{DCM}}$. $\tag{9}$

Results and discussion

The ranges of results of experimental parameters regarding the Eq. 2 are given in Table 2. The minimum discharge of flow in experiments which covered the floodplains was equal to $0.335(\text{m}^3/\text{s})$ and during the experiments the roughness of main channels were found to be 0.0139 and for floodplains values between 0.0139 and 0.0165 were found. Regarding the derived experimental data the performance of analytical approaches were assessed and are shown in Fig. 5. To carefully assess the accuracy of these methods other error indices such as determination of coefficient (R^2), Root Mean Square Error (RMSE), Relative Error(ER), Absolute Percentage Error (APE), Mean Absolute Percentage Error (MAPE), and Mean Absolute Error (MAE) were calculated and are given in Table 3. It is notable that CMS is cubic meter per second.

Reviewing the Table 3 and Fig. 5 shows that the DCM$_{v-i}$, DCM$_{h-e}$ and DCM$_{h-i}$ are the most accurate through the analytical approaches and worst accuracy is related to the SCM method. To compare the results with the other previous studies the theoretical methods were assessed using collected data set. The results of evaluating the performance of theoretical methods are given in Fig. 6 and Table 4. Reviewing Table 4 and Fig. 6 shows that the DCM$_{h-i}$ and DCM$_{v-i}$ are the most accurate methods among the empirical approaches. These results ensured the results of experimental runs. The results of this study uphold the results of studies which were conducted by Seckin (2004) and Unal et al. (2010) that stated the accuracy DCM is better than the other empirical formulas. The results of this study also uphold the results of studies which were carried out by Khatua et al. (2012) and Mohanty and Khatua (2014) that proposed a Modified divided channel method for calculating the discharge of flow in compound open channel.
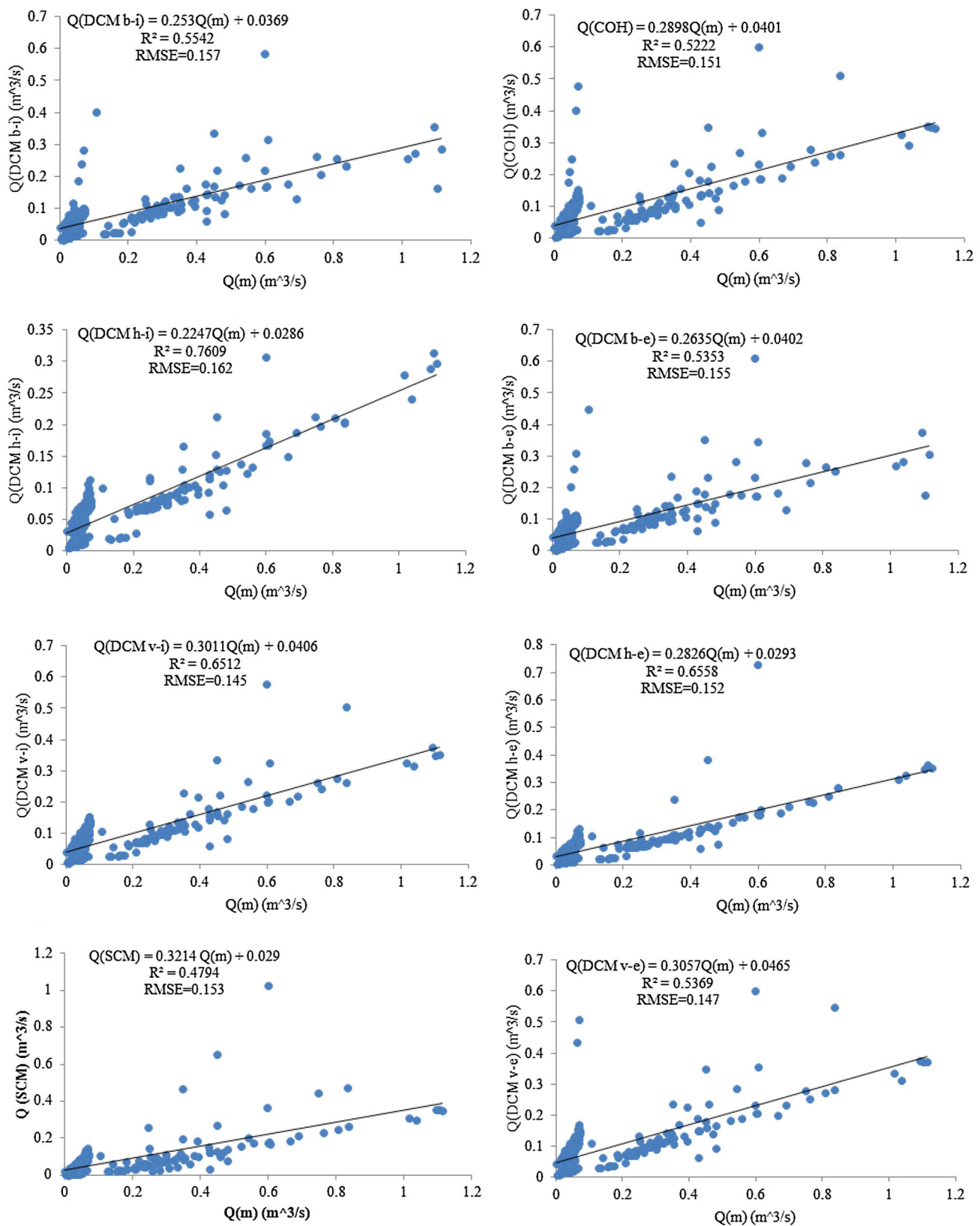
Fig. 6 Correlation between the results of analytical approaches versus the measured discharge (collected data set)

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Table 4 Error indices result of the analytical approaches

Method	R^2	RMSE	MAE	APE	MAPE	E_R
SCM	0.48	0.153	0.101	85.6	58.8	−0.106
DCM_{v-e}	0.54	0.147	0.093	109	73.9	0.128
DCM_{v-i}	0.65	0.145	0.093	105	68.8	0.087
DCM_{h-e}	0.66	0.152	0.106	86.9	45.4	−0.093
DCM_{h-i}	0.76	0.162	0.103	94.3	58.8	−0.019
DCM_{d-e}	0.53	0.155	0.099	105.6	65.9	0.093
DCM_{d-i}	0.55	0.637	0.099	101.1	60.8	0.048
COHM	0.52	0.151	0.097	86.5	64.9	−0.097

Conclusion

The results of this study showed that the classical formula for calculating the discharges of flow in compound open channel has no suitable performance. Therefore, modifications of these formulas are inescapable. The divided channel section is the accurate approach which has suitable performance for calculating the discharge of flow in compound open channel. The results of this study show that assuming the vertical separated boundary line in the divided channel method for individualizing the subsections increases the performance of estimating the discharge of flow.

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