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Issam A. Al-Khatib[a], Khaled A. Abaza[b] & Jumana I. Khatib[c]

[a] Institute of Environmental and Water Studies, Birzeit University, Birzeit, Palestine

[b] Department of Civil Engineering, Birzeit University, Birzeit, Palestine

[c] Faculty of Graduate Studies, Institute of Environmental and Water Studies, Birzeit University, Birzeit, Palestine

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An empirical discharge prediction model for smooth asymmetric compound rectangular channel validated using area method

Issam A. Al-Khatib[a]*, Khaled A. Abaza[b] and Jumana I. Khatib[c]

[a]*Institute of Environmental and Water Studies, Birzeit University, Birzeit, Palestine;* [b]*Department of Civil Engineering, Birzeit University, Birzeit, Palestine;* [c]*Faculty of Graduate Studies, Institute of Environmental and Water Studies, Birzeit University, Birzeit, Palestine*

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This paper presents an empirical, non-linear, multivariable regression model for predicting discharge in smooth asymmetric compound rectangular channel. The model is developed using experimental discharge data generated from testing nine different channel cross-sections with varied geometric dimensions. The predictive strength of the developed regression model is validated using several major statistics. All deployed statistics have indicated that the developed model is highly significant. In addition, the area method has been used to validate the model's discharge predictive strength. The area method predicts discharge mainly based on the cross-section geometry and apparent shear stress. As obtained from the literature, a sample of three different regression-based models has been used to estimate the apparent shear stress. Therefore, three different sets of discharge have been predicted using the area method. The four sets of discharge predicted using the developed regression model and area method have been compared to their corresponding experimental values using the sum of squared errors (SSE). The outcome is that seven channel cross-sections out of nine tested ones resulted in minimum SSE values when discharge predicted using the developed regression model.

Keywords: area method; discharge prediction; regression analysis; compound cross-section

1. Introduction

Many rivers have attracted ancient civilizations as they contribute to the human well-being by providing convenient transportation, sustainable energy, water for household consumption, industry and irrigation, and scenic and wildlife habitat (Bousmar 2002; Sun 2007). Discharge measurement in open channels is one of the main concerns in hydraulic, irrigation, and drainage engineering (Yen 2002; Seckin 2004; Luo 2011; Al-Khatib et al. 2012). Since the early works by Sellin (1964), many researchers have studied compound channel flow and proposed several computational methods to model the stage–discharge relationships (Ervine and Baird 1982; Knight and Demetriou 1983; Bousmar and Zech 1999).

Stage–discharge modeling in compound channels is a convoluted matter. Indeed, due to the higher velocities in the main channel compared to the floodplains, development of shear layers at the interfaces between the main channel and floodplains, and the channel conveyance is affected by a momentum transfer associated with these shear layers (Myers 1978; Keller and Rodi 1988; Lyness et al. 1997; Zeng et al. 2012; Rimkus 2013).

Hydraulic engineers are always searching for suitable methods to estimate the mean discharge in a variety of channel sizes and shapes with a minimal need for substantial measurement (Jan and Chang 2009). Not only is the currently used metering often expensive and difficult to carry out, but also the multipoint gauging required for high accuracy cannot easily be carried out fast enough at times of changing flow characteristics, which is not uncommon for almost all natural and some manmade channels (Maghrebi and Ball 2006; Huthoff et al. 2008; Khatua et al. 2012).

It is necessary to understand the flow characteristics of rivers considering both overbank and inbank flow conditions. When the flow occurs during a flood, there is a significant increase in the complexity of flow behavior, even for relatively straight reaches (Castanedo et al. 2005; Van Prooijen et al. 2005). In a prismatic compound channel, the velocity differences between the main channel and floodplain flows may produce strong lateral shear layers, which can lead to the generation of large-scale turbulent structures as indicated by different researchers (Sellin 1964; Ikeda 1999; Bousmar 2002; Ikeda et al. 2002; Rezaei and Knight 2011; Hubert 2013).

Flooding in a river is a complex phenomenon which affects the economic condition and livelihood of the region. A two-course compound channel usually results when flooding flow overtops the river course and spreads around the floodplain. It has been observed that the flow velocity in the actual river course is faster than that in the floodplains. This can produce large shear layers between sections of flow and produces turbulent structures which generate additional uncertainty and resistance in flow estimation. Researchers have adopted different empirical, analytical, and numerical models to analyze this complex situation (Meile et al. 2011; Sahu et al. 2011; Sahu et al. 2014).

The objective of this study is to present a multivariable regression model that can predict discharge in smooth asymmetric compound rectangular channel using mainly the channel cross-section geometry and flow depth. In addition, the

*Corresponding author. Email: ikhatib@birzeit.edu

area method has been used to validate the prediction strength of the developed regression model. A sample of three models for predicting apparent shear stress has been used in conjunction with the area method.

1.1. *Theoretical considerations of the area method*

In a study performed by Stephenson and Kolovopoulos (1990), a method developed by Holden (1986), called the area method, was analyzed. In this method, the main channel and floodplain are separated by an inclined interface such that there is a zero shear on the interface as depicted in Figure 1. Therefore, the interface is not included in the wetted perimeter of the main channel.

Holden (1986) was able to calculate the additional area to be added to the floodplains or subtracted from the main channel flow by employing momentum principles. The area correction (ΔA) is derived theoretically from the equilibrium of the shear forces acting on the floodplain region when a vertical interface divides the main channel from the floodplain. The equilibrium of these shear forces can be stated as presented in Equation (1).

$$F_{bf} - \tau_{av}(h - z) = \gamma A_f S_o \tag{1}$$

where F_{bf} = the total boundary shear force acting on the floodplain; τ_{av} = apparent shear stress acting on the vertical interface; h = water depth in the main channel; z = step height of model cross-section; γ = specific weight of water; S_o = bottom slope of the main channel; and A_f = cross-sectional area of the floodplain.

If an inclined interface is used, as shown in Figure 1, such that there is zero shear acting on the interface, then the total shear force will be as indicated by Equation (2).

$$F_{bf} = \gamma(A_f + \Delta A)S_o \tag{2}$$

By combining Equations (1) and (2), an expression for the area correction (ΔA) can be obtained as provided in Equation (3).

$$\Delta A = \tau_{av}(h - z)/\gamma S_o \tag{3}$$

In the literature, there are several models developed for predicting the apparent shear stress for compound channels. These models are essentially empirical regression-based models that depend largely on the channel cross-section geometry and flow characteristics. For example, Prinos and Townsend (1984), Christodoulou (1992), and Martin-Vide and Moreta (2008) proposed different regression-based models for estimating the apparent shear stress as presented in Equations (4)–(6), respectively. These three outlined models predict the apparent shear stress using mainly the cross-section dimensions and velocity difference (ΔV_v). These three models will be used in the validation process as the input requirements for using them are readily available from the experimental work. Another set of similar models for predicting the apparent shear stress is provided in Table 1 for future reference. However, the three models presented in Equations (4)–(6) will only be used to compare and validate the results obtained from the regression model presented in this paper. The authors believe that using only three models is adequate for carrying out the validation process without undermining the standing of the non-used ones.

$$\tau_{av} = 0.874\left(\frac{h - z}{h}\right)^{1.129}\left(\frac{B_f}{B}\right)^{-0.514}(\Delta V_v)^{0.92} \tag{4}$$

$$\tau_{av} = 0.005\rho\left(\frac{B_o}{B}\right)(\Delta V_v)^2 \tag{5}$$

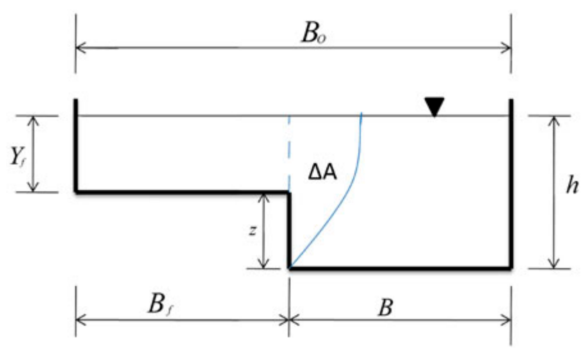


Figure 1. Schematic representation of the inclined interface plane.

Table 1. Sample apparent shear stress models found in the literature.

Equation	Reference
$\tau_{av} = \rho \frac{7.1}{N_{of}} (\Delta V_v)^2$	Ervine and Baird (1982)
N_{of} = number of floodplains	
$\tau_{av} = 13.84(\Delta V_v)^{0.882} \left(\frac{H}{h}\right)^{-3.123} \left(\frac{B_f}{b}\right)^{-0.727}$	Wormleaton et al. (1982)
$\tau_{av} = \left[\left(\frac{50}{[\propto -1]\delta+1}\right) - \frac{1}{2}\left\{100 - 48[\propto -0.8]^{0.289}(2\delta)^{\frac{1}{m}}\left(1 + 1.02\delta^{\frac{1}{2}}\log_{10}(\emptyset)\right)\right\}\right]\left(\frac{\rho g A S_0}{H-h}\right)$	Knight and Hamed (1984)
$\propto = \left(\frac{b+B_f}{b}\right),\ \delta = \left(\frac{H-h}{H}\right),\ \emptyset = \frac{n_f}{n_{mc}}$	
$\tau_{av} = 3.325(\Delta V_v)^{1.451}(H-h)^{0.345}B_f^{0.519}$	Wormleaton and Merrett (1990)
$\tau_{av} = 0.03\rho(\Delta V_v)^2$	Smart (1992)

τ_{av} (N/m^2), ρ (kg/m^3), g (m/s^2), A_{mc} (m^2), S_o (m/m), h (m), Z (m), ΔV_v (m/s), B_f (m), B (m).

$$\tau_{av} = 0.002\rho \frac{B_o}{B}\left(\frac{2z}{B}\right)^{-1/3}\left[\frac{(h-z)}{h}\right]^{-1/3}(\Delta V_v)^2 \tag{6}$$

where ΔV_v = difference in velocities between floodplain and main channel with vertical interface as obtained from the Manning's formula; B = width of the main channel; B_f = width of the floodplain; and ρ = water density.

Therefore, the discharges in the main channel and floodplain can be estimated from Manning's formula as indicated by Equations (7) and (8), respectively. It can be noted that the correction area (ΔA) is subtracted from the main channel area (A_{mc}) while it is added to the floodplain area (A_f).

$$Q_{mc} = \frac{(A_{mc} - \Delta A)}{n_{mc}} R_{mc}^{2/3} S_o^{1/2} \tag{7}$$

$$Q_f = \frac{(A_f + \Delta A)}{n_f} R_f^{2/3} S_o^{1/2} \tag{8}$$

where n_{mc} = Manning's roughness coefficient of the main channel taken to 0.013; n_f = Manning's roughness coefficient of the floodplain taken to be 0.013; $R_f = A_f/P_f$ = hydraulic radius of the floodplain; P_f = wetted perimeter of the floodplain; and Q_f = discharge in the floodplain. Consequently, the total discharge (Q) in the asymmetric compound channel is obtained as provided in Equation (9).

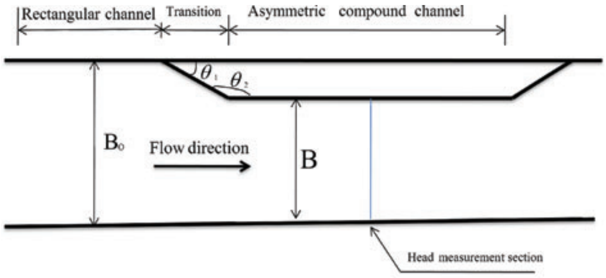
$$Q = Q_{mc} + Q_f \tag{9}$$

2. Setup and experiments

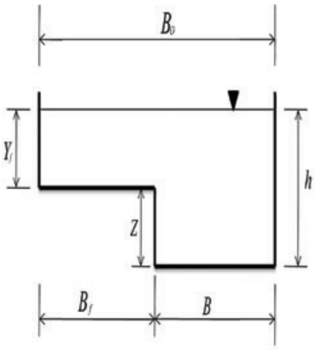
The experiments were carried out in a glass-walled horizontal laboratory smooth flume 7.5 m long, 0.30 m wide, and 0.3 m deep with a bottom slope of 0.0025 at the fluid mechanics laboratory, Mechanical Engineering Department, Birzeit University, Palestine. The discharge was measured volumetrically at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

Models of asymmetric rectangular compound cross-sections were manufactured from Plexiglas and placed at about mid length of the laboratory flume. Figure 2 shows the plan view and cross-section of the models with symbols designating important dimensions of model elements. The dimensions of the nine models used in the experiments are given in Table 2. In this study, the nine models tested are denoted by Mi (i = 1–9) with different combinations of (B) and (z) values. The (B) and (z) represent the width and step height of the main channel of the asymmetric compound cross-section, respectively.

The required experiments were first conducted using models of smallest B value (10 cm) with varying z values (4, 6, and 8 cm), then B was increased to 15 cm with the same three values of z (4, 6, and 8 cm), and finally for (B = 20 cm) with the same z values. The entrance angles (θ_1 and θ_2) were taken to be 26.565° and 153.35°, respectively. The transition length was twice of the floodplain width (B_f). Readers can consult reference Al-Khatib et al. (2012) for additional details about the experimental setup and experiments.



(a) Plan view



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

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

Table 2. Dimensions of tested models.

Types of models	B (cm)	z (cm)	B_f (cm)	B_0 (cm)	θ_1 (°)	θ_2 (°)	B/z (–)	B_0/B (–)	B_f/B (–)	B_0/B_f (–)
M1	10	4	20	30	26.57	153.43	2.50	7.50	2.0	1.5
M2	10	6	20	30	26.57	153.43	1.67	5.00	2.0	1.5
M3	10	8	20	30	26.57	153.43	1.25	3.75	2.0	1.5
M4	15	4	15	30	26.57	153.43	3.75	7.50	1.0	2.0
M5	15	6	15	30	26.57	153.43	2.50	5.00	1.0	2.0
M6	15	8	15	30	26.57	153.43	1.88	3.75	1.0	2.0
M7	20	4	10	30	26.57	153.43	5.00	7.50	0.5	3.0
M8	20	6	10	30	26.57	153.43	3.33	5.00	0.5	3.0
M9	20	8	10	30	26.57	153.43	2.50	3.75	0.5	3.0

3. Presentation and discussion of results

In this section, a multivariable regression model is presented for predicting discharge in a compound rectangular channel. In addition, the discharge has been predicted using the outlined area method with apparent shear stress estimated as outlined in Equations (4)–(6). The area method is mainly used to validate the results obtained from the regression-based model. This has been achieved by comparing the predicted discharges from the developed regression model against their corresponding values predicted using the area method with three different apparent shear stress models. The best-fit model amongst the four predictive discharge models has been identified based on the minimization of the sum of squared errors (SSE).

3.1. *Multivariable regression analysis*

The experimentally measured discharges associated with the nine outlined compound channel cross-sections were used to develop a multiple variable regression model as presented in Equation (10). The independent variables are five dimensionless parameters defined using the cross-section geometric dimensions (B_o, B_f, z) and flow depths (Y_f and h). The discharges were measured using flow depth ratio ranges (Y_f/h and Y_f/B_f) as provided in Table 4 for the nine tested channel cross-sections. The developed multivariable regression model was tested for reliability using several key statistics as provided in Table 3. They include the model R-square, standard error, and F-statistic which are all highly significant. Also, provided are the t-statistics associated with the model coefficients which are all associated with 99.99% confidence level.

Table 3. Summary of statistics for developed multivariable regression predictive model.

Predicted parameter	Model R-square	Model standard error	Model F-statistic	Model coefficients	Coefficient t-statistic	Confidence level (%)	Coefficient VIF
Ln(Q)	0.979	0.0023	971.5	–*	–	99.9	–
				−0.287	−73.506	99.9	–
				0.016	48.717	99.9	4.229
				0.081	30.455	99.9	2.181
				−0.038	−24.696	99.9	9.383
				−0.046	−7.889	99.9	7.526

*Not applicable.

In addition, the variance inflation factor (VIF) indicator has been estimated for each coefficient and all values are below the recommended threshold value of 10. The VIF measures the impact of collinearity among the independent variables in a regression model on the precision of estimation. It expresses the degree to which collinearity among the predictors degrades the precision of an estimate. The predictive strength of the developed multivariable regression model has been validated and compared to the discharges predicted using the area method incorporating the three outlined apparent shear stress models.

$$\mathrm{Ln}(Q) = -0.287 + 0.016\left[\left(\frac{B_o}{Z}\right)\right] + 0.081\frac{1}{\left(\frac{B}{Z}\right)^{0.5}} - 0.038\left(\frac{Y_f}{Z}\right) - 0.046\left(\frac{Y_f}{h}\right)^{0.5} \tag{10}$$

3.2. *Area method application*

The discharge in the compound rectangular channel can be predicted using the outlined area method. The required area correction (ΔA) has been estimated using Equation (3) with the apparent shear stress (τ_{av}) calculated from three different regression-based models as provided in Equations (4)–(6). The discharges in the main channel (Q_{mc}) and floodplain (Q_f) are then estimated using Manning's formula as outlined in Equations (7) and (8), respectively. The total channel discharge is estimated as the sum of both discharges. The discharge has been predicted at different flow depths with the corresponding flow depth ratio ranges (Y_f/h and Y_f/B_f) as provided in Table 4 for the nine tested channel cross-sections. Three different discharges have been predicted for a specific water depth ratio using the three referenced regression-based models as provided in Equations (4)–(6). The three used regression-based models are referenced to the researchers who had developed them and the regression model developed in this paper is called Equation (10).

3.3. *Best-fit prediction model selection*

The predicted discharges (Q_p) have been plotted against the corresponding measured discharges (Q_m) for each tested compound channel cross-section type (M1-M9) as shown in Figures 3–11, respectively. Each figure shows four plotted curves

Table 4. Potential and best-fit discharge prediction models for tested channel cross-section type.

Channel cross-section type	(Y_f/h) Range	(Y_f/B_f) Range	Potential models	Best-fit model
M1	0.394–0.669	0.130–0.405	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Equation (10)
M2	0.268–0.559	0.110–0.380	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Martin-Vide and Moreta (2008)
M3	0.158–0.543	0.075–0.475	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Equation (10)
M4	0.385–0.639	0.167–0.473	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Equation (10)
M5	0.155–0.504	0.073–0.407	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Prinos and Townsend (1984)
M6	0.111–0.506	0.067–0.547	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Equation (10)
M7	0.286–0.649	0.160–0.740	Equation (10), (Prinos and Townsend 1984; Cristodoulou 1992; Martin-Vide and Moreta 2008)	Equation (10)
M8	0.167–0.512	0.120–0.630	Equation (10), Prinos and Townsend (1984)	Equation (10)
M9	0.158–0.470	0.150–0.710	Equation (10), Martin-Vide and Moreta (2008)	Equation (10)

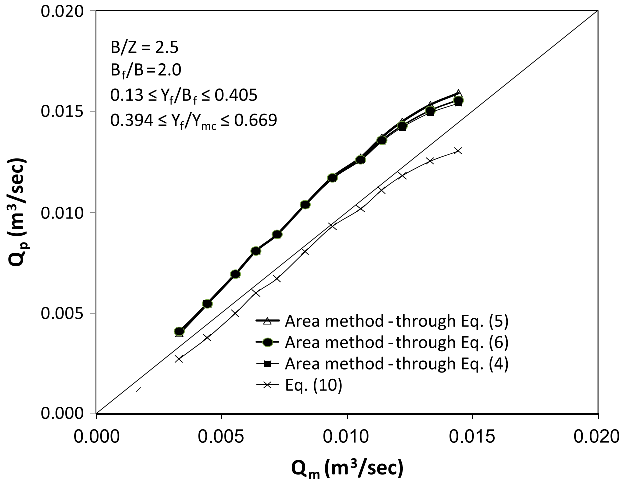


Figure 3. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M1.

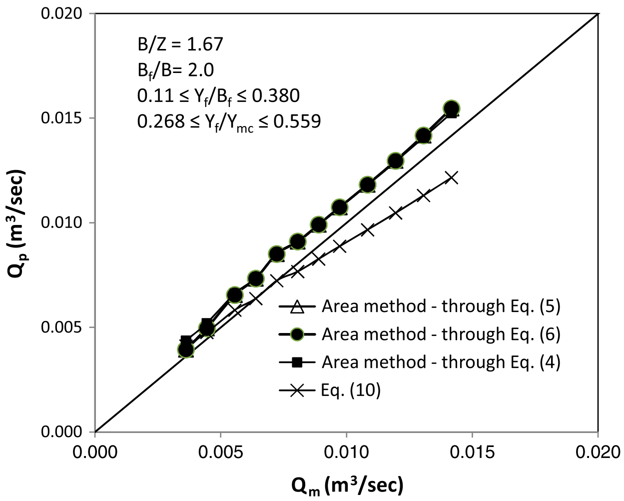


Figure 4. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M2.

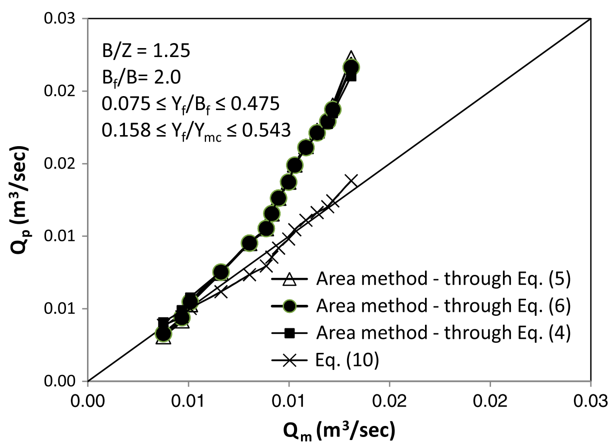


Figure 5. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M3.

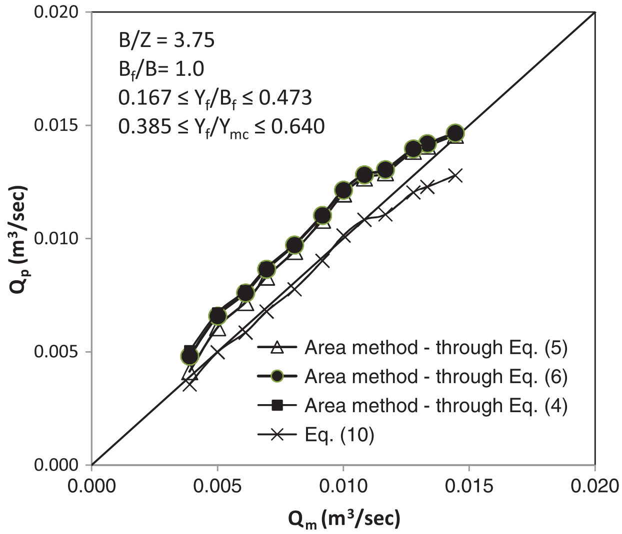


Figure 6. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M4.

representing the four predicted discharges as obtained from the regression model developed in this paper (Equation (10)), and the other three are based on the works of the researchers Prinos and Townsend (1984), Christodoulou (1992), and Martin-Vide and Moreta (2008). Examination of the plotted curves reveals that the four predicted discharges are closely similar to each other in few cases such as tested model types (M5 and M6) shown in Figures 7 and 8, respectively, while they are not that similar in the remaining cases. In addition, the four predicted discharges are closely similar to their corresponding measured values in certain cases. In each tested model, those models with predicted discharges being close to their corresponding measured ones are visually identified as potential predictive models as provided in Table 4. However, the best-fit model is identified based on minimizing the SSE as defined in Equation (11) with the error being defined as the difference between the predicted discharge and the corresponding measured value. Table 4 provides the best-fit predictive model for each tested compound channel model type (M1–M9). It can be noted that the multivariable regression model presented in this paper (i.e. Equation (10)) has been identified as the best-fit model in seven cases out of nine. This indicates that the presented multivariable regression model is highly reliable in predicting discharge in asymmetric compound rectangular channel.

$$\text{Min.SSE} = \sum_{n} (Q_p - Q_m)^2 \tag{11}$$

where Q_p = predicted discharge (m^3/s); Q_m = experimentally measured discharge (m^3/s); and n = number of discharge data points used in the analysis.

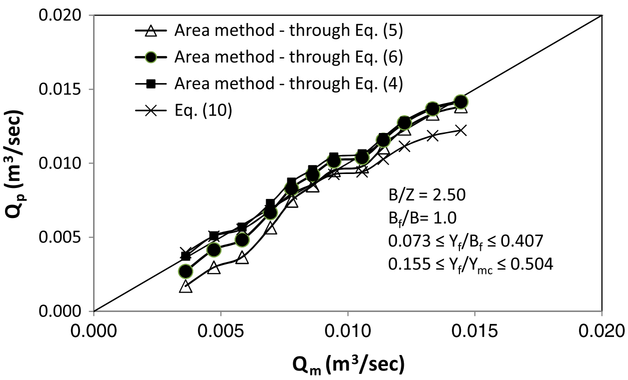


Figure 7. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M5.

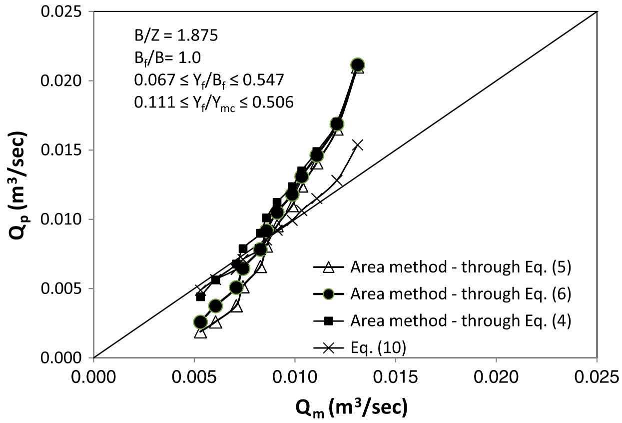


Figure 8. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M6.

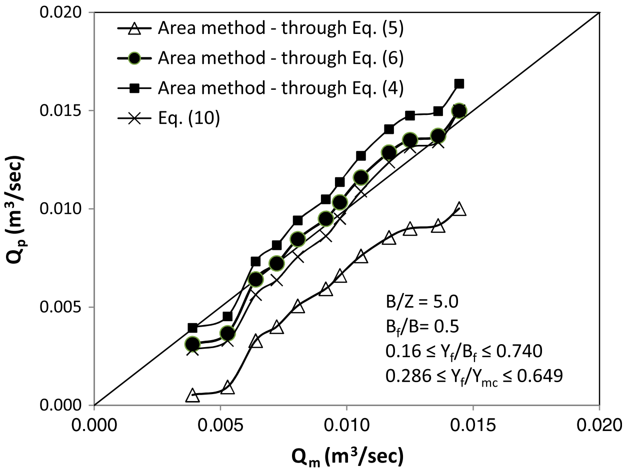


Figure 9. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M7.

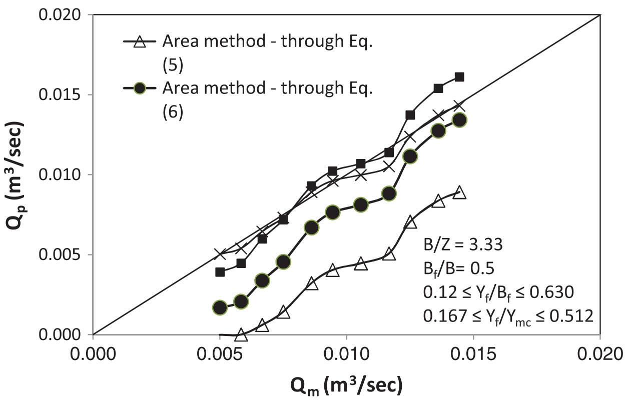


Figure 10. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M8.

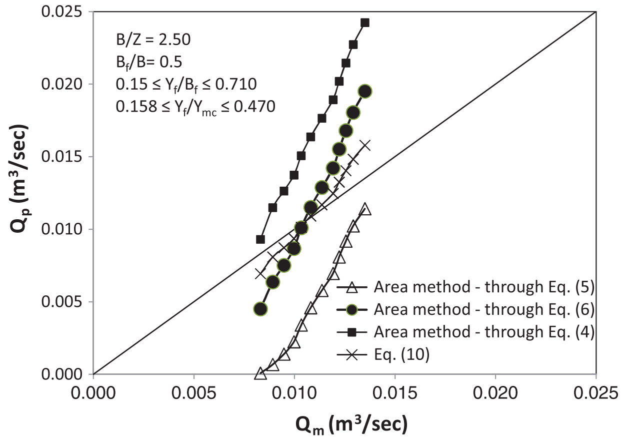


Figure 11. Comparison of discharge calculation methods using the area method by introducing the value of τ_{av} from Equations (4)–(6) with measured discharges for model M9.

4. Conclusions and recommendations

The discharges in smooth asymmetric compound rectangular channel were experimentally measured using nine different channel cross-section types with varied dimensions. The discharges were measured using variable flow depths resulting in specified ranges of flow depth ratios, namely, (Y_f/h and Y_f/B_f), for each tested cross-section model. The experimentally measured discharges as obtained from the nine constructed channel cross-section types were used to develop a multivariable regression model. The developed multivariable regression model can predict the discharge using five independent variables representing five dimensionless ratios defined using the cross-section geometry and flow depth. The discharges predicted from the regression model have been compared to their corresponding experimental values, and close agreement has been observed in the nine tested cross-sections. In addition, the key statistics used to validate the predictive strength of the developed regression model have all indicated its high confidence and reliability.

In addition, the predicted discharges have been validated using the outlined area method which requires the estimation of an area correction to be used in the Manning's formula. The area correction is a function of the apparent shear stress which has been estimated using three different regression-based models representing the works of three researchers. Therefore, three different sets of discharge were predicted using the area method besides the one predicted from the developed regression model. The four predicted sets of discharge have been compared to their corresponding experimental values using minimization of SSE. The result is that seven out of nine tested channel cross-section types showed that the smallest SSE values are associated with discharges predicted using the developed multivariable regression model. This is another indicator that the developed regression model is a reliable one to be used in predicting discharge in asymmetric compound rectangular channel.

For future research, it is recommended that discharge prediction validation can be performed using advanced methods appearing in literatures among which are the methods presented by Shiono and Knight (1991), Ackers (1993a, 1993b), Yang et al. (2005), Wang et al. (2007), Huthoff et al. (2008), Khatua et al. (2012), and Mohanty and Khatua (2014). In this paper, the area method is only used because of its simple and minimal data requirement, and because the apparent shear stress is estimated from regression-based models that are compatible to the regression model presented in this paper.

Notations

The following symbols are used in this paper:

A_f	floodplain cross-sectional area;
A_{mc}	main channel cross-sectional area;
B	width of the main channel;
B_f	bottom width of floodplain;
B_o	bottom width of the upstream channel;
F_{bf}	total boundary shear force acting on the floodplain;
g	acceleration of gravity;
h	main channel water depth;
n_{mc}	manning roughness coefficient of the main channel;
n_f	manning roughness coefficient of the floodplain;
$R_f = A_f/P_f$	hydraulic radius of the floodplain;

P_f wetted perimeter of the floodplain;
Q_f discharge in the floodplain;
Q_{mc} discharge in the main channel;
Q total volumetric rate of flow; $Q = Q_{mc} + Q_f$
R-square determination coefficient;
S_o bottom slope of the main channel;
VIF variance inflation factors;
Y_f floodplain water depth = $h - z$;
Z step height of model cross-section;
ΔV_v difference between velocity on floodplain and in main channel with vertical interface from the manning formula;
τ_{av} apparent shear stress on the vertical interface;
τ_r relative apparent shear stress;
ΔA area correction;
P water density;
A energy correction coefficient;
θ_1 and θ_2 entrance angles;
γ specific weight of water;

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