A NEW APPROACH FOR DISCHARGE PREDICTION IN A PARTLY VEGETATED CHANNEL: ADAPTATION OF THE INTERACTING DIVIDED CHANNEL METHOD (IDCM)

Mouldi Ben Meftah [1*], Francesca De Serio [1], Diana De Padova [1], Michele Mossa [1] & Danish Ali Bhutto [2]

*(1) Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica, Politecnico di Bari (Bari); (2) Dipartimento di Scienze Agro Ambientali e Territoriali, Università degli Studi di Bari *email: mouldi.benmeftah@poliba.it*

KEY POINTS

- *Discharge prediction in partly vegetated channel flows*
- *Adaptation of the Interacting Divided Channel Method (IDCM)*
- *Consideration of curved interface and large-scale roughness elements*

1 INTRODUCTION

Predicting discharge in vegetated channels can be challenging due to the complex flow dynamics resulting from the presence of vegetation which impacts flow resistance and hence discharge. Natural watercourses, i.e., rivers, streams, wetlands, and estuaries, can often be considered compound channels, characterized by an unvegetated main channel and one or more vegetated areas (*White & Nepf*, 2007; *Ben Meftah et al.*, 2014; *Ben Meftah & Mossa*, 2016, 2023; *Ben Meftah et al.*, 2024). Accurate estimation of flow conveyance in natural watercourses can help reduce the impact of floods on human life and property. Partly vegetated channels exhibit hydrodynamic behaviors like those of a compound channel, consisting of a main channel and one or two-side floodplains of varying geometry and roughness (*Tang*, 2017; *Yang et al.*, 2019). In a partly vegetated channel with emergent vegetation, a shear layer forms at the interface between the main channel and an adjacent vegetated area. The large velocity gradient that occurs at the interface generates high turbulence and transverse momentum transfer from faster to slower flow subareas (*Ben Meftah & Mossa*, 2023). The variation in flow structures between different subsections increases the difficulty in accurately estimating flow discharge in compound channels. The familiar methods often used to predict channel discharges are the Single Channel Method (SCM) and Divided Channel Method (DCM). Both methods are based on standard Chezy, Manning, and Darcy-Weisbach equations, treating the cross-section as a single channel or dividing it horizontally, vertically, or diagonally into noninteracting subareas (*Huthoff et al.*, 2008; *Tang*, 2017).

Previous studies (e.g., *Prinos & Townsend*, 1984; *Al-Khatib et al.*, 2012), confirmed that conventional SCM and DCM methods overestimate or underestimate flow discharge in open channel flows. In general, the DCM predicts better results as compared to SCM and it is currently used, because of its simplicity, for most practical models for open channel flows, i.e., HEC-RAS, SOBEK, MIKE 11 (*Tang*, 2017).

Because the classical 1-D methods, such as the DCM method, are simple and easy to apply for modelling stage-discharge relations in compound channels, in this study, we tried to adopt the Interacting Divided Channel Method (IDCM) proposed by *Huthoff et al*. (2008), for compound channels with floodplains without large-scale roughness elements (such as vegetation stems), to predict the discharge of a partly vegetated channel. The peculiarity of the IDCM method is that it includes the effects of lateral momentum transfer, which improves the reliability of discharge predictions. The novelty of this study is the consideration of both large-scale roughness elements (consisting of vegetation stems) and a curved-division interface plane by applying the IDCM method. The approach was supported by providing a series of experiments in addition to data collected from previous studies.

2 IDCM APPROACH TO PARTLY VEGETATED CHANNEL

In this study, we adapted the IDCM method by *Huthoff et al*. (2008) based on the concept of apparent shear stress at an arbitrary curved inclined interface plane between the vegetated and unvegetated regions. Figure 1 shows a descriptive scheme (zone III) of the curved inclined interface plane. The curved line originates from the bottom boundary layer at the interface between zone I and zone III (y = 0) and ends at the free surface flow, at the intersection between zone III and zone II. The curved line (blue color in Figure 1) separates the cross-section area A3 of zone III into subareas of cross-sections Aa3 (subject of apparent shear stress) and Ab3 (subject of boundary shear stress).

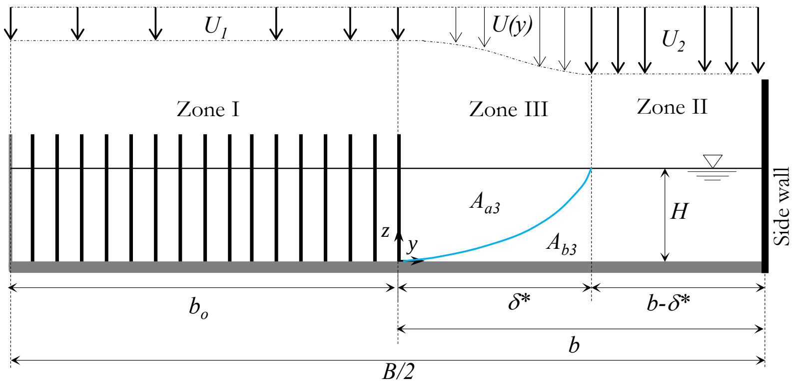

Figure 1. Problem description at the interface between the vegetated and unvegetated domains, where *B* is the channel width, *b* is the unobstructed width, b_o is the obstructed width, *H* is the flow depth, *U* is the streamwise velocity, U_1 is the flow pore velocity inside the vegetated region, U_2 is the free-stream velocity in the unvegetated area, (*y*,*z*) are the transversal and vertical coordinates, and δ^* is the shear layer width.

The momentum balance per unit length in the streamwise direction of channel subareas, separated by the curved interface, as shown in Figure 1, can be written as:

$$\rho g A_{23} S = \rho f_{23} {U_{23}}^2 P_{23} + \tau_a h' \tag{1}$$

$$\rho g A_{13} S = \rho f_{13} {U_{13}}^2 P_{13} + F_d - \tau_a h' \tag{2}$$

The left-hand sides of eqs. (1) and (2) represent the streamwise component of the gravitational force per unit length in the unobstructed and obstructed (by vegetation) subareas of cross-sections A_{23} and A_{13}. The first terms on the right-hand side of eqs. (1) and (2) represent the boundary shear forces per unit length along the wetted perimeters of the cross-sections A_{23} and A_{13}. The second term, F_d, on the right-hand side of eq. (2) represents the vegetated-induced drag force per unit length. The last terms on the right-hand side of eqs. (1) and (2) represent the apparent shear force per unit length along the interface curved plane (blue line in Figure 1) between the subareas of cross-sections A_{23} and A_{13} (*Tang*, 2019). In eqs. (1) and (2), ρ is the water density, g is the gravitational acceleration, $A_{23} = A_{b3} + A_2$ and $A_{13} = A_{a3} + A_1$ are the cross-sectional areas delimited by the interface curved plane, A_1 and A_2 are the cross-sectional areas of zone I and zone II, respectively, S is the free surface slope, f_{23} and f_{13} are respectively the frictional factors of the subareas A_{23} and A_{13}, U_{13} and U_{23} are the mean velocities in the cross-sections A_{13} and A_{23}, respectively, P_{13} and P_{23} are the wetted perimeters (excluding the interface length) relative to the cross-sections A_{13} and A_{23}, respectively, τ_a is the apparent shear stress acting at the interface curved plane, and h' is the interface length (blue line in Figure 1).

According to previous studies (e.g., *Huthoff et al.*, 2008; *Tang*, 2019) the interfacial apparent shear stress is directly proportional to the difference in squared velocities U_{23} and U_{13} of the mean and obstructed subareas and can be expressed as:

$$\tau_a = \frac{1}{2}\rho\gamma\left({U_{23}}^2 - {U_{13}}^2\right) \tag{3}$$

where γ is an interface constant to be determined.

After some algebra arrangements (*Ben Meftah & Mossa*, 2023) one can obtain the following unified equations for U_{23} and U_{13}:

$$ {U_{23}}^2 = {U_{23,0}}^2 - \frac{\frac{1}{2}\gamma\epsilon_{23}}{1+\frac{1}{2}\gamma(\epsilon_{23}+\epsilon_{13})}\left({U_{23,0}}^2 - {U_{13,0}}^2\right) \tag{4}$$

$$U_{13}{}^{2} = U_{13,0}{}^{2} + \frac{\frac{1}{2}\gamma\epsilon_{13}}{1+\frac{1}{2}\gamma(\epsilon_{23}+\epsilon_{13})}\left(U_{23,0}{}^{2} - U_{13,0}{}^{2}\right) \tag{5}$$

where

$$U_{23,0}{}^{2} = \frac{gR_{23}S}{f_{23}} \; and \; \epsilon_{23} = \frac{h'}{f_{23}P_{23}}; \qquad U_{13,0}{}^{2} = \frac{gR_{13}S}{f_{13}} - \frac{F_d}{\rho f_{13}P_{13}} \; and \; \epsilon_{13} = \frac{h'}{f_{13}P_{13}} \tag{6}$$

The novelty of this study lies in the consideration of the vegetation-drag effect (not addressed in previous studies) in the expression of $U_{13,0}$, as shown in Eq. (6). In eq. (6) $R_{23} = A_{23}/P_{23}$ and $R_{13} = A_{13}/P_{13}$ are respectively the hydraulic radii of the subarea of the main channel of cross-section A_{23} and the obstructed one of cross-section A_{13}.

The procedure to follow for the prediction of the zonal discharge and total discharge is:

Step 1: the process begins with a detailed determination of the different characteristics of the partly vegetated channel. Ben Meftah and Mossa (2023) proposed an expression to predict the width of the shear layer (zone III) δ^*.

Step 2: calculate the interface length h'.

Step 3: calculate the hydraulic radii R_{23} and R_{13}.

Step 4: calculate the coefficients ϵ_{23} and ϵ_{13}, using Eq. (6). Herein, the frictional factors will be calculated based on Manning's formulas as: $f_{23} = g(n_{23})^2(R_{23})^{-1/3}$ and $f_{13} = g(n_{13})^2(R_{13})^{-1/3}$.

Step 5: calculate the zonal mean velocities $U_{23,0}$ and $U_{13,0}$, using Eq. (6).

Step 6: calculate the predicted zonal mean velocities U_{23} and U_{13} based on Eqs. (4) and (5), respectively, with a given value of the coefficient γ.

Step 7: calculate the predicted zonal and total discharges.

3 EXPERIMENTAL SETUP

The physical model of partly vegetated channel was realized on a very large channel 15 m long, 4 m large and 0.4 m deep. The water was pumped from a large steel tank downstream to another upstream, using a Flygt centrifugal electric pump with a maximum discharge of 100 l/s. The vegetation was simulated using arrays of vertical, rigid, circular, and threaded steel cylinders. The cylinder height, h, is 0.31 m and its diameter, d, is 0.003 m. The array of cylinders is partially mounted in the central part of the channel, forming the experimental area of 3 m long and $2b_o$ width. Two symmetric lateral regions immediately adjacent to the channel sides, each of width b, are left for free flow circulation (Figure 2). Four experimental configurations, based on the contraction ratio C_r, were investigated, varying b and b_o. Cylinders are regularly arranged and spaced with a distance s = 5.0 cm, giving rise to a density, N, of 400 cylinders/m^2. The three flow velocity components were accurately measured using an Acoustic Doppler Velocimeter (ADV)-Vectrino, manufactured by Nortek.

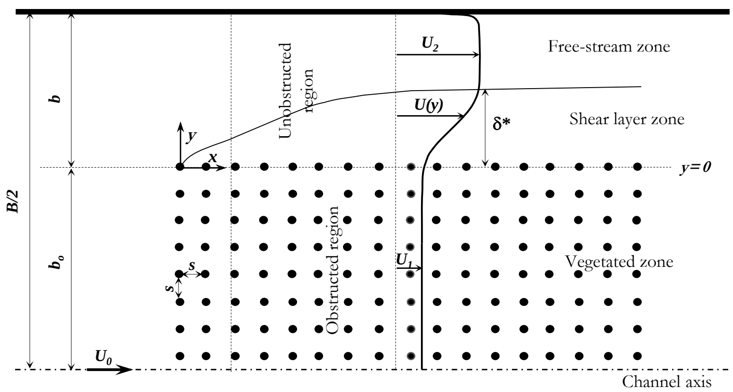

Figure 2. Schematic representation of the partly vegetated channel, where x is the longitudinal coordinate.

4 RESULTS

Figure 3 shows a comparison between the measured and predicted (applying the IDCM method) total channel discharges for all runs of the present study. It is worth mentioning that the results depicted in Figure 3 were obtained after testing different values of the curved interface line *h'* to reach the best performance, by varying the values of α (between 0 and 1) and γ. For all runs, the most accurate discharge prediction was obtained with values of $\alpha = 0.20$ ($\lambda = 0.80$) and $\gamma = 0.023$. A good performance of the IDCM method was also obtained with a similar value of γ (= 0.020) in a previous study by *Huthoff et al.* (2008), predicting flow discharges in a compound channel.

Based on the results achieved in this study, the IDCM method with a curved interface plane showed better performance in predicting the flow discharge in partly vegetated channels than the classical Divided Channel Method (DCM).

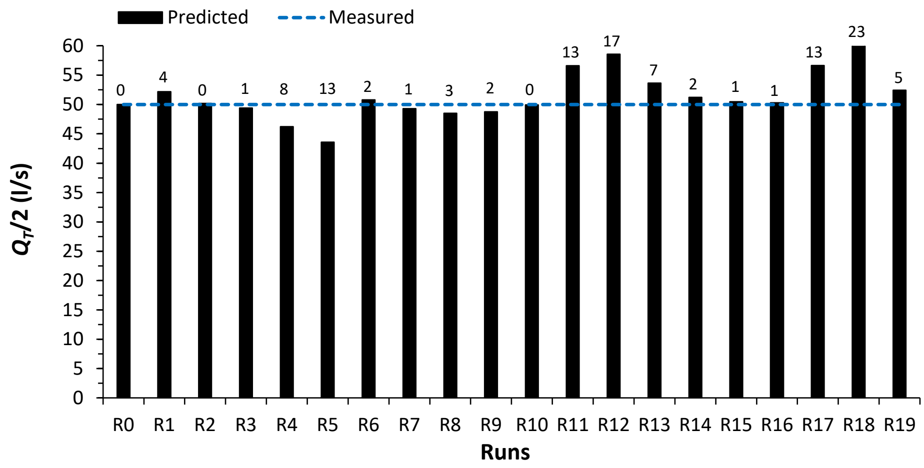

Figure 3. Predicted compared to measured total discharges using the IDCM method with a curved interface plane: $\alpha = 0.20$ ($\lambda = 0.80$) and $\gamma = 0.023$. The values of mean absolute percentage error $E_Q = 100[|Q_p\text{-}Q_m|/Q_m]$ of the different runs are shown above the histograms.

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