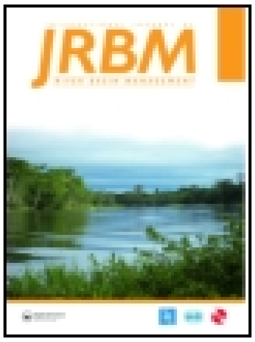

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RESEARCH PAPER

Estimation of water surface profiles using rating curves

Mahmoud F. Maghrebi and Ghadeer Ali

Civil Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran

ABSTRACT
Water surface profiles (WSPs) are among the most valuable information in artificial and natural open channels. Most of the conventional methods for computing the WSPs in compound channels are based on the water surface calculated by the divided channel method (DCM) which is used by HEC-RAS. However, this approach cannot predict the water surface with good accuracy when dealing with compound channels. Therefore a new approach is implemented to calculate the WSP. This approach consists of two steps. In the first step, the rating curve is computed based on the newly proposed method by Maghrebi et al. In the second step, based on the governing equations for gradually varied flow including energy equation, the WSP is computed. The experimental results reported for three sets of measured WSPs in compound channels and WSP measurements of the Main River are used to evaluate the accuracy of the proposed method. The results show that the proposed technique can predict the WSP with better accuracy in comparison to the HEC-RAS and CES models.

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CES; conveyance; HEC-RAS; rating curve; water surface profile

1. Introduction

Until now, economic damages and life's losses coupled with flooding are repeated near the river plains. Accurate estimation of water surface profiles (WSPs) is fundamental for the evaluation of hydraulic hazard, risk assessment, forecast and management as well as identification of the flow inundation areas under a specific discharge, planning and design of flood defense system and other waterworks (Vatankhah and Easa 2011, Cantero *et al.* 2015).

The estimation of WSPs relies on gradually varied flow principles such as energy or momentum equation, discharge prediction, velocity correction coefficients and critical depth (Sturm and Sadiq 1996, Chaudhry 2007). Prediction of discharge curve directly influences other related WSPs computation parameters such as energy line and critical depth (Cantero *et al.* 2015). Errors in estimating discharge may lead to significant errors in computing energy and momentum fluxes (Wormleaton and Hadjipanos 1985). Estimation of discharge is one of the major areas of uncertainty in natural rivers (Khatua *et al.* 2012). River channels usually have compound sections, which are consisting of the main channel for low discharges beside one or two floodplains when a high rainfall occurs. The flow in compound channels is typically 3-D with a faster speed in the main channel than in the floodplains resulting a lateral momentum transport and generating a large shear layer near the interface of the main channel and floodplains.

Conventional methods such single channel method (SCM) and divided channel method (DCM) are used commonly for prediction of discharge and water level. The SCM supposes that the velocity is uniform in the whole cross-section and solves the Manning equation for computing the discharge. The carrying capacity of this method for compound sections is underestimated (Rezaei 2006). Lotter (1933) proposed to divide the whole section into subsections, where the velocity is more uniform. Thus, discharge is computed based on the Manning equation for each subsection so the whole discharge is the sum of subsection discharges. This method is called the DCM. The line division may be either vertical, diagonal, or horizontal, with the most common and practical choice being the vertical ones. The results of the DCM are better than the SCM. Therefore the DCM is widely used in commercial software such as HEC-RAS (Hydrologic Engineering Center-River Analysis System). Ackers (1993) proposed the Coherence Method (COHM) where each subsection discharge calculated by the DCM is corrected using an empirical factor. Lambert and Myers (1998) developed the Weighting Divided Channel Method (WDCM). This method uses weighting factors resulting as the ratio of the averaged subsection velocity obtained from DCM with the vertical and horizontal divisions to correct the discharge. Shiono and Knight (1991) have developed the lateral Shiono and Knight method (SKM), which is based on the depth-averaged Reynolds Averaged Navier-Stocks equations (RANS). The roughness, the eddy viscosity and the secondary current effects are incorporated in the SKM method. Rezaei and Knight (2011) developed the SKM to work with non-prismatic channels. The SKM is used in the commercial software CES (Conveyance Estimation System) which is produced by the Government Department for Food and Rural Affairs, with contributions from the Scottish Government and the Rivers Agency in Northern Ireland, HR Wallingford, and the Environment Agency (EA), UK (Knight *et al.* 2009). Bousmar and Zech (1999) have presented the Exchange Discharge Model (EDM) as a 1-D model. They assumed that there is a momentum transfer proportional to the product of the velocity gradient at the interface of the main channel and floodplains by the mass discharge exchanged through this interface. Bousmar *et al.* (2004) using the EDM considered the effects of the momentum transfer in converging channels incorporated into an additional head loss. Proust *et al.* (2009) have presented ISM (Independent Subsections Method) for compound channels which treat the flow into each subsection

CONTACT Mahmoud F. Maghrebi maghrebi@um.ac.ir

separately. Khatua *et al.* (2012) proposed the modified divided-channel method (MDCM) to calculate the discharge in compound channels. They developed an equation for interaction length of interface for the calculation of momentum transfer. Maghrebi (2006) presented a technique for drawing the normalized isovel contours in an open or closed channel. He used the normalized isovel contours and the velocity measurement at a single point of a cross section to estimate the discharge in uniform flow channels. Maghrebi *et al.* (2017) based on the isovel contours and the geometrical parameters of the cross sections introduced a stage-discharge relationship for open channel flows.

Although 2-D and 3-D models are developed, which allow a more detailed nature of flow, when the nature of flow is not so complicated, it is preferred to use the 1-D models. One dimensional (1-D) modelling has many significant advantages when compared with 2-D and 3-D models. They can be listed as: less effort for collection of the initial data, shorter computational time and rapid interpretation of the results (Khatua *et al.* 2012). Therefore, multi-dimensional models should not replace 1-D modelling that is simple to use with low computational cost. The main purpose of this paper is to use the relationship introduced by Maghrebi *et al.* (2017) to estimate the conveyance of channel and to employ it in 1-D numerical models such as step method which is based on the energy equation for evaluating WSPs. Thence, the published experimental measurements of M1 and M2 water surface profiles by Sturm and Sadiq (1996), and Bousmar (2002), and measurements of the Main River in Northern Ireland are used as the most accurate profiles. Eventually, the performance of all of the water surface profiles such as HEC-RAS and CES as well as the one which is calculated by the proposed model are compared with each other.

2. Materials and methods

2.1. Gradually-varied flow

When the water surface slope is parallel to the channel bed, the flow is uniform. The gradually-varied flow (GVF) is a non-uniform flow with gradual changes in its water surface depth (Chaudhry 2007). The computation of the non-uniform flow is based on the energy and momentum conservation laws. In derivation of the energy GVF equation, the total energy H for an arbitrary section of a prismatic channel can be written as:

$$H = z + h + \frac{\alpha V^2}{2g} \tag{1}$$

where z is the elevation of the channel bed above the datum, h is the flow depth, V is the mean velocity, α is the velocity correction coefficient, and g is the gravity acceleration. Differentiating with respect to longitudinal coordinate x gives:

$$\frac{dH}{dx} = \frac{dz}{dx} + \frac{dh}{dx} + \alpha\frac{d}{dx}\left(\frac{V^2}{2g}\right) \tag{2}$$

where $dz/dx = -S_0$ is the bottom channel slope, and $dH/dx = -S_f$ is the friction slope. Equation 2 can be written as:

$$\frac{dh}{dx} = \frac{S_0 - S_f}{1 - Fr^2} \tag{3}$$

where $Fr = \alpha Q^2 T/(gA^3)$ is the Froude number, T is the water surface width, A is the cross-sectional area, and Q is the discharge. There are many procedures for solving the latest differential equation such as step method and standard step method. The conventional methods are based on the Manning equation in estimating the friction slope. Equations 4 and 5 describe how to evaluate the discharge and the friction slope using the SCM:

$$Q = \frac{1}{n}R^{2/3}A\sqrt{S_f} = K\sqrt{S_f} \tag{4}$$

$$S_f = \left(\frac{Q}{K}\right)^2 = \frac{n^2Q^2}{A^2R^{4/3}} \tag{5}$$

where n is the Manning coefficient, K is the section conveyance, and R is the hydraulic radius. Both HEC-RAS and CES are using the energy equation for water surface profile computation.

2.2. HEC-RAS 1-D model

HEC-RAS was developed by the US Army Corps of Engineers. HEC-RAS computes the water surface profile from the control section to the next section by applying the energy equation (Eq. 3) and solving it using the iterative procedure 'standard step method' (Brunner 2002). It uses the DCM to calculate the total conveyance and the velocity coefficient. The cross-section is divided based on the n-value break point and the conveyance for each cross section is computed. The total conveyance is $K = \sum K_i$. The kinetic energy coefficient is calculated as:

$$\alpha = \frac{(A_t)^2((K_{lob}^3/A_{lob}^2) + (K_{ch}^3/A_{ch}^2) + (K_{rob}^3/A_{rob}^2))}{K_t^3} \tag{6}$$

where the subscripts *t, lob, ch* and *rob* refer to the whole cross-section, left overbank, main channel and right overbank, respectively.

2.3. CES model

The CES (Conveyance Estimating System) solves the Averaged Reynolds Nervier Stokes equation to compute the discharge. Equation 7 gives the final equation adopted within the CES conveyance methodology as (Knight *et al.* 2009):

$$gHS_0 - \Psi\frac{f}{8}\frac{q^2}{H^2} + \frac{\partial}{\partial y}\left(\lambda\left(\frac{f}{8}\right)^{1/2}Hq\frac{\partial}{\partial y}\left(\frac{q}{H}\right)\right) - C_{uv}\frac{\partial}{\partial y}\left(\frac{q^2}{H}\right) = 0 \tag{7}$$

where f is the Darcy-Weisbach friction factor, λ is the dimensionless eddy viscosity, q is the unit flow rate, and C_{uv} is the meandering channel coefficient. The unit flow rate is estimated by Eq. 7 and the total flow rate is evaluated from Eq. 8:

$$Q = \int_0^B q\,dy = \int_0^B U_d\,dA \tag{8}$$

where U_d is the depth-averaged velocity and B is the width of the cross-section. The magnitude of the parameters f, λ and C_{uv} affects the results, and the calibration always is requested. The *CES* backwater approach is based on computing the conveyance corresponding to known water depth, and applying the step method for water surface calculation.

2.4. Cross-sectional isovel contours

Maghrebi (2006) proposed that the wall influence the water flow within the cross-section is similar to the effects of the electromagnetic forces on particles in a magnetic field. The flow in a channel cross section is simulated by using the Biot-Savart Law that was used for simulating the field of a current flowing inside a wire. First, the cross-section of the channel is covered with triangular meshes as shown in Figure 1. Then, the boundary effects are calculated at the centre of each triangular element. The wetted perimeter is divided into infinitesimal elements d**s**. The effect of d**s** from the wetted perimeter on the velocity at the centre of each triangular element is $d\mathbf{u}_{\mathrm{SPM}}$ which can be calculated as follows:

$$d\mathbf{u}_{\mathrm{SPM}} = f(\mathbf{r}) \times c_1 d\mathbf{s} \tag{9}$$

where d**u** is the velocity deviation, c_1 is a constant which depends on the boundary roughness and $f(\mathbf{r})$ is the velocity function. The seventh root power law relationship is used as a velocity function for natural river channels (Maghrebi and Ball 2006). By integrating along the wetted perimeter, and applying the seventh root power law relationship as a velocity function, the local velocity u_{SPM} at the centre of each element of the flow section is computed as:

$$u_{\mathrm{SPM}} = \int_{\text{boundary}} c.r^{1/7}.\sin\theta.ds \tag{10}$$

where c is a constant related to the boundary roughness and boundary shear velocity, and it is assumed to be equal to the unity (Maghrebi *et al.* 2017), θ is the angle between the positional vector **r** and the boundary element vector d**s**.

The mean velocity U_{SPM} is defined as follows:

$$U_{\mathrm{SPM}} = \frac{\int_A u_{\mathrm{SPM}} dA}{A} \tag{11}$$

where dA is the area of the mesh element and A is the whole flow cross sectional area.

2.5. Stage-discharge relationship

To set up a rating curve, it is essential to identify the main variables which are affecting the discharge. It is assumed that discharge in a channel is related to the geometrical parameters of the flow cross section. They can be listed as the area A, the wetted perimeter P, the width of the free surface

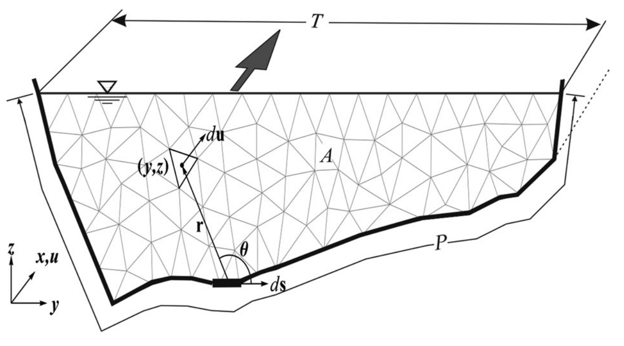

Figure 1. Illustrative geometry for the effect of boundary on the velocity of an arbitrary point with coordinates (*y*, *z*) at a river cross section (Maghrebi 2006).

T, the Manning roughness coefficient n, the longitudinal slope of the bed S_0, and the mean velocity of the cross section, which can be replaced by any kind of theoretical or experimental mean velocities includingU_{SPM}, as given by Eq. 11 (Maghrebi *et al.* 2017):

$$Q = f(A, P, T, n, U_{\mathrm{SPM}}, S_0) \tag{12}$$

Discharge can be connected to the relevant variables in the following:

$$Q \propto A^{a1} P^{a2} P_t^{a3} U_{\mathrm{SPM}}^{a4} n^{a5} S_0^{a6} \tag{13}$$

where $P_t = P + T$ is the sum of the wetted perimeter and the width of the water surface. The concept of the total perimeter of the cross-sectional area P_t is used for dealing with the sudden increment in the wetted perimeter in compound channels. A general relationship between discharges at two different water levels of the cross-section can be described in the form of a ratio, the longitudinal slope of the bed S_0 is constant for all water levels, and therefore it is deleted from the ratio. The relationship is presented as follows:

$$\frac{Q_e}{Q_r} = \left(\frac{A_e}{A_r}\right)^{a1} \left(\frac{P_e}{P_r}\right)^{a2} \left(\frac{(P_t)_e}{(P_t)_r}\right)^{a3} \left(\frac{(U_{\mathrm{SPM}})_e}{(U_{\mathrm{SPM}})_r}\right)^{a4} \left(\frac{n_e}{n_r}\right)^{a5} \tag{14}$$

where the subscripts e and r refer to the estimated and referenced parameters, respectively.

According to the continuity equation in the form of $Q = AV$, the velocity has a power of 1, and since the concept of U_{SPM} is similar to the concept of the velocity, a value of 1 is assigned to a_4. Also, inspiring from the Manning equation, which shows an inverse relationship between the velocity and n, the exponent of n ratio is specified as $a_5 = -1$. The remaining exponent values in Eq. 14 are evaluated using the statistical measure $\overline{NRMSE}$. The $\overline{NRMSE}$ is defined as:

$$\overline{NRMSE} = \frac{(1/N)\sum_{i=1}^{N}\sqrt{(1/N)\sum_{j=1}^{N}((Q_e)_i - (Q_r)_j)^2}}{(Q_r)_{\max} - (Q_r)_{\min}} = \frac{\overline{RMSE}}{(Q_r)_{\max} - (Q_r)_{\min}} \tag{15}$$

where the subscripts i and j refer to the reference and estimated values, respectively, and N is the number of investigated points. Variations of i and j subscripts in Eq. 15 are shown in Figure 2. When a water level is selected as a reference point, then its observed discharge Q_r, which is shown by a diamond mark in Figure 2, is considered as the most accurate discharge. The total number of created rating curves can reach to the total number of water levels where the discharge has been measured. At the same water level, the discharge estimated by other rating curves produced by different values of observed discharges, which is shown by $(Q_e)_i$ and marked by hollow circles in Figure 2. Then the differences as appear in Eq. 15 will be used to compute the statistical measure of $\overline{NRMSE}$.

Maghrebi *et al.* (2017) used stage-discharge data from two cross-sections as referenced data. One of them is a rectangular section and its analytical stage- discharge values were computed using the Manning equation. The other section is a compound one. Highly accurate experimentally stage- discharge collected data from FCF-Series 01 (Flood Channel Facility Series 1) was used to take into account the behaviour of flow in compound cross-sections. The minimization

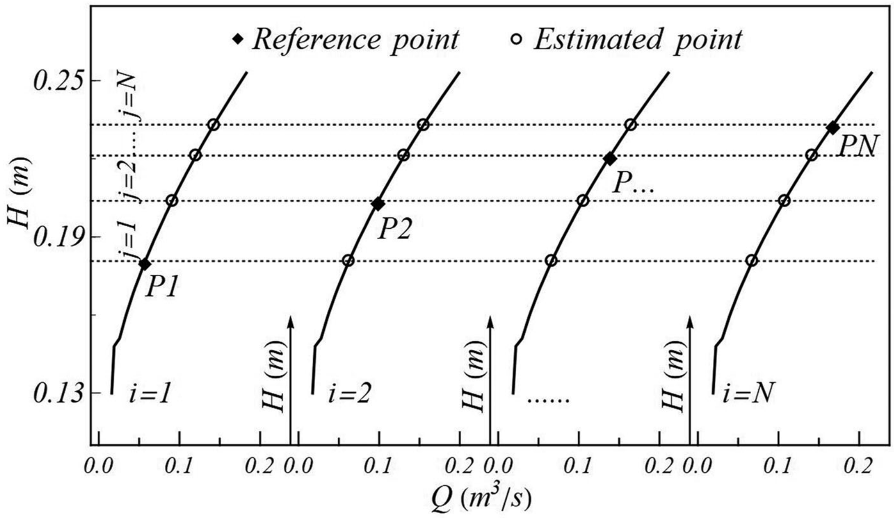

Figure 2. Rating curves based on different reference points.

process was applied to the summation of the statistical measure $\overline{NRMSE_T}$ using the following relationship:

$$\overline{NRMSE_T} = \overline{NRMSE_R} + \overline{NRMSE_C} \tag{16}$$

where the subscripts R and C refer to the rectangular and compound cross sections, respectively. Using Multivariate Newton's method, the process of minimization was performed, and the exponents of Eq. 14 appear in Eq. 17 as follows:

$$Q_e = Q_r\left(\frac{A_e}{A_r}\right)^{0.972}\left(\frac{P_e}{P_r}\right)^{-1.268}\left(\frac{(P_t)_e}{(P_t)_r}\right)^{0.832}\left(\frac{(U_{\mathrm{SPM}})_e}{(U_{\mathrm{SPMs}})_r}\right) \times \left(\frac{n_e}{n_r}\right)^{-1} \tag{17}$$

Equation (17) can be applied to straight and prismatic channels with uniform flow. It is applied to six FCF compound cross sections. The accuracy of the proposed model is quite high. Based on the whole water levels, the mean values of the statistical measures $MAPE$ and $\overline{NRMSE}$ were within 3.1% and 0.023, respectively. Based on each water level, a unique rating curve will be produced. However, the rating curve based on higher water levels are associated with more accurate results, (Maghrebi *et al.* 2017).

3. Results

3.1. Rating curves

To sufficiently examine the performance of the proposed method, the results reported by Sturm and Sadiq's (1996), and Bousmar's (2002) are used. Sturm and Sadiq (1996) carried out the experiments in a flume flow with a compound cross-section as shown in Figure 3. The bed slope of the channel was 0.005. The Manning roughness for the main channel and floodplains were determined as 0.0176 and 0.0171, respectively. The observed stage-discharge curve is shown in Figure 5. The depth of water was controlled by a tailgate placed at the downstream of the channel. Additionally, the WSP measured by Bousmar (2002) in a flume flow with an asymmetric compound cross-section, as shown in Figure 4, is implemented. The longitudinal bed slope was 0.85×10^{-3}. The Manning roughness coefficients for the main channel and floodplains were 0.0107. At the end of the channel, water was falling in an outlet tank at the station of $x = 10$ m, and the M2 water surface profile was formed in the channel.

Figure 5 shows the observed rating curve that it is taken for overbank flow by Sturm and Sadiq (1996). The CES, HEC-RAS and proposed models are implemented to determine the rating curves and the results are compared with the observed data. Figure 6 shows the results of rating curve based on the default values of n, λ and Γ for the CES model.

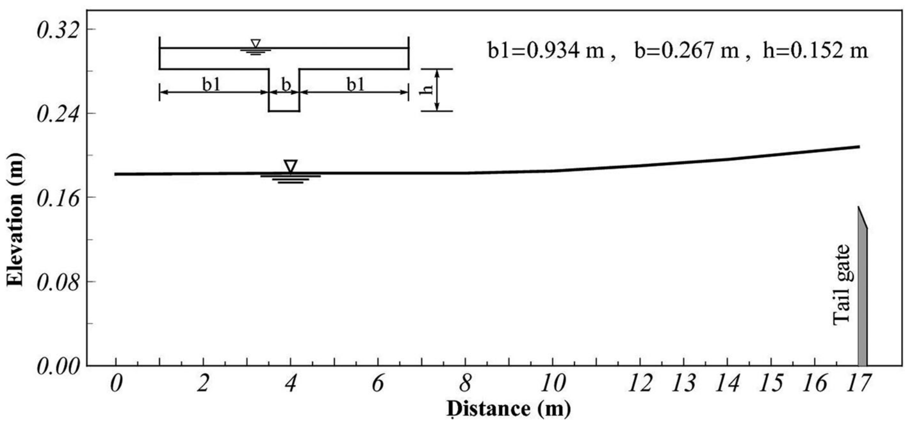

Figure 3. The longitudinal profile and the cross section of Sturm and Sadiq's (1996) experiments.

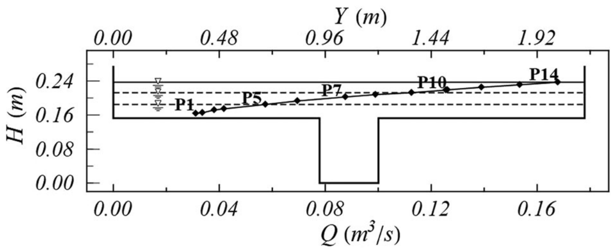

Figure 5. The observed stage-discharge curve obtained by Sturm and Sadiq (1996).

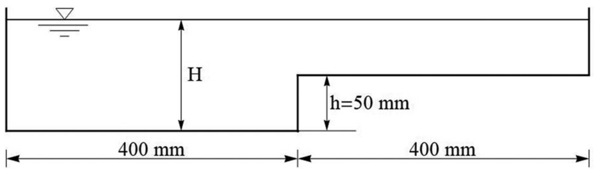

Figure 4. The cross section of Bousmar's (2002) flume.

The proposed model can estimate rating curves. In order to estimate the rating curve, one pair of the observed data in the form of (Q_r, H_r) is required, then the parameters A_r, P_r, $(P_t)_r$ and U_r in Eq. 17 are computed. Finally, discharge for any arbitrary stage can be estimated by the use of Eq. 17. Therefore, different stages are considered and their corresponding parameters A_e, P_e, $(P_t)_e$ and $(U_{SPM})_e$ are calculated. Then, discharge for each stage is estimated. Figure 6 shows four rating curves based on four referenced levels. It is expected that the difference between the resulting rating curves should be low. The *MAPE* (mean absolute percentage error) and *NRMSE* (normalized root mean square error) based on the observed and calculated discharges are used to determine the accuracy of the different cases of the proposed method. *MAPE* and *NRMSE* are defined as follows:

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{(Q_r)_i - (Q_e)_i}{(Q_r)_i}\right| \tag{18}$$

$$NRMSE = \frac{\sqrt{(1/N)\sum_{i=1}^{N}((Q_r)_i - (Q_e)_i)^2}}{(Q_r)_{\max} - (Q_r)_{\min}} \tag{19}$$

As seen in Figure 6, the rating curves of the HEC-RAS is located between the ones of the proposed model and the CES. From Figure 6, it is seen that MAPEs for P12 and P14 based on HEC-RAS are lower than those of the proposed method, while for P7 and P8 the MAPEs based on the proposed method are smaller than those obtained based on HEC-RAC. At low water levels below the floodplain level, any slight changes into the affecting parameters on discharge will lead to a significant variation in the rating curve. However, in compound channels above the floodplain(s) level, a small variation in water level is associated with a large variation in discharge for large ratio of the floodplain to the main channel width and vice versa.

Figure 7 shows the values of *MAPE* and *NRMSE* for rating curves of Sturm and Sadiq's (1996) flume. Using the proposed model at different referenced points, the mean values of *MAPE* and *NRMSE* of the referenced points in Figure 6 are 10.2% and 0.06, respectively, while the corresponding values for the CES model are 15.5% and 0.11, respectively. The HEC-RAS rating curve is compared with the proposed and CES models. The values of *MAPE* and *NRMSE* for HEC-RAS model are 9.5% and 0.05, respectively.

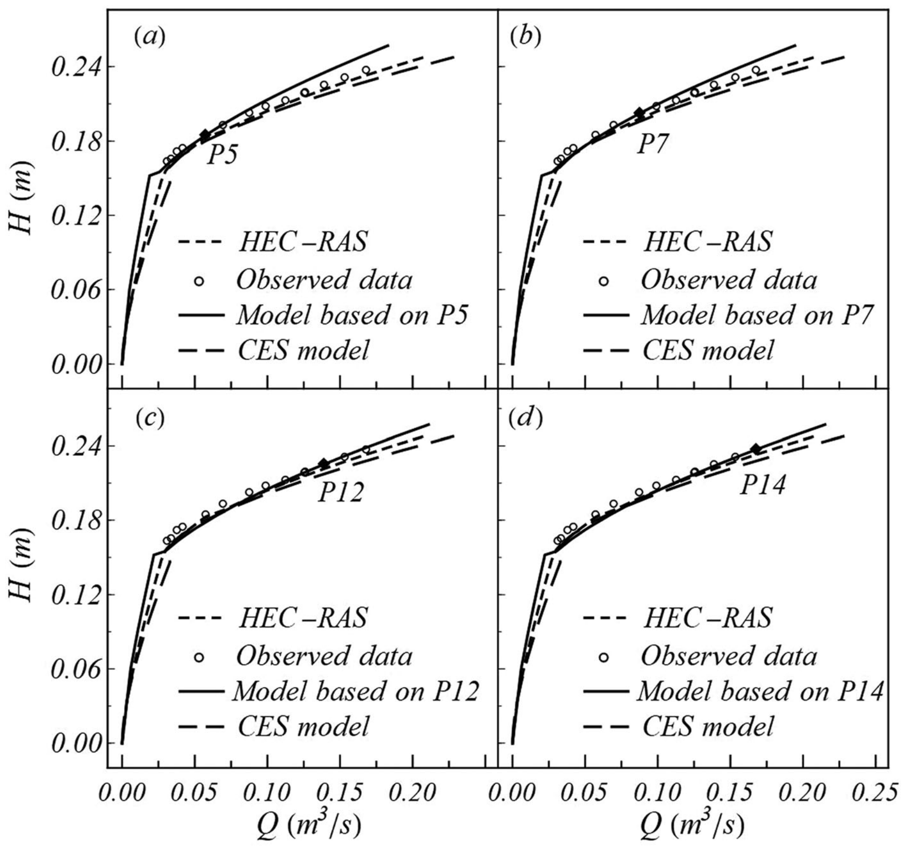

Figure 6. Estimated rating curves by the use of different referenced levels, HEC-RAS and CES models for Sturm and Sadiq's (1996) experiments.

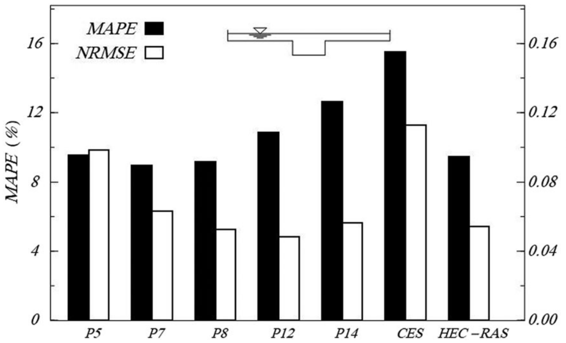

Figure 7. A comparison between *MAPE* and *NRMSE* values obtained by different models for Sturm and Sadiq's (1996) experiments.

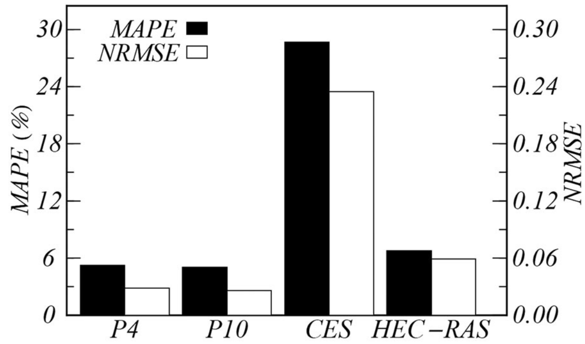

Figure 9. A comparison between MAPE and NRMSE values obtained by different models for the Bousmar's (2002) experiments.

Figure 8 shows two rating curves based on two reference stages estimated by CES and HEC-RAS models for Bousmar (2002) experiments. All other reference points also give close rating curves. Therefore, only two reference points are used. Figure 9 shows the values of *MAPE* and *NRMSE* for rating curves for the different mentioned models of Bousmar's (2002) measurements. Using the proposed model and two different reference points in Figure 8, the mean values of *MAPE* and *NRMSE* are 5.2% and 0.03, respectively, while the corresponding values for the CES and HEC-RAS models are 28% and 0.23, and 6.7% and 0.06, respectively. All of the rating curves, which are obtained by the proposed relationship, are in better agreement in comparison to the observed data when compared with the rating curve of the CES model. However, the accuracy of HEC-RAS is a little bit lower than the one obtained by the proposed model.

3.2. Water surface profiles

The introduced relationship by Maghrebi *et al.* (2017) is simple, feasible and it doesn't need any calibration. Therefore, the following steps should be taken for the prediction of the WSPs: (1) the rating curve is estimated for each cross-section; (2) for each stage, H, the discharge is derived from the rating curve and the conveyance of channel is calculated as $K = Q/\sqrt{S_0}$ where Q is the estimated discharge; (3) the slope of the energy line S_f is computed from Eq. 5 where Q is the real discharge; (4) using the step method, the energy equation (Eq. 3) is solved and the WSP is calculated.

The HEC-RAS and CES models, as well as the proposed method are used for calculating the WSPs for the experimental works of Sturm and Sadiq (1996) and Bousmar (2002). The two experimental observations of the WSPs of M1 and M2 for Sturm and Sadiq (1996), which have been carried out at a discharge of $Q = 0.113$ m^3/s, are corresponding to the water depths of $H = 0.241$ and 0.207 m at the control section, shown in Figures 10 and 11, respectively. A unique rating curve can be obtained by the use of each observational cross-section.

Using the proposed method, based on four observational points, four different rating curves are estimated. Then, the water surface profiles of M1 and M2 can be calculated by the use of energy equation. The profiles of the HEC-RAS and CES models are also calculated. All of the estimated water surface profiles of the M1 and M2 are shown in Figures 10 and 11, respectively. *MAPE* and *NRMSE* based on the observed and predicted values are used to determine the accuracy.

Figures 12 and 13 show the values of *MAPE* and *NRMSE* for different methods and different water surface profiles based on different referenced points for the M1 and M2 profiles, respectively. They are corresponding to Figures 10 and 11, respectively. For the proposed method, the maximum values of *MAPE* and *NRMSE* for the M1 and M2 profiles are 3.5% and 0.34, and 3.5% and 1.55, respectively, which are based on *P*5.

The mean values of *MAPE* and *NRMSE* for M1 obtained by the proposed relationship are 1.5% and 0.15, while these values for HEC-RAS profile are 1% and 0.1, respectively. For the CES profile, the corresponding values are 2.2% and 0.22, respectively. The mean value of *MAPE* and *NRMSE* for M2 by the proposed relationship are 1.3% and 0.62, while these values for the HEC-RAS profile are 0.6% and 0.35 and for the CES profile are 2.4% and 1.1, respectively.

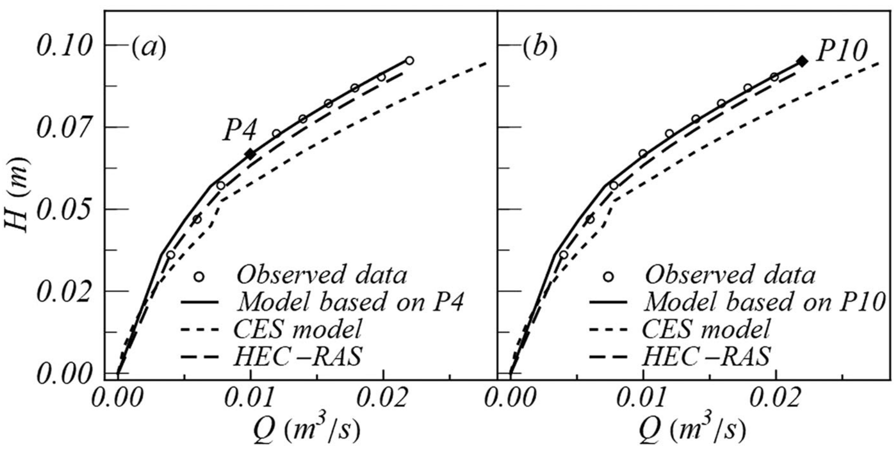

Figure 8. Estimated rating curves by the use of different reference levels, HEC-RAS and CES models for the Bousmar's (2002) experiments.

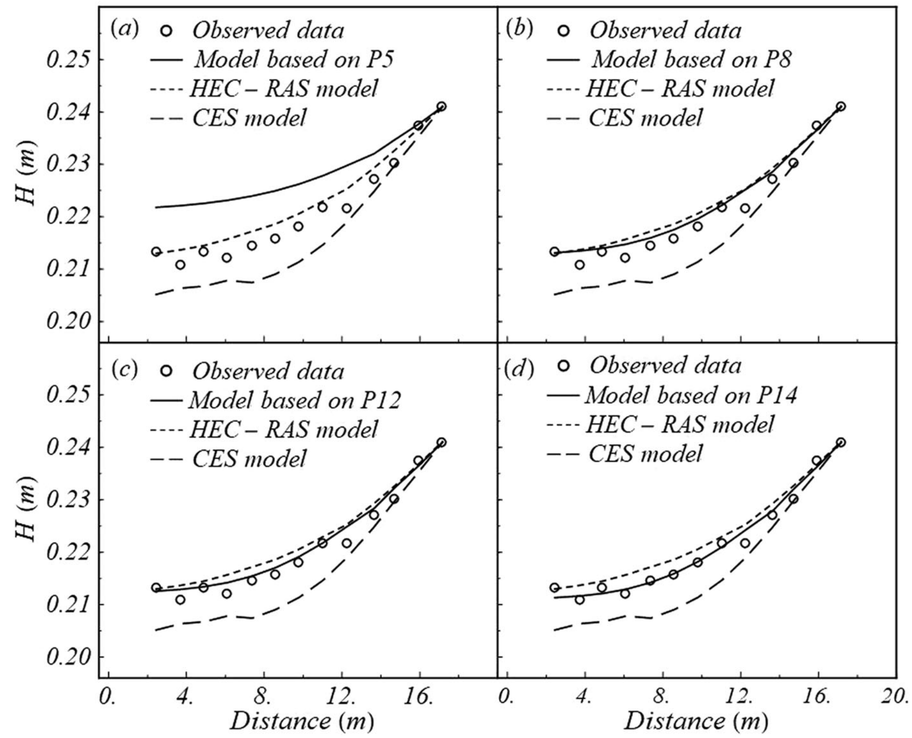

Figure 10. Different water surface profile of M1 based on proposed model, HEC-RAS and CES for Sturm and Sadiq's (1996) experiments.

In Bousmar's (2002) experiments, discharge was $Q = 0.01$ m^3/s, and the flow depth at the control section for the M2 profile was $H = 0.055$ m. The water surface profile of M2 for the proposed method accompanied by the results of HEC-RAS and CES models are shown in Figure 14. The rating curves based on two water levels in Figure 8 are identical so one of the rating curves is used for calculating the WSP. The WSP for the CES model is a straight line parallel to the bed of the channel.

Figure 15 shows the values of *MAPE* and *NRMSE* for different methods. For the proposed method, the values of *MAPE* and *NRMSE* are 1.3% and 0.17, while these values for the HEC-RAS profile are 3.5% and 0.35 and for the CES profile are 7.5% and 0.71, respectively. In other words, when dealing with accurate rating curves, the corresponding WSPs will be associated with high accuracies, as well.

3.3. Case study- Main River

To examine the performance of the proposed method for large scale rivers, available measurements of WSP for a reach of the Main River in Northern Ireland are used.

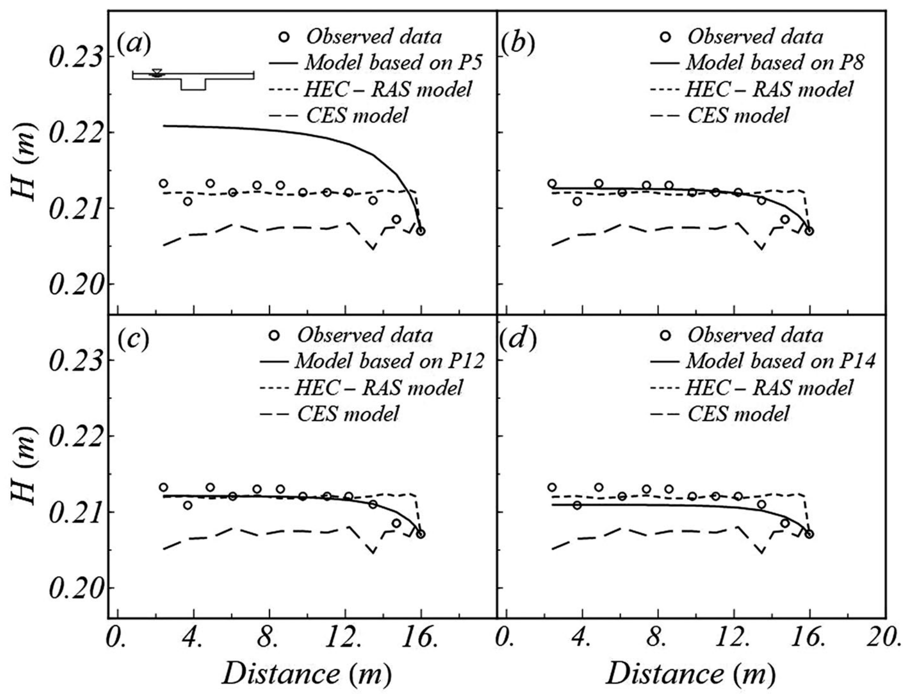

Figure 11. Different water surface profiles of M2 based on the proposed model, HEC-RAS and CES for the Sturm and Sadiq's (1996) experiments.

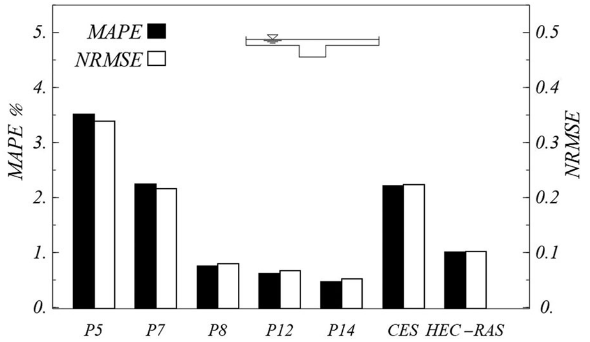

Figure 12. Calculated *MAPE* and *NRMSE* values for the estimated water surface profiles of M1 by different models for Sturm and Sadiq's (1996) experiments.

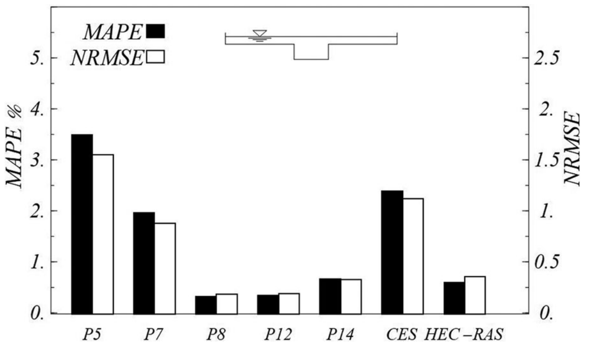

Figure 13. Calculated *MAPE* and *NRMSE* values for the estimated water surface profiles of M2 by different models for Sturm and Sadiq's (1996) experiments.

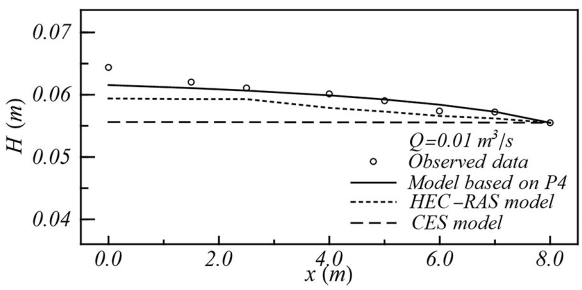

Figure 14. Different water surface profiles of M2 based on the proposed model, HEC-RAS and CES for Bousmar's (2002) experiments.

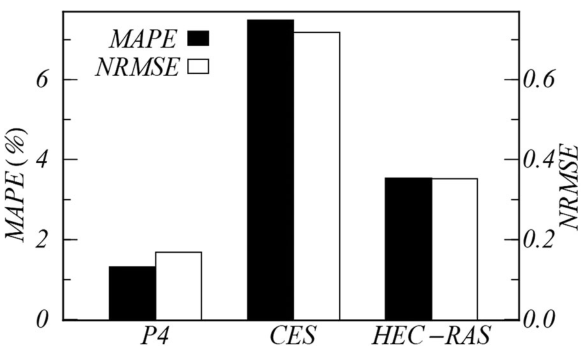

Figure 15. Calculated *MAPE* and *NRMSE* values for the estimated water surface profiles of M2 by different models for Bousmar's (2002) flume.

The reach length is 800 m long. The flow section is a trapezoid compound cross-section, as shown in Figure 16. It consists of a main channel with a bank-full depth of 0.9–1.0 m, a top width of 14 m, two berms with floodplains making a width of 27.3–30.4 m. The mean longitudinal bed slope is

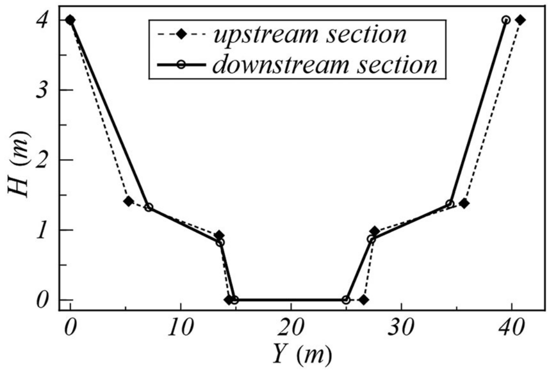

Figure 16. The upstream and downstream cross-sections of Main River.

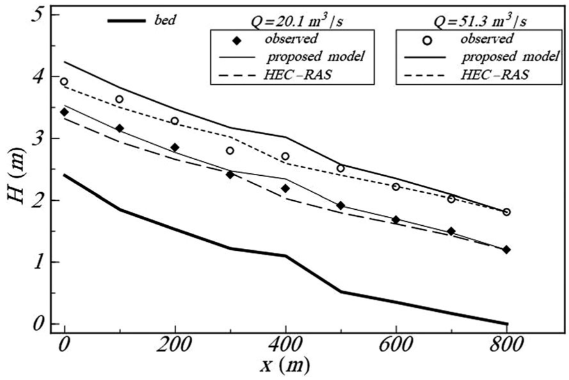

Figure 17. WSPs in Main River.

0.00297 (Knight *et al.* 2009). The calibrated Manning roughness for the main channel and floodplains was 0.040 and 0.028, respectively (Wark 1993). Nine sections with 100 m interval are identified on the reach. Two measured WSPs data are available. Therefore, based on each WSP as a reference, the other WSP is calculated. In other words, the measured WSP for $Q = 51.3\ m^3/s$ is used to compute the rating curves at nine sections. Then, the resulting rating curves are used to calculate the WSP for a discharge $Q = 20.1\ m^3/s$. Similarly, the measured values of the WSP for $Q = 20.1\ m^3/s$ are used to calculate the rating curves at nine sections. Then, the WSP for a discharge $Q = 51.3\ m^3/s$ is computed. Figure 17 shows the WSPs obtained by the proposed method and HEC-RAS. The accuracy of the results is varying with the reference point. For the first case, where $Q = 20.1\ m^3/s$, MAPE and NRMSE of the WSP obtained by the proposed relationship are 2.48% and 0.04, while these values for HEC-RAS profile are 4.84% and 0.07, respectively. For the second case, where $Q = 51.3\ m^3/s$, MAPE and NRMSE for WSP obtained by the proposed relationship are 7.12% and 0.12, while these values for HEC-RAS profile are 3.01% and 0.06, respectively. The calculation of backwater module in the CES covers only subcritical flow. The flow in one section based on CES calculation is supercritical. Therefore, it can be concluded that CES cannot calculate this profile.

4. Discussion

Prediction of the WSPs in compound channels is usually accompanied with some uncertainties due to the lack of existing a general formula for calculating the discharge at a certain level. The DCM, which is used in conventional numerical and commercial softwares, is not able to accurately estimate the discharge in complicated cross sections such compound channels. It is believed that when dealing with complicated compound cross sections, the good accuracy of the obtained results implies that the proposed methodology can be applied generally for the estimation of the WSP in any kind of cross sections. In the current article, for the first time the application of a new methodology, which is proposed by Maghrebi *et al.* (2017), is implemented to calculate the rating curves in compound channels. Then, the results are implemented in calculation of the WSPs in two experimental compound channels: one with large ratio of the floodplain to the main channel width and with an asymmetric one sided floodplain. The obtained results show a good accuracy when compared with two other available techniques such as CES and HEC-RAS. Also, the results from a field case show good accuracy. All the calculated rating curves based on higher water levels as the reference sections, are in very good agreement with the observed data. Therefore, it is recommended to use higher reference levels when dealing with WSP calculations. Maghrebi *et al.* (2017) mentioned that, in general, the accuracy of the rating curves obtained based on the reference points at high water levels are much better than those based on low water levels. The proposed method requires minimum data to setup the rating curves as well as the WSPs. Consequently, it is able to reduce the cost and time. It should also be noted that the proposed method does not need any calibration while other methods do. As a disadvantage of the proposed method is that when the considered water level is much further from the reference level, the accuracy of discharge estimation and in turn the accuracy of the WSPs will be reduced.

5. Conclusions

In complicated flow cross sections such as compound channels, due to the lack of a general formula for estimation the discharge at a certain water level, calculation of the WSPs are usually accompanied by some uncertainties. As a first step, based on the concept of the isovel contours, a simple and feasible relationship for estimation of the rating curve has been introduced by Maghrebi *et al.* (2017). Then, having obtained the rating curves at some cross section of the flow, a 1-D numerical model based on the energy equation and the conveyance is employed to calculate the free WSPs. In the current paper, experimental data of Sturm and Sadiq (1996), and Bousmar (2002) in compound channels and a measured WSP of the Main River are compared with the results obtained by the use of the proposed model. First, a good agreement is observed between the calculated rating curves based on the proposed model and the experimental data. Then, the results of calculated WSPs based on the proposed method in combination with 1-D modelling are compared with the observed WSPs, which shows a good agreement. In order to verify the performance of the new methodology, the results are compared with two numerical models namely HEC-RAS and CES. The results provided by the CES are accompanied by lower precision either in the rating curves or the calculated WSPs. However, the results of the HEC-RAS in some cases, are better than those provided by the proposed method. There can always be found a number of reference points that the corresponding results both for the rating curves and WSPs are associated with much higher accuracy in comparison to the HEC-RAS ones.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Ghadeer Ali http://orcid.org/0000-0002-1631-7374

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