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Uncertainty in Rating-Curves Due to Manning Roughness Coefficient

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Abstract

River stage-discharge rating curve are very crucial for flood control and sustainable development of the river basin. The stage and discharge data can be extracted by rating curves. Recently, a new approach based on the concept of isovel contours for estimating the rating curves is introduced by Maghrebi et al. (2016). It uses the geometric properties of the flow section and roughness variations of the boundary. One of the essential parameters in setting up the rating curves is the Manning roughness coefficient. However, the determination of this parameter is accompanied by some uncertainties. In natural rivers, due to heterogeneous of boundary roughness, changing equivalent roughness with the stage will be important. A proper estimation of equivalent roughness in the proposed rating curve can significantly help to reduce the errors of stage-discharge prediction. The total number of investigated equations of equivalent roughness is 30, which are divided into four groups. Each one of these equations is examined in the La Suela and Trent rivers. This study has shown that choosing the right method to determine the equivalent roughness can significantly affect the performance of the model and play a substantial role in the more accurate estimation of the rating curve. The results show that in the La Suela and Trent rivers, roughness variations in banks create significant uncertainty in the estimation of the rating curves.

Keywords Rating-curve · Equivalent manning roughness · Uncertainty · Natural Rivers · Monte Carlo

1 Introduction

Good knowledge of uncertainty in flow discharge is essential for water management applications and scientific analysis (Kiang et al. 2018). It is also mentioned by McMillan et al. (2017), that the uncertainty in river flow data can affect the costs of the water management projects.

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They have also shown that the analysis of stream uncertainty may improve public acceptance of water management policies and economic efficiency.

Therefore, in addition to understanding the causes and characteristics of the current uncertainty, how to better evaluate it. is a significant research task (Kiang et al. 2018). Streamflow data are mostly computed through the rating curve that relates the measured river stage to discharge values. The rating curve is developed by using simultaneous measurements of discharge and stage as calibration data. Direct measurement of streamflow is a tough task, especially in the flood events. Alternatively, as an indirect method, one can easily measure the stage and estimate the discharge. This indirect calculation of discharge from the stage, in addition to uncertainties in stage height and channel conditions, generates discharge uncertainties. These uncertainties are not always reported to users of streamflow data. Determining the uncertainty of roughness coefficient poses a challenge to hydrologists since there is no determinate way or a method to derive the coefficient. Due to the seasonal changes in roughness coefficient values, different discharges may correspond to the same stage conditions. Thus, understanding the processes for changes in roughness coefficient is of significant concern. Classical studies present roughness coefficients as physically interpretable parameters which can be recognized based on river-bed characteristics (Chow 1959). Recent literature shows that the roughness coefficient should rather be regarded as an only calibration coefficient, which compensates for several error sources while describing roughness conditions (Domeneghetti et al. 2012). Consequently, calibration of roughness coefficients may recognise as optimal values which are not physically justifiable. Therefore, one of the valid parameters in estimating the rating curve is the Manning roughness coefficient that the accuracy of the determination can play a crucial role in predicting the desired flow rate.

Some methods have been used to evaluate the rating curve uncertainty. Le Coz et al. (2014), used a Bayesian analysis to specify the uncertainties in individual gaugings. Petersen-Øverleir et al. (2009), presented a Bayesian framework for the quality appraisal of streamflow time-series collected at gauging stations. Di Baldassarre and Montanari (2009) performed a quantitative numerical analysis to estimate the uncertainty of river discharge observations due to measurement errors, interpolation, and extrapolation error of the rating curve, seasonal variations of the state of the vegetation and effects of unsteady flow conditions by using one-dimensional hydraulic model. Domeneghetti et al. (2012) showed the general uncertainty in discharge measurement in rivers and suggested a framework for analyzing uncertainty in rating curves and considered their effects on the model calibration. Tomkins (2012) developed deviation analysis in discharge gaugings from the rating curve, a simple empirically based method that can provide valuable information about the uncertainty of the rating curve and the reliability of the flow data. Pappenberger et al. (2005), Di Baldassarre and Claps (2010) and Mukolwe et al. (2013), investigated the impact of Manning's roughness uncertainty on the hydraulic model by applying Generalized Likelihood Uncertainty Estimation (GLUE) methodology. However, many parameters, including the assumptions adopted, lead to the absence of a desirable method for estimating discharge uncertainty (Kiang et al. 2018).

There are alternative methods that can be used to estimate discharge and its uncertainty without using a rating curve. In this study, the rating curves, which are the most practical, are only considered. Power (Herschy 2009, Pappenberger et al. 2006) and polynomial (Yu, 2000) relations, characterized by physical-based parameters, are mainly used to estimate rating curves. Nevertheless, in this study, a model for the stage-discharge relation in natural rivers based on single-point velocity measurements and observation data, which has already been introduced by Maghrebi et al. (2016), is used. The proposed method was explored in a developed form in the compound channels (Maghrebi et al. 2017).

The purpose of this study is to investigate the accuracy of the equivalent roughness coefficient of the Manning formula in the proposed rating curve introduced by Maghreb. et al. (2017). To calculate the equivalent roughness coefficient, the behavior of each equation collected by Yen (2002) and Chen and Yen (2002) is explored. Then, considering the best equations for each river, sensitivity analysis is performed to determine the effect of roughness coefficient on the estimation of the proposed rating curve.

2 Methodology

2.1 Study Area and Data

Figure 1 shows the cross-sectional and observational data, extracted from Knight et al. (2010) studies, in each river. The La Suela River has no floodplain, while the Trent River has a broad floodplain on one side (Fig. 1). The width of the Trent River at the floodplain level is 80 m. The materials of the channel bed are composed of coarse gravel and the ones

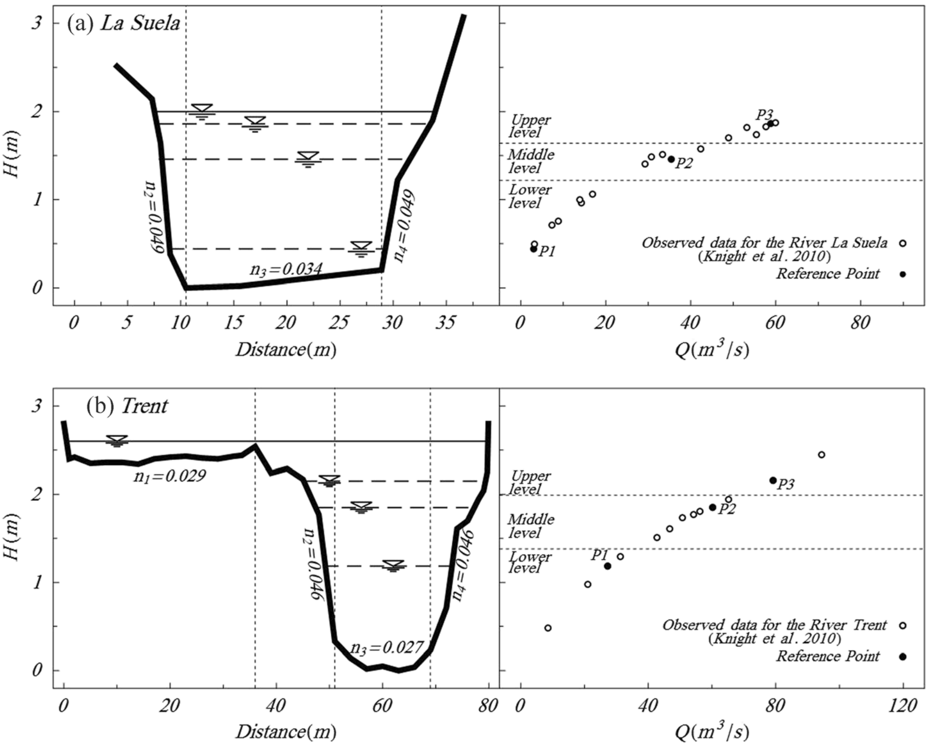

Fig. 1 Cross-sectional view and observed rating curves of **a** La Suela and **b** Trent rivers

of the channel banks, and floodplains are composed of sand, height-varying grass and turf. The La Suela River located in the north-east of Córdoba, Argentina, with 25 m wide, 2 m deep and a longitudinal bed slope of 0.001355. Discharge variation is recorded in the range of 50 to 70 m^3/s (Knight et al. 2010).

2.2 The Proposed Stage-Discharge Relationship

Maghrebi et al. (2016), assumed that discharge at any stage of a channel could be expressed as a function of the following parameters:

$$Q = f(A, P, T, P_t, U_{SPM}, n, S_0) \tag{1}$$

where Q is the discharge, A is the cross-section area, P is the wetted perimeter of the flow section, P_t is the sum of P and the width of the water surface ($P_t = P + T$), U_{SPM} is the cross-sectional mean flow velocity in the streamwise direction (Maghrebi 2006), n is the Manning roughness and S_0 is a longitudinal bed slope. The variables affecting the amount of discharge are chosen according to the following equation:

$$Q \propto A^{a_1} P^{a_2} P_t^{a_3} U_{SPM}^{a_4} n^{a_5} S_0^{a_6} \tag{2}$$

According to Eq. 2, a general form of the stage-discharge relationship is as follow:

$$\frac{Q_e}{Q_r} = \left(\frac{A_e}{A_r}\right)^{a_1} \left(\frac{P_e}{P_r}\right)^{a_2} \left(\frac{(P_t)_e}{(P_t)_r}\right)^{a_3} \left(\frac{(U_{SPM})_e}{(U_{SPM})_r}\right)^{a_4} \left(\frac{n_e}{n_r}\right)^{a_5} \left(\frac{(S_0)_e}{(S_0)_r}\right)^{a_6} \tag{3}$$

where the subscripts r and e refer to the referenced and estimated values, respectively. The value of exponent a_6 was set to zero because the effect of the bed slope of the channel, which stays fixed at all water levels, can be ignored in the computational processing. Maghrebi et al. (2017), demonstrated that the most reliable relation is the one with the lowest *NRMSE* values. Ultimately, they suggested their relationship as follows:

$$Q_e = Q_r \left(\frac{A_e}{A_r}\right)^{0.972} \left(\frac{P_e}{P_r}\right)^{-1.27} \left(\frac{(P_t)_e}{(P_t)_r}\right)^{0.83} \left(\frac{(U_{SPM})_e}{(U_{SPM})_r}\right) \left(\frac{n_e}{n_r}\right)^{-1} \tag{4}$$

The parameter U_{SPM} in Eq. 4 plays the role of the velocity parameter; thus, the power of it is kept constant, i.e.$a_4 = 1$. On the other hand, considering the inverse relation between the discharge and the equivalent Manning roughness, the exponent $a_5 = -1$ is defined. In order to estimate the discharge at a certain water level by the use of Eq. 4, all of the hydro-geometric parameters are needed to be calculated for the specified water level. In this process, only one reference point (observed data) is required for discharge estimation.

2.3 Equivalent Roughness Calculation Methods

With a proper estimation of Manning roughness, it is possible to determine the flow through the natural channels accurately. There are several methods to estimate the Manning roughness, including the use of standard tables, region images and graphs in reference books (e.g. Chow, 1959). As another example, the Roughness Advisor (RA) incorporates a database of information on the hydraulic roughness of different surfaces including field surveys, photographs, and roughness unit values, based on an extensive literature review of over

700 references, to estimate roughness values (Knight et al. 2010. It should be mentioned that the unit roughness presents the roughness due to an identifiable segment of boundary friction per unit length of the channel (Knight et al. 2010). In most cases, the roughness of different parts of the river and its constituent materials are heterogeneous and varies from point to point. In general, the river bed is less rough than the floodplains. Researchers (e.g. Yen, 2002) have proposed several methods for predicting the Manning equivalent roughness coefficient in composite channels. In these methods, the cross-sectional area is divided into some subsections, each consisting of a part of a wetted perimeter and a particular cross-section area with uniform roughness. Therefore, using the general form proposed by Yen (2002), the Manning equivalent roughness coefficient for open channels with non-uniform roughness is estimated as follows:

$$n_e = \sum_{i=1}^{N} w_i n_i \tag{5}$$

where n_e is the equivalent roughness, N is the number of sections of the channel, n_i is the Manning roughness coefficient, and w_i is the weighted parameter in the sub-section i of the channel cross-section, which is a function of A the cross-section area, P the wetted perimeter, and R the hydraulic radius in each sub-area. Among the different methods of dividing the channel cross-section, the most common method is the use of vertical lines.

The equivalent roughness can be calculated by the use of several relations. Yen (2002) and Chen and Yen (2002) have collected 30 equations, presented in Table 1. These equations can be divided into four groups based on effective parameters. Some assumptions have been used to derive these relationships, such as the equality between the total discharge with sum of the discharge at each subsection (e.g., A3, B2 and C13 in Table 1), the equality between the total shear velocity and sum of the shear velocity of each subsection (e.g., A1, B4 and C8), the equality between the total resistance force and the sum of resistance force of each section (e.g., A2, B3 and C1) and logarithmic distribution of velocity along the depth (relationship D1). By calculating the equivalent roughness by the equations in Table 1 and replacing in the proposed stage-discharge relationship (Eq. 4), one can see the effect of each of them in the estimation of the rating curve. In this regard, the equivalent roughness coefficient can be considered as a parameter for the calibration of the model.

To use the model, as the first step, all the effective geometrical and hydraulic parameters appear in Eq. 4, must be calculated at all desired levels. Then, by substituting the geometric and hydraulic information of a reference level in the proposed relation, the rating curve is plotted for different reference points. In the following, the impact of each of the equations in Table 1 is examined on the proposed relationship in the La Suela and Trent rivers. The results of the Conveyance Estimation System or *CES* software are also compared with the results of the proposed method. *CES* is a software which is developed to compute the depth-averaged velocity U_d at any lateral position of the streamflow cross-section by using the finite element method based on the Shiono-Knight Method or *SKM* (Knight et al. 2010).

2.4 Performance Evaluation

In order to investigate the performance of the models, some of the statistical measures, including the mean absolute percentage error (*MAPE*) and the normalised root mean square error (*NRMSE*) are computed as follows:

Table 1 Methods for calculating the equivalent roughness coefficient

Eqs.	n_e	*Eqs.*	n_e	*Eqs.*	n_e	Eqs.	n_e	Eqs.	n_e
A1	$\frac{\sum n_i A_i}{A}$	*B3*	$\left[\frac{1}{P}\sum\left(n_i^2 P_i\right)\right]^{1/2}$	*C4*	$\left[\frac{\sum n_i^{3/2} P_i R_i^{1/4}}{PR^{1/4}}\right]^{2/3}$	*C10*	$\left[\frac{\sum n_i^{1/2} P_i R_i^{7/12}}{PR^{7/12}}\right]^2$	*C16*	$\frac{R^{7/6}\sum P_i\sqrt{R_i}}{\sum\frac{P_i}{n_i}R_i^{5/3}}$
A2	$\sqrt{\sum n_i^2\frac{A_i}{A}}$	*B4*	$\frac{\sum(n_i P_i)}{P}$	*C5*	$\left[\frac{\sum n_i^{3/4} P_i R_i^{3/8}}{PR^{3/8}}\right]^{4/3}$	*C11*	$\left[\frac{\sum n_i^{1/2} P_i R_i^{2/3}}{PR^{2/3}}\right]^2$	*C17*	$\frac{\sum\left(n_i P_i R_i^{1/2}\right)}{PR^{1/2}}$
A3	$\frac{A}{\sum(A_i/n_i)}$	*B5*	$\left[\frac{1}{P}\sum\left(n_i^{3/4} P_i\right)\right]^{4/3}$	*C6*	$\left[\frac{\sum n_i^{3/4} P_i R_i^{1/2}}{PR^{1/2}}\right]^{4/3}$	*C12*	$\left[\frac{\sum n_i^{1/2} P_i R_i^{5/12}}{PR^{5/12}}\right]^2$	*C18*	$\frac{\sum\left(n_i P_i R_i^{1/3}\right)}{PR^{1/3}}$
A4	$\left[\frac{\sum\left(n_i^{3/2} A_i\right)}{A}\right]^{2/3}$	*C1*	$\left[\frac{R^{1/3}}{P}\sum\frac{n_i^2 P_i}{R_i^{1/3}}\right]^{1/2}$	*C7*	$\left[\frac{\sum n_i^{3/4} P_i R_i^{1/8}}{PR^{1/8}}\right]^{4/3}$	*C13*	$\frac{PR^{7/6}}{\sum\frac{P_i}{n_i}R_i^{7/6}}$	*C19*	$\frac{\sum\left(n_i P_i R_i^{1/6}\right)}{PR^{1/6}}$
B1	$\left[\frac{1}{P}\sum\left(n_i^{3/2} P_i\right)\right]^{2/3}$	*C2*	$\left[\frac{\sum n_i^2 P_i R_i^{2/3}}{PR^{2/3}}\right]^{1/2}$	*C8*	$\frac{\sum n_i P_i/R_i^{1/6}}{P/R^{1/6}}$	*C14*	$\frac{PR^{5/3}}{\sum\frac{P_i}{n_i}R_i^{5/3}}$	*C20*	$\frac{\sum\left(n_i P_i R_i^{5/6}\right)}{PR^{5/6}}$
B2	$\frac{P}{\sum(P_i/n_i)}$	*C3*	$\left[\frac{\sum n_i^{3/2} P_i R_i^{3/4}}{PR^{3/4}}\right]^{2/3}$	*C9*	$\left[\frac{\sum n_i^{1/2} P_i R_i^{1/3}}{PR^{1/3}}\right]^2$	*C15*	$\frac{\sum P_i R_i{}^{5/3}}{\sum\frac{P_i}{n_i}R_i^{5/3}}$	*D1*	$e^{\left[\frac{\sum P_i h_i^{3/2}\ln n_i}{\sum P_i h_i^{3/2}}\right]}$

$$MAPE(\%) = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{(Q_o)_i-(Q_e)_i}{(Q_o)_i}\right| \tag{6}$$

$$NRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[(Q_o)_i-(Q_e)_i\right]^2}}{(Q_o)_{\max}-(Q_o)_{\min}} \tag{7}$$

where Q_e is estimated discharge and Q_o is observed data.

On the other hand, a statistical measure which can be used as a reliable goodness of fit is the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe 1970). It is a reliable statistical index for assessing the performance of a hydrological model which is usually shown as:

$$NSE = 1-\frac{\sum_{i=1}^{N}\left((Q_o)_i-(Q_e)_i\right)^2}{\sum_{i=1}^{N}\left((Q_o)_i-\left(\overline{Q}_o\right)_i\right)^2} \tag{8}$$

where Q_e, $Q_o$and $\overline{Q}_o$are the estimated, observed and mean observed discharges, respectively. The range of this coefficient lies between$-\infty$and 1 (perfect fit).

For further examination, the statistical parameter of mean percentage error (*MPE*) is defined as follows:

$$MPE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{(Q_e)_i-(Q_o)_i)}{(Q_o)_i}\right. \tag{9}$$

where the *MPE* is evaluated as a function of roughness variation. For this purpose, the correlation coefficient, which indicates the relationship between the two variables, is used. In Eq. 10 the Pearson correlation coefficient, defined between two random variables, is equal to their covariance divided by their standard deviation that is utilised to specify the linear correlation between two variables. As a result, the Pearson correlation coefficient is used to investigate the effect of roughness variations on the corresponding *MPE* as follows:

$$r = \frac{\sigma_{X,Y}}{\sigma_X \cdot \sigma_Y} \tag{10}$$

where r is the population correlation coefficient, σ is the standard deviation, and X and Y are the two variables whose correlation is calculated. The correlation coefficient has a value between −1 and 1. Positive values indicate that X and Y tend to increase and decrease together, and negative values indicate that two variables tend to move in opposite directions (Helton et al. 2006).

3 Results and Discussion

3.1 Rating Curves and Error Analysis

The observational data in the La Suela and Trent rivers are used to examine the behaviour of each equation for calculating the equivalent roughness coefficient in the proposed stage-discharge formula. In the following, by calculating the effective geometric and the hydraulic parameters in each stage and considering the effect of each of the equations of the equivalent roughness coefficient (Table 1), the proposed rating curve is estimated by utilising Eq. 4.

In Fig. 2, the variation of roughness with the stage in the La Suela and Trent rivers are shown. In group A, the significant parameters in the calculation of the equivalent roughness include the area (*A*) and the local roughness (*n*). As seen, there is a slight difference between the results of this group, especially at high levels. The results of equations in Group A for the Trent River show that the variations of equivalent roughness at the lower levels are more noticeable than higher levels. In the equations of group B, the wetted perimeter (*P*) plays an essential role. As shown in Fig. 2b (group B), some discontinuities in the equivalent roughness coefficient at the floodplain level can be observed. The difference between the results of the relations of this group is negligible. The two parameters appearing in the equations of group C, are *P* and *R*. For the equations in Group C, by increasing the stage, the roughness variations are getting more substantial, and consequently, the rating curves may be disarticulated at the higher stages.

Finally, the result of eq. D1, which is inspired by the logarithmic velocity profile, becomes similar to those of group B. In conclusion, a comparison of the results for the two rivers shows that the equivalent roughness variations in the Trent River are more significant because of its wider floodplain. Therefore, a great discrepancy in the rating curve of the Trent River at the upper stages of its floodplain is expected.

In Fig. 3, the results of the efficiency coefficient of the model for the two studied rivers show that in the La Suela River, the *NSE*, in most cases, is higher than 0.9. Also, for the lower reference points (e.g. *P1*), the efficiency is less than the middle reference (e.g. *P2*). A comparison of the rating curves based on *P2* and *P3* (upper reference point) shows that the performance based on *P2* is slightly better than *P3*. Therefore, C17 is selected as the most appropriate equation for the estimation of the equivalent roughness since the *NSE* is more than 0.97 in all three reference points. In the Trent River, due to the existence of a broad floodplain, the performance of the model, especially for C11, shows undesirable results. It is a sign of model sensitivity to the equivalent roughness coefficient. The results of the Trent River at different levels are similar to the La Suela River. They show better performance at the mid-observational reference data. The best performance of the model is found among the relations in group B. So it can be concluded that in rivers with broad floodplains, the relations of this group can be used to increase the accuracy in estimation of the rating curves. Finally, according to Fig. 3, C17 and B4 show the best results for the La Suela and Trent rivers, considering all three reference points, respectively.

In the next step, the rating curves of the *CES* method and proposed models based on different reference points are compared with each other, as shown in Fig. 4. Following that, Fig. 5 depicts the statistical analysis of the *NRMSE* and *MAPE* for the rating curves based on the proposed method as well as the *CES*. There is a lower error for the proposed model based on the middle reference point (*P2*) in comparison to the *CES* method. In the La Suela River, the *NRMSE* and *MAPE* for the proposed method, based on *P2*, are 0.051 and 10.3%, which are correspondingly equal to 0.053 and 11.3% for the *CES* method, respectively. According to the proposed method, in the Trent River for all three reference levels, the *NRMSE* and *MAPE* are 0.032 and 8.32%, respectively. These values for the *CES* are 0.032 and 9.95%, respectively. This demonstrates the superiority of the proposed model.

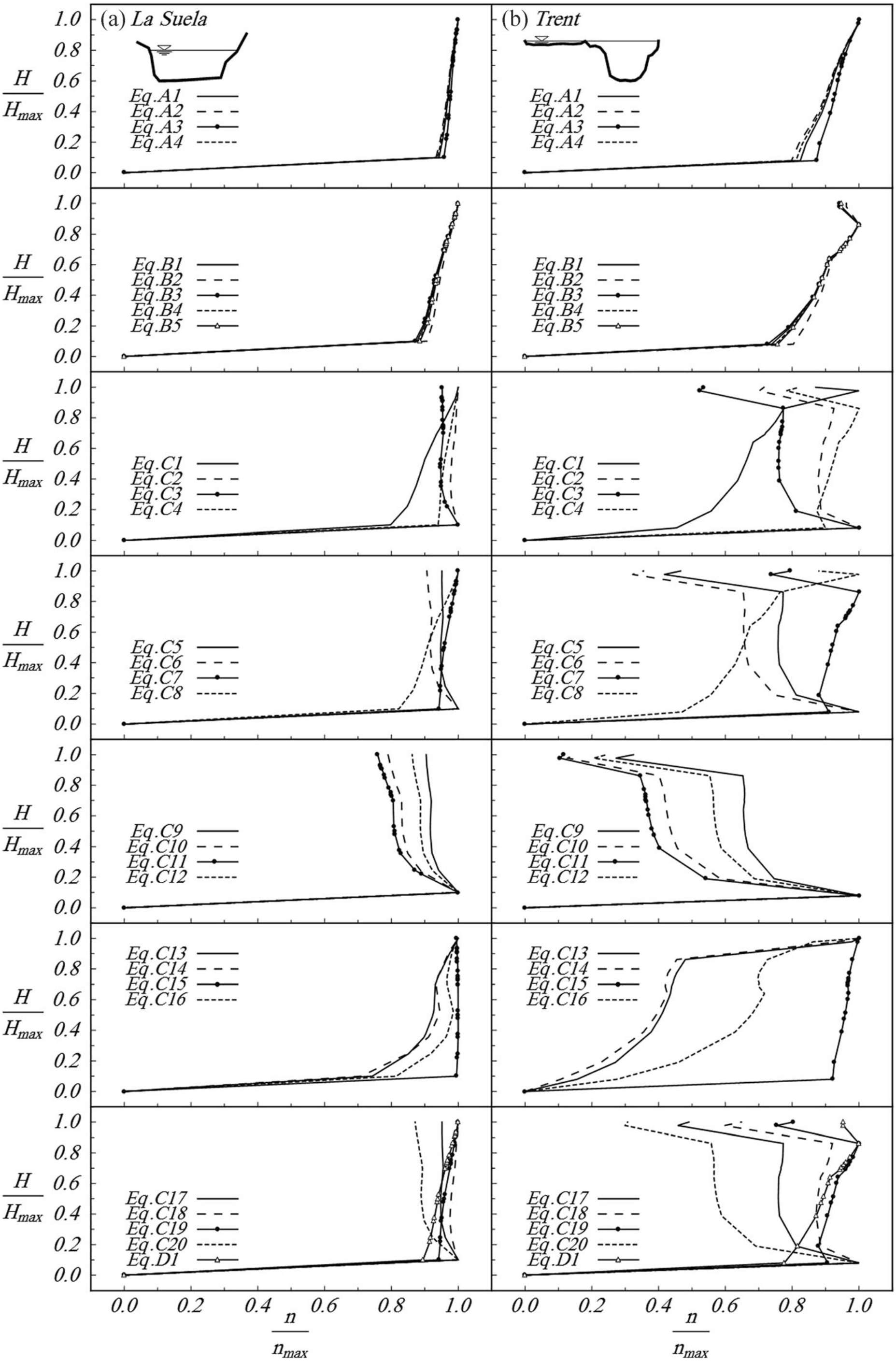

Fig. 2 Variation of the relative values of n for **a** La Suela and **b** Trent rivers

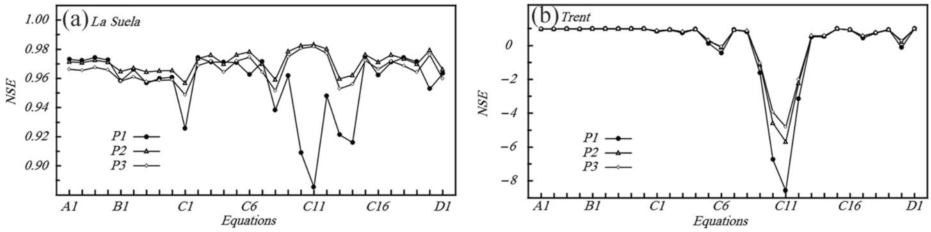

Fig. 3 Nash–Sutcliffe model efficiency coefficient for **a** La Suela and **b** Trent rivers

3.2 Roughness Uncertainty Analysis

The uncertainty in determining the Manning coefficient is inevitable. Sensitivity analysis can be used to analyse the uncertainty in roughness coefficients. One of the methods of sensitivity analysis is sampling-based methods, computed based on the mapping between the input-output relation generated by the Monte Carlo simulation (Ekström and Broed 2006). The sensitivity analysis of the rating curves has been performed by the Monte Carlo simulation due to the variation of the equivalent roughness.

By choosing 10,000 random data in the range of minimum and maximum roughness values and assuming the uniform distribution within intervals, roughness values for each river cross-section are calculated. The minimum and maximum roughness data in the La Suela and Trent rivers are shown in Table 2.

In the beginning, the roughness values are randomly generated for 10,000 times. Then, based on each roughness value, the rating curves are estimated by using the proposed relation. Figure 6 shows the uncertainty in the equivalent roughness estimation. As shown in Fig. 6, the distribution of roughness creates a series of possible scenarios.

The rating curves are estimated at three reference points at the lower, middle and upper levels due to the roughness uncertainty. The uncertainty due to roughness, shown in grey, is the lowest around the reference point (Fig. 7). However, when the estimated rating curve values are away from the reference point, the uncertainties will be increased. It can be intensified for those levels above the reference point. Clearly, this issue is shown in Fig. 7e and f. Additionally, the calculated uncertainties based on different reference points are roughly within the results of the *CES* for the maximum and minimum roughness values.

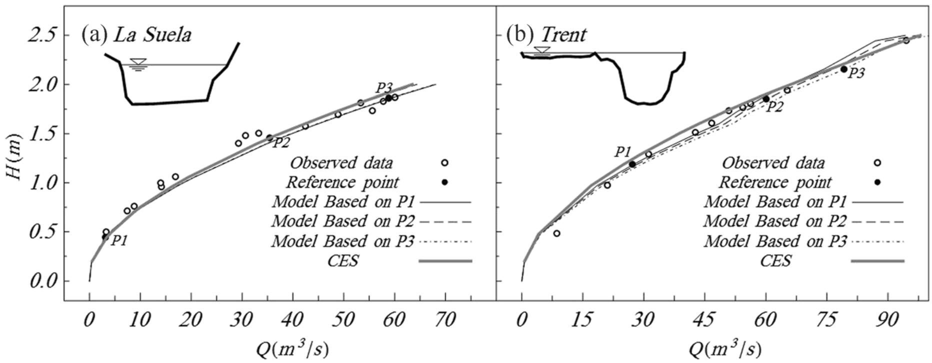

Fig. 4 Comparison of the proposed model based on different observation points and the *CES* method in **a** La Suela and **b** Trent rivers

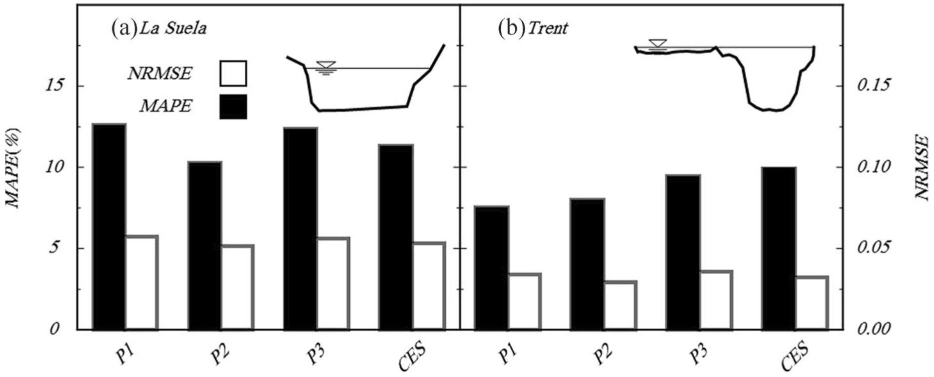

Fig. 5 A comparison between *MAPE* and *NRMSE* obtained from the *CES* with the proposed model at different referenced levels in the **a** La Suela and **b** Trent rivers

The values of *MPE* for the selected reference points at the lower (*P1*), middle (*P2*) and upper (*P3*) levels for the two rivers, related to the unit roughness, are shown in Figs. 8 and 9 with white points. Furthermore, the black line on the graphs represents the linear regression between the roughness variations and *MPE*. The value of the correlation coefficient (*r*) for each reference point can be seen separately in Figs. 8 and 9. As shown in the illustrations, from left to right, roughness variations in different parts of the river, including floodplains, banks and bed, and from top to bottom, the changes in lower, middle and upper reference points have been investigated. Figures 8 and 9 represent the value of roughness in the floodplain, left bank, bed and right bank of the rivers as n_1, n_2, n_3 and n_4, respectively.

In the La Suela River, due to roughness changes, the most considerable influence on the estimation of the rating curves is on the right bank (Figs. 8g-i) which can be seen in all three reference levels. In the Trent River, the effect of roughness variations on the floodplain is almost negligible (Figs. 9a-c). As shown in Figs. 8 and 9, the values of roughness in banks (n_2 and n_4) have a dramatic effect on the accuracy of the stage-discharge estimation; besides, the correlation coefficient values of banks are higher than the bed (Fig. 9). It could be noticed that the homogeneity of the sign of the correlation coefficient on the banks of two rivers shows the same effect of roughness variation on the rating curve. Therefore, any changes in the roughness values due to vegetation in these areas are accompanied by uncertainty in the discharge estimation. Generally, it can be concluded that changes in bed roughness have a smaller effect on the uncertainty of the rating curve than the river banks.

Table 2 The minimum and maximum local roughness coefficient in the La Suela and Trent rivers

	bed			*bank*			*floodplain*		
River	*Unit Roughness*	*Lower*	*Upper*	*Unit Roughness*	*Lower*	*Upper*	*Unit Roughness*	*Lower*	*Upper*
La Suela	*0.0336*	*0.027*	*0.042*	*0.0491*	*0.032*	*0.085*			
Trent	*0.027*	*0.025*	*0.03*	*0.0456*	*0.0262*	*0.0838*	*0.029*	*0.0248*	*0.0346*

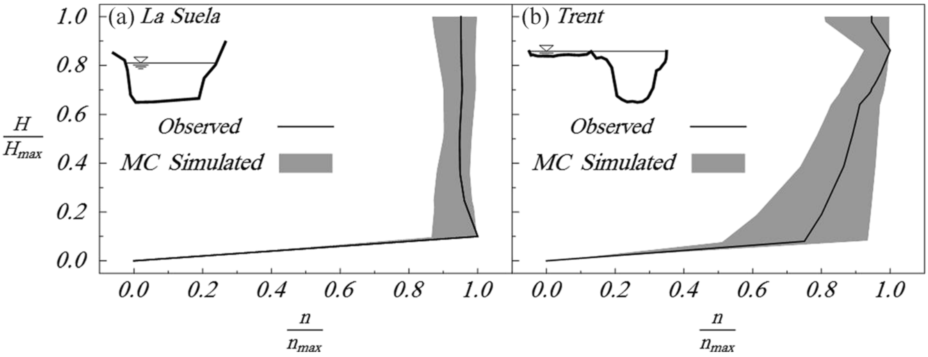

Fig. 6 Variations of relative values of *n* by considering uncertainty for determination of the local roughness in **a** La Suela and **b** Trent rivers

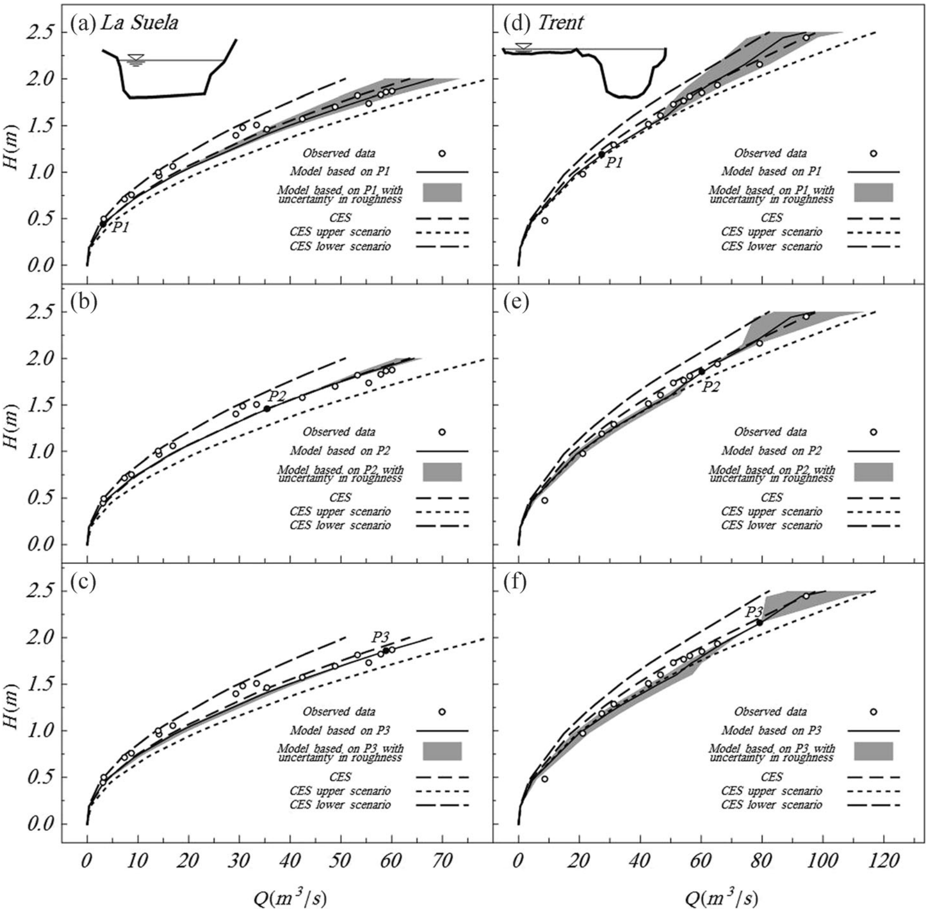

Fig. 7 Stage-discharge curves by considering the uncertainty in local roughness based on different reference points: **a** *P1*, **b** *P2* and **c** *P3* for the La Suela River and **d** *P1*, **e** *P2* and **f** *P3* for the Trent River

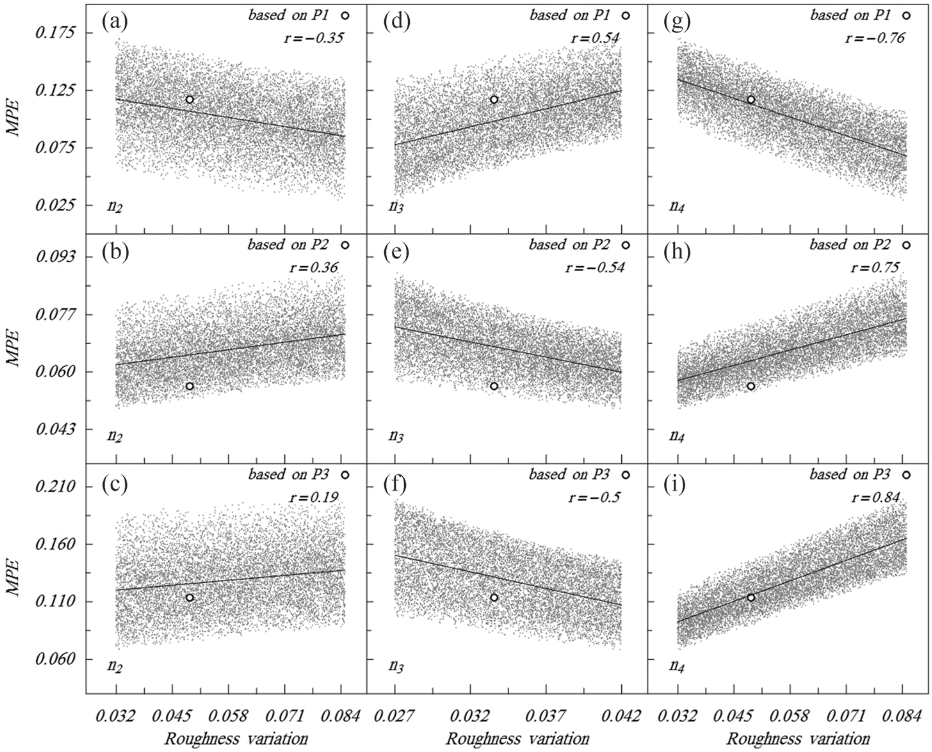

Fig. 8 Variations in *MPE* values due to uncertainty in local roughness in the La Suela River for rating curve based on different reference levels

4 Conclusion

Manning roughness coefficient imposes significant effects on the estimation of discharge. When a range of uncertainty is applied to the roughness, a considerable variation in the rating curve will occur. It is recognisable that the most appropriate value for the equivalent roughness will lead to the most reliable values of discharge in each river. In this study, by the use of 30 equations, introduced by Yen (2002) and Chen and Yen (2002), the effect of the Manning roughness coefficient is investigated. Although the results are acceptable in most of the roughness equations, it is possible to find the most appropriate relation. According to the geometric and hydraulic characteristics of the flow, the most proper relations may differ from a river to another. In the La-Suela River, the results of C17 are associated with the lowest value of discrepancy with actual results, while in the Trent River B4 is the most appropriate relation. Consequently, eqs. C17 and B4 are found as the best relations in the La Suela and Trent rivers, respectively. Additionally, the uncertainty in the local roughness coefficient is investigated. The results demonstrate that both in the La Suela and Trent rivers, the roughness changes in the bank, in comparison to the bed, create a more noticeable uncertainty in the estimation of the rating curve. Thus, due to seasonal changes in the condition of the vegetation and human intervention (e.g. land-use change), the roughness variation becomes very important in the banks.

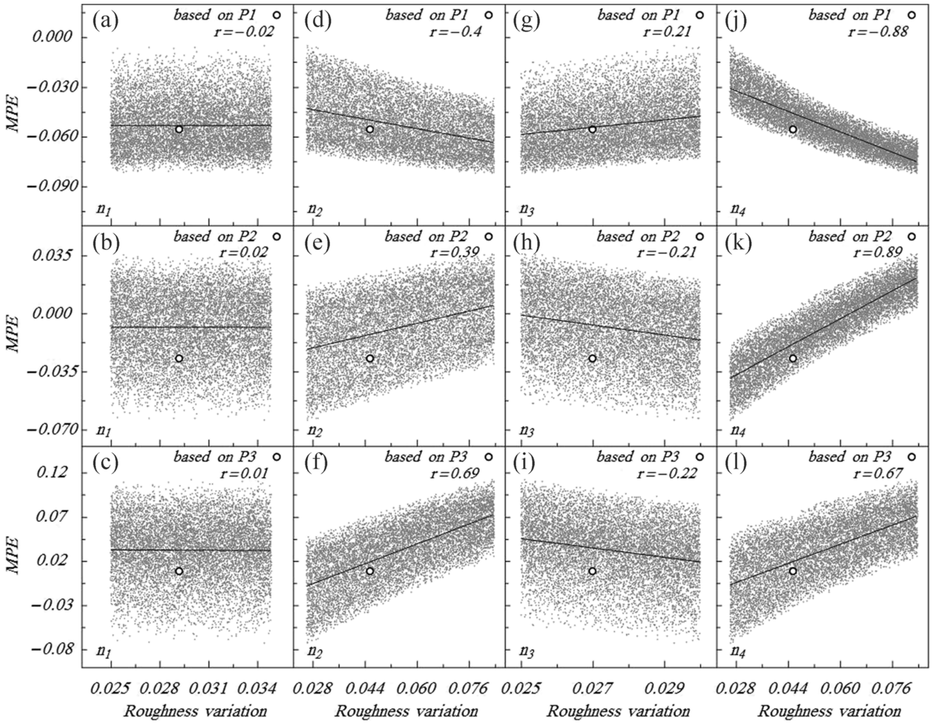

Fig. 9 Variations in *MPE* values due to uncertainty in local roughness in the Trent River for rating curve based on different reference levels

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