Estimation of reliable Stage-Discharge Curve in meandering river using Conveyance Estimation System (CES) Model

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Abstract. Water level estimation in river is important for management of schemes working on it. Uncertainty in estimation would increase the likelihood of confusion in scheme management and fail to achieve its objective. Consequently, reliable water level estimation enables to inform assessments regarding design and operation. In this paper, the experimental work has been conducted to verify the estimated rating curve using Conveyance Estimation System (CES) with uncertainty estimation based on the upper and lower roughness values built in. A straight channel is carved into the sand races of the experimental flume with an initial small bend at the upstream to provide a disturbance region. This disturbance induces the straight channel to take the meandering path. The water levels and the bed elevations are measured at specified cross sections along the channel when it reaches the state of equilibrium with different steady flows in order to construct the actual rating curve at specified cross sections. The obtained geometric and hydraulic data have been used for CES model to estimate the rating curve with uncertainty estimation. Results of the computations indicate that the CES model could adequately produce the stage-discharge curve in agreement with the observed values. It is anticipated that the results presented in this paper will aid the researchers in using the CES model as a predicting tool in the field of river engineering.

Keywords
Meandering river, CES model, rating curve, river engineering

1. Introduction
The right plotting of the stage-flow relationship is the basic information used by engineers for the management scheme, the channel operation and the maintenance purposes. If the path of the channel is meandering rather than straight one, further complex mechanisms take place in the channel flow due to presence of secondary flow which arises out of complex geometry and irregular bottom topography of the channel. The estimation of reliable stage - flow curve is often hard to attain due to complex nature of the flow pattern in meanders. The resistance coefficients for meandering rivers were found to be different with boundary friction, flow depths, width to depth ratio, sinuosity, secondary flow, turbulence and slope. These factors produce differences between the predicted stage-flow curve and the measured ones. Therefore, several methodologies of field and/or experimental studies, simplified analytical analysis and numerical approximation are often applied for analyzing meandering channel. Sellin et. al (1993), investigated the effect of channel geometry, floodplain width and roughness on the water level-discharge relationship. Wark et. al (1994), proposed a method to estimate the conveyance in meandering channels with overbank flow based on the horizontal division of the cross section. Shiono et. al (1999), carried out flow measurements for overbank flow in a two-
stage meandering channel with different sinuosity, bed slopes and water levels. Ervine et. al (2000), developed a practical technique to calculate the flow characteristics in meandering channels. Khatua et. al (2010), investigated experimentally the variation of roughness coefficient for meandering channel, where a simple formula for roughness coefficient was developed. Khatua et. al (2012), used one-dimensional numerical model to predict stage-discharge relation for straight and smooth compound channels using available experimental data. Adhikari et. al (2017), adopted CES model and other numerical methods for stage-discharge prediction in straight channel.

In the present study, an experimental work has been conducted to verify the predicted stage-flow curve using Conveyance Estimation System (CES) model as an important issue for the management scheme, operation and maintenance in the meandering channel.

2. Description of the CES model
The development has been presented by the Department for Environment, Food and Rural Affairs of a Conveyance Estimation System (CES) software, in order to reduce the uncertainty associated with water level predictions (Refer to Ref. DEFRA/EA, 2002 and 2003). A key element of the CES model was to quantify the uncertainty in water levels for the given flow rate, and explain it in a manner which can be readily interpreted by the decision makers with more informed decisions.

CES estimates the stage-discharge relationship and flow characteristics, in both flumed and natural channels. CES model reflects all the physical flow processes that are present in flow condition as it included empirical coefficients based on previous research and expert advice. The uncertainty in water level estimation is based on the upper and lower roughness values provided in the CES model. These values are based on expert advice from a multi-disciplinary team of specialists in surface roughness. It is expected that the stage-discharge curve usually lies within these upper and lower bands. Therefore, the computations of CES model provide some indication of the confidence in the predicted water level (DEFRA/EA,2002:2003).

3. Calibration CES model
The computation method adopted in CES model is governed by the depth-integrated Reynolds averaged Navier-Stokes equations for flow. Calibration within the CES environment, suggest that the internal model parameters such as; dimensionless eddy viscosity and the secondary flow parameters are not altered. These parameters have been exposed to rigorous analysis and are set at the optimum performance values. Therefore, calibration is established on altering the roughness zones, i.e. roughness values and its extents in the cross section due to that the water level is most sensitive to variations in roughness values.

4. Description of experimental flume setup
Figure1. shows the plan and side sketch of the experimental flume. The length of the flume is 6 m width 1.5 m and depth 0.22 m. The selected sediment that is used as a bed material in the experimental flume is taken from Kufa River located at middle district of Iraq because it is well graded to ensure non uniformity in size distribution. The laboratory test for specimen of this material shows that it is classified as non-cohesive and non-uniform alluvial sand at median size d50=0.3mm and standard deviation, σg=3.83.

The sand would be transported as a bed load and suspended load, if the particle size is small and velocity is too large, sediment entirely being suspended with current and the probability of deposition is rarely possible. Whilst, if the size of sand is large and at the same time, the velocity is small, there would be no sediment transport or it may be transported as a bed load. In the present work, for each run, the average velocity of the flow was compared with the critical depth average velocity (ūc) for the mean particle size to achieve the required flow conditions that enable the sediments to be initiated to transport. These hydraulic conditions subject to the current experimental work was selected to satisfy the hydraulic conditions to be consistent with the context of the flow usual in the rivers.
5. Experiment procedure
The experimental flume was filled with sand to a depth of 10 cm. The surface was flattened to a specified initial slope then a straight channel was carved along the centerline of the flume with initial bending at the upstream side at an angle of 30° to the longitudinal axis of the flume. This bending ensures the occurrence of initial disturbance to develop the pattern of meander. The initial straight channel was incised (width/bank depth<5) with rectangular cross section of (0.14×0.06m). The water was circulated by centrifugal pump, via calibrated flow meter for discharge measurements. The discharge is adjusted manually by a controlling valve. During the time, the initial channel was developed from straight to meandering until achieving the equilibrium state. According to the flow and geometrical conditions of the present work, this state has been achieved after 12hr from the beginning of run. The visual indication of the equilibrium is no scour or occurrence of deposition. Figure 2 illustrates the time dependent meandering evolution till the equilibrium state is achieved. The developed meander is then used to study the stage-flow curve. To construct the stage-flow curve in the developed meander, a series of experimental runs was conducted with steady flow ranged from 1.25 l/s to 4.5 l/s. This range of discharge was used to be consistent with the hydraulic and geometry limitations of the experimental setup. Through the runs, the water level was measured along the meander by the point gauge.
6. Modeling with (CES)

The equilibrium meandering channel obtained from the experimental work was located between the cross sections 1 and 3 (see Figure 2-e). Geometrical characteristics of selected cross sections was measured and input to the CES software. The roughness coefficient, n was provided for the bed and banks for each cross section as a range (upper and lower value as identified in CES model) to evaluate the uncertainty in estimating the stage-flow curve due to unreliable assessment of roughness value for banks and bed. Table 1 lists the upper and lower values of Manning’s roughness coefficient for bed and banks as identified in CES model which were selected based on the median particle size (grain roughness), irregularity in cross sections, layouts of meander and pools-point bars within the meander reach. Figure 3 shows the roughness zones assigned for the identified cross-sections. After data was assigned, it is possible to predict the CES stage–discharge curve.

Table 1. The upper and lower values of Manning’s n used in CES model

| Zone        | Factor                | Lower resistance value | unit roughness* | Upper resistance value | unit roughness* | Average roughness |
|-------------|-----------------------|------------------------|-----------------|------------------------|-----------------|-------------------|
| Bed         | skin friction         | 0.017                  | 0.0177*         | 0.025                  | 0.0269*         | 0.022             |
|             | bed form              | 0.005                  |                 |                        |                 |                   |
| Banks       | skin friction         | 0.017                  | 0.0197*         | 0.025                  | 0.0390*         | 0.029             |
|             | Pool and deposition   | 0.01                   |                 |                        |                 |                   |

* The unit roughness was estimated by the equation: \( *n = (n_{sur}^2 + n_{irr}^2 + n_{veg}^2)^{1/2} \) which adopted by CES model, where; \( n_{sur} \), \( n_{irr} \) and \( n_{veg} \) are the roughness values owing to surface material, irregularity and vegetation, respectively.
7. Analysis of CES computation results
The predicted stage-discharge curves were generated at each cross section with the upper and lower bands of uncertainty (i.e., upper and lower values of Manning roughness). These curves were denoted as the central, upper and lower. The upper and lower bands are plotted together with the central curve in order to illustrate the effects of the uncertainty of roughness on it. Figure 4 shows the comparison among these rating curves for the cross sections undertaken. This figure shows that the overprediction of the roughness value leads to a rise in the stage at the section. Conversely the indication of the underprediction of the roughness value is a lowering in the stage. Consequently, the uncertainty of roughness estimation means unreliability in estimation of the stage-discharge curve.

Figure 3. Roughness zones assigned to CS1, 2 and 3

Figure 4. Stage-discharge curve from CES for CS1, 2 and 3
Accordingly, the reliability of the predicted CES stage-discharge curves for the selected cross sections should be altered through the verification with those obtained from the experimental data. Fig.5 shows the spread and trend of experimental data as compared with the stage-discharge curve that is estimated by CES model for CS1. The figure shows that there is a good agreement between the estimated curve and the measured data. However, the measured data entirely lies within the uncertainty bands but it is closer to the upper limit.

**Figure 5.** Comparison of CES stage-discharge curves with the measured values at CS1

Based on this correlation, the stage-discharge curve of CS1 does not need calibration. The same context has been followed for other cross sections (e.g., CS2 and CS3). For CS2, the stage-discharge curve that is estimated by CES was somewhat located below the experimental data which indicated underprediction within the bank as shown in Fig.6. So the calibration seems important for better fitting the CES stage-discharge curve with the measured values. Increasing the bank resistance will generate high error at low flow but a good fit at higher flows. Therefore, the roughness value should be adjusted for the bed and bank through calibration to become 0.03. The calibrated CES curve shows the expected enhancement. At the same time the uncertainty bands comprise both the estimation curve by the CES and that measured through the experiments as shown in Fig.7.

**Figure 6.** Comparison of CES stage-discharge curves with measured values at CS2

**Figure 7.** Comparison of calibrated CES stage-discharge curves at CS2
For cross section 3, the estimation of the upper limit and the central curve of the stage-discharge by CES lie above the experimental data. That is an indication of the resistance tending to overprediction within the bank as illustrated in Fig.8. The Calibration process is through modifying the roughness value manually to being 0.025 instead of the initial value 0.029 to reproducing the final form of the CES curve as shown in Fig.9.

![Figure 8](image1.png)

**Figure 8.** Comparison of CES stage-discharge curves with measured values at CS3

![Figure 9](image2.png)

**Figure 9.** Comparison of calibrated CES stage–discharge curves at CS3

### 8. Statistical analysis

Two statistical indicators have been adopted for testing the reliability of the CES model when used in estimating the stage-discharge curve for specified cross sections, these are the BIAS, and the Mean Absolute Error (MAE) which can be calculated by the following formulas;

\[
BIAS = \frac{1}{N} \sum_{i=1}^{N} (X_{pred} - X_{exp}) \\
MAE = \frac{1}{N} \sum_{i=1}^{N} |X_{pred} - X_{exp}|
\]  

(1)  

(2)

Where, \(X_{pred}\) and \(X_{exp}\) are the predicted and measured values respectively and \(N\) is the number of measured data. The BIAS Index measures the tendency of the predicted values to be larger or smaller than the measured ones; the well perfect is when \(BIAS=0\), positive values indicate a tendency to overestimation, and the negative values are an indication of underestimation. The same context can be said to mean absolute error, where the perfect agreement between the estimated and measured is when \(MAE=0\). Table 2 lists the statistical evaluation of predicted values at selected cross sections.

| Table 2. the Statistical Evaluation for calibrated stage-flow curve (Central Estimate) at specified cross sections |

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Cross section | Stage | MAE | BIAS
--- | --- | --- | ---
1 | 0.0012 | -0.000018
2 | 0.0019 | -0.000021
3 | 0.00114 | 0.00013

The calculated values of MAE and BIAS showed reasonably satisfactory between the central estimate values and the experimental ones.

9. Conclusions

(1) An inadequate resistance coefficient leads to overestimation or underestimation in stage and then error in discharge estimation.
(2) Results from CES model were reasonably satisfactory although a slight variation was found at some stages. This was attributed to the fact that the hydraulic and geometric measurements being implemented in experimental meandering channel had a significant variation at inner and outer banks due to curvature in flow path.

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