Calibrating the discharge of the Kut Barrage using related equations at different gates openings

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Abstract. The Kut Barrage is one of the most important hydraulic structures in Iraq, which is in place to regulate the flow from the Tigris River and distribute it between Graf River, Dujelah Channel, Dalmch Channels, and other irrigation projects. The barrage includes 56 sluice gates, each 6 m wide, which control the discharge of the Tigris River at the individual locations. According to observations and measurements, about 90% of the flow at the downstream has been modular (free flow) within the last five years. In the present study, a trial was attempted to calibrate some universal formulas that would offer a reliable means of determining the discharge under gates such as those presented by Rajaratnam and Subramanya, Swamme, and Ferro, which would make them suitable for Kut Barrage discharge calculation over a wide range of scenarios in terms of gate openings. A recent formula presented by Maatooq for canal operation was also adopted in order to test whether it was appropriate for application under the flow and geometric boundary conditions of the Kut Barrage. The available data was also used to extract an empirical equation for the coefficient of discharge used for calibration. A total of 221 measurements taken at the head at upstream, nine different gate openings, and at the discharges were employed for calibration, and 28 data points taken at six different gate openings were adopted for verification. The determined discharges using the calibrated formulas show good agreement with the measurements with the coefficient, R^2 ranging between 0.874 using Rajaratnam and Subramanya and 0.880 using Maatooq.
Keywords: Kut Barrage, free flow, coefficient of discharge, sluice gate, multiplication factor, calibrated formula, determination coefficient.

1. Introduction

Sluice gates are widely used in irrigation projects to control water elevation, and sluice gates can also be used for flow measurement with reasonable accuracy. To obtain this objective, study of sluice gates as measuring structures is required, however. In spite of the fact that sluice gate structure is simply designed to give the determination of discharge, further applications are required in hydraulic engineering to estimate the accurate values of the contraction coefficient and energy loss factors where both are affected by the discharge coefficient. The contraction coefficient can be determined accurately when the vena-contracta becomes well featured. This state occurs when free hydraulic jump is achieved downstream, and the initial depth is thus a section of vena-contracta. Accordingly, the flow rate under sluice gates can be obtained accurately if the contraction coefficient is known [4]. Henry [5] implemented extensive experimental work to determine the discharge coefficient for sluice gates under free and submerged flow conditions, and a graphical solution for both flow conditions was introduced. Rajaratnam and Subramanya [8] proposed a new approach, based on energy and momentum concepts, that calculates the discharge coefficient as a function of head-discharge relationships for both free and submerged sluice gates. Swamee [10] presented two formulae to distinguish free and submerged flow conditions based on Henry's curve, while Ferro [3] deduced the head-discharge relationship by theoretical analysis based on dimensional analysis of Π-theorem coupled with experimental investigations using laboratory flumes. Shayan and Farhoudi [9] investigated the characteristics of flow from sluice gates under free flow and submerged flow conditions using the energy and momentum equations, the results showed that at free flow condition, a minimum contraction coefficient can be obtained under a certain value of relative gate opening. Dabral et al [2] studied the discharge coefficient under sluice gates in a laboratory channel; they thus found that the average discharge coefficient was equal to 0.76. Belaud et al [1] concluded that the contraction coefficient varies with the relative size of the gate opening and the relative submergence, especially for large gate openings: the contraction coefficient may be similar in submerged flow and free flow for small openings, but not for large ones. Lozano et al. [6] employed an energy–momentum method with 16,000 field-measured data points to evaluate the accuracy of several sluice gate calibration methods. They found that the best empirical fit was obtained by setting the discharge coefficient as a parabolic function of vertical gate opening. The authors indicated that the conventional equation proposed by USBR [11], with a suitable choice of empirical discharge coefficient formula, could also be considered an accurate method. Maatooq [7] adopted an extensive experimental programme for both free and submerged flow conditions. The collected data were analysed to present practical equations and charts based on five methodologies.

The discharge formulas of sluice gates must be supported by site-specific calibration. In this study, some of the known universal formulas from the literature, and a new formula proposed by Maatooq [7], have been selected to calibrate the discharge calculations for the Kut Barrage for different scenarios of gate opening under free flow conditions. Overall, 221 measurements, including the head at upstream, nine different gate openings, and the discharges, were employed for calibration and 28 data points at six different gate opening were adopted for verification.

2. Deterministic Formulas

2.1. Rajaratnam and Subramanya

The discharge calculation used by this formula depends on the accurate estimation of both the head and the contraction coefficients:

$$Q = C_d \, G \, b \, N \sqrt{2g \, (H - C_c \, G)} \tag{1}$$

where C_d is the discharge coefficient, G is gate opening, b is the width of the gate, N is the number of gates of barrage under operation, and H is the upstream head. Here, C_c=0.61 is used as a reliable value in practice.
For free flow conditions, Rajaratnam and Subramanya suggested that the discharge coefficient can be calculated using the following equation for $\frac{G}{H} < 0.3$.

$$C_d = 0.0297 \frac{G}{H} + 0.589 \tag{2}$$

2.2. Swamee

In order to, calculate the discharge amount, this author considered that the discharge under a sluice gate for free flow conditions could be treated as a flow form orifice. Based on this theoretical concept, the discharge equation takes the form

$$Q = C_d \, G \, b \sqrt{2g \, H} \tag{3}$$

where

$$C_d = 0.611 \left(\frac{H-G}{H+ c_o G}\right)^{c_1} \tag{4}$$

and $c_o = 15$, c_1= 0.072.

2.3. Ferro

The Ferro Formula can be expressed as

$$Q = b\,N\sqrt{g\,\left(G * k_o\left(\frac{H}{G}\right)^{k_1}\right)^3} \tag{5}$$

where k_o and k_1 are the coefficient and exponent of the power form correlation between the critical depth, the head at upstream, and the gate opening such that

$$\frac{y_c}{G} = k_o\left(\frac{H}{G}\right)^{k_1} \tag{6}$$

where y_c is the critical depth, as calculated from the following equation used for rectangular cross-sections:

$$y_c = (q^2/g)^{1/3} \tag{7}$$

Here, q is the discharge per unit width and g is g the acceleration due to gravity.

2.4. Maatooq

To simplify discharge determination, Maatooq proposed numerous formulas for different situations that may encountered in practice for both free and submerged flow conditions. The formulae for the situation of free flow are

$$\frac{y_f}{G} = -0.00003\left(\frac{H}{G}\right)^3 + 0.0022\left(\frac{H}{G}\right)^2 - 0.0349\left(\frac{H}{G}\right) + 0.9079 \tag{8.a}$$

and

$$q = \sqrt{g{y_f}^3}\left[2.0974Ln\left(\frac{H}{G}\right) - 0.1714\right] \tag{8.b}$$

where y_f is the depth of flow at vena-contracta and q is a discharge per unit width.

2.5. Empirical Formula

Discharge may be calculated theoretically based on the flow through the orifice. The equation takes the same form as equation (3), but without the discharge coefficient. Accordingly, the discharge coefficient as seen in equation (3) is simply an expression of an adjustment factor between the actual and theoretical discharges. Practically, and as adopted by previous authors, this coefficient is thus a function of the head upstream to the gate opening. In the present work, an attempt is made to present the equation for C_d that could best be used for barrage undertaken. The power form is the most reliable function, and is thus widely adopted in engineering applications:

$$C_d = a\left(\frac{H}{G}\right)^b \tag{9}$$

3. Data Selection

Water level measurements (upstream and downstream) and the discharge of the Kut Barrage as provided by the Kut Barrage Directorate for the years 2012 up to 2017 were used in this study. The water levels were recorded using staff gauges fixed at gage stations, and the differences between these levels used to distinguish between free and submerged flow conditions. The observed discharges were measured using an Acoustic Doppler Current Profile (ADCP) SonTek - M9 instrument for each water level. Measurements at the head upstream of the gate, H, ranged between 3.6 m and 6.1 m, and the discharge through different gate openings within the period of measurements ranged between 135 m^3/s and 350 m^3/s. These data were recorded with nine different gate openings ranging between 0.09 m and 0.17 m. The total number of gates in the Kut Barrage is 56, and within the period of the data collection, all of these were opened at the same opening width for each scenario of operation. Figure 1 shows a location map of the Kut Barrage. For all gate openings and flow discharges undertaken, the flow was under free conditions (modular flow). The adoption of this condition was based the suggestion proposed by [10] according to the following equations:

$$\text{Free flow:} \qquad H \geq 0.81\, y_t \left(\frac{y_t}{G}\right)^{0.72} \tag{10}$$

$$\text{Submerged flow:} \quad y_t < H < 0.81\, y_t \left(\frac{y_t}{G}\right)^{0.72} \tag{11}$$

where H and y_t are the head at upstream and the tail water, respectively.

The maximum water level at the downstream for the available data was 11.45 m a.s.l., which means that y_t can be taken equal to zero as compared with the crest level (see figure 2). Thus, H was always greater than the right-hand side of the equation (10) for data gathered.

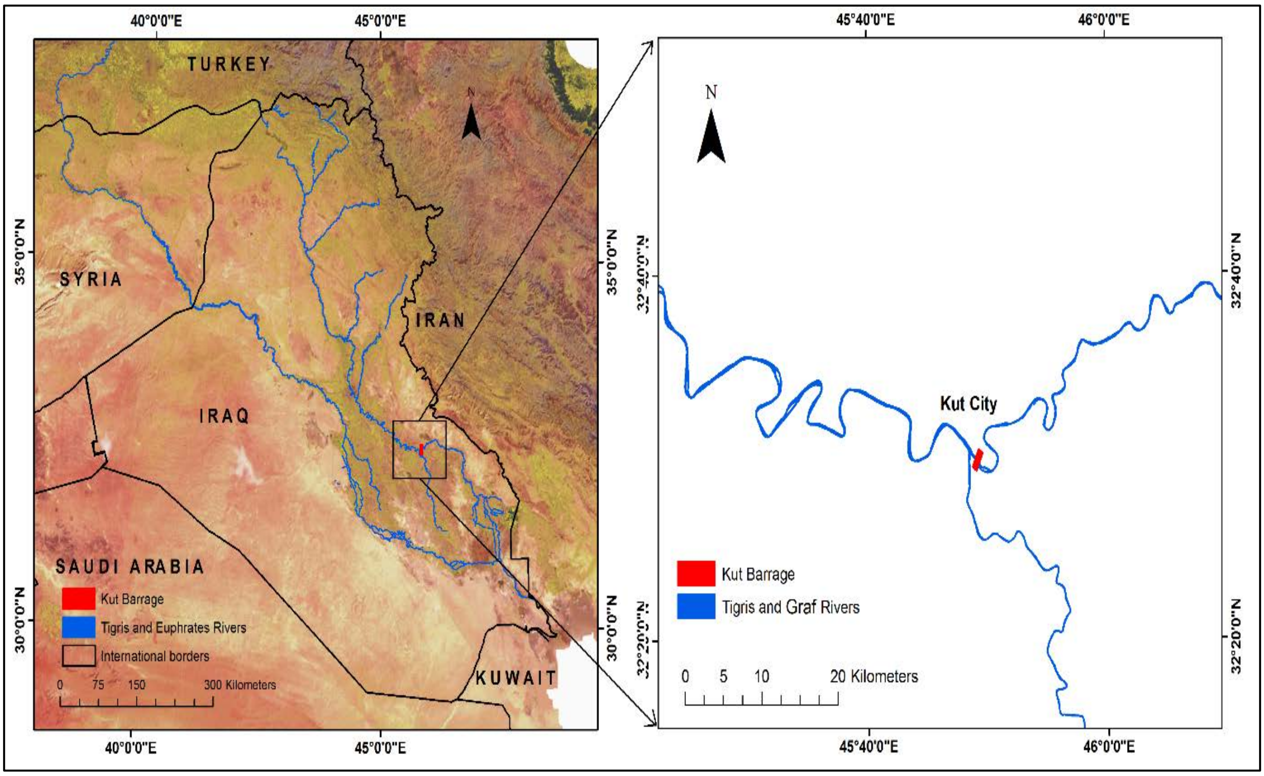


Figure 1. Location map of the Kut Barrage (Kut Barrage Directorate)

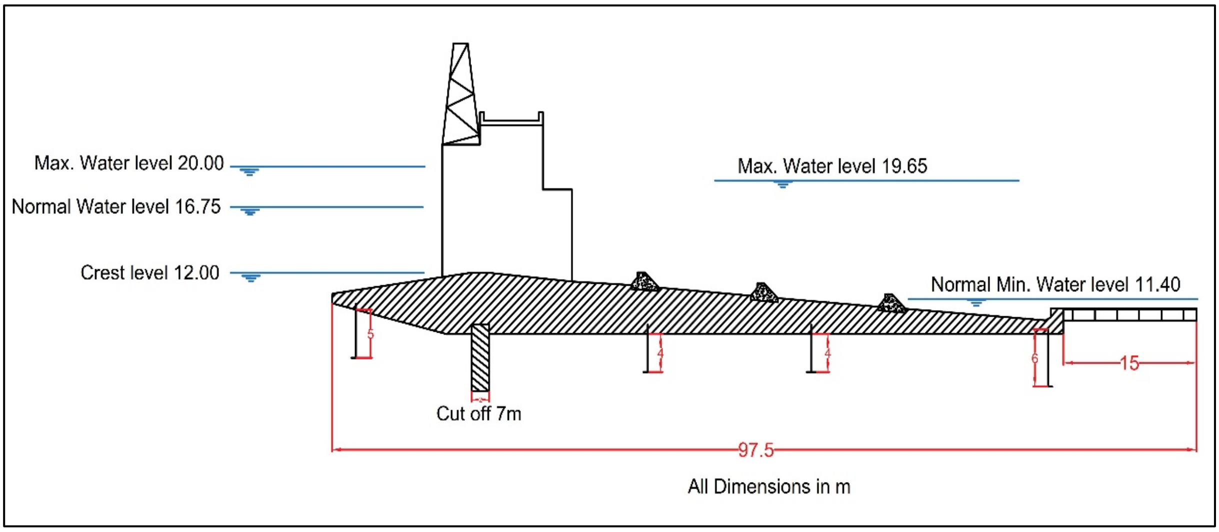


Figure 2. Dimensions of the Kut Barrage.

4. The Calibration of Selected Equations for the Kut Barrage

The Rajaratnam and Subramanya, Swamee, Ferro, and Maatooq formulas were used to calculate the discharge of the Kut Barrage for each gate opening. For all these formulas, the results diverged from the measured values by appreciable amounts. Thus, they required modification using a modification factor, denoted as *K*, which was used as a multiplication factor with the original form of the selected equation. The value of this parameter is a product of dividing the measured discharge to that calculated from the equation under investigation. In context, the *K* parameter was correlated with the relative head to gate opening, *H/G*.
The results of the correlation for the Rajaratnam and Subramanya equation are illustrated in figure 3. From this figure, the following equation for *K* at R^2=0.418 can be deduced:

$$K = 0.319\left(\frac{H}{G}\right)^{0.283} \quad (12)$$

Using the *K* from equation (12) as a multiplication factor to modify equation (1) led to an improvement of the determination coefficient between the measured and calculated discharges from R^2=0.785 to R^2=0.874.
To calibrate the Swamee formula for discharge calculation of the Kut Barrage, the same procedure is used. The appropriate *K* can be found by using the following equation for R^2=0.393 or by using figure 4:

$$K = 0.339\left(\frac{H}{G}\right)^{0.265} \quad (13)$$

After modification of equation (3) by this *K*, improvement is achieved, with an enhancement of the value of R^2 from 0.798 to 0.878.

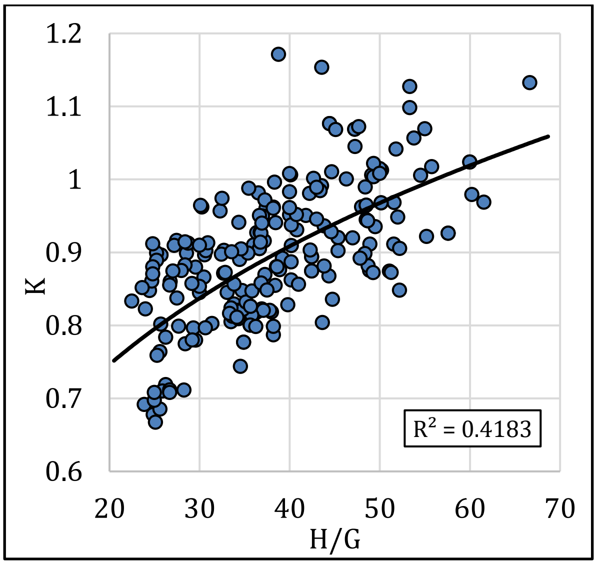


Figure 3. Modification factor for Rajaratnam and Subramanya formula.

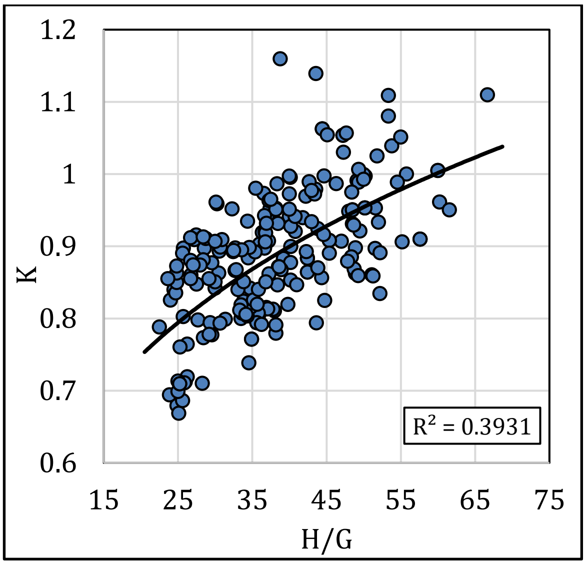


Figure 4. Modification factor for Swamee formula

The Ferro formula was modified using another method. The aim is to find the coefficient, k_o, and exponent, k_1, of equation (6) based on the Kut Barrage database to make it usable for operation of that structure. The regression analysis is restated as the following equation at R^2=0.851 and its design curve is shown in figure 5:

$$\frac{y_c}{G} = 0.41\left(\frac{H}{G}\right)^{0.525} \tag{14}$$

The available data was introduced by equation (14), then the results substituted into equation (5) to find the calculated discharges. Good agreement between the measured and calculated discharges was demonstrated by the R^2=0.876.

Maatooq's practical approach for canal applications was adopted as an attempt to calibrate the portion of the free flow conditions most appropriate for use in Kut Barrage operations. A total of 206 data points were adopted for calibration, including discharge measurements of between 134 m^3/sec and 325 m^3/s within the range of gate openings 0.09 m to 0.17 m to achieve a head of between 3.6 m to 6.1 m. The results denote that the calibration factor used for modification of the Maatooq equation can be derived from the following equation at R^2=0.8247:

$$K = 0.00003\left(\frac{H}{G}\right)^3 - 0.0024\left(\frac{H}{G}\right)^2 + 0.06\left(\frac{H}{G}\right) + 0.103 \tag{15}$$

The design curve of this coefficient is shown in figure 6.

The calculated discharges determined by the modified equation (8.b) show close agreement with the measurements at the Kut Barrage, with a determination coefficient R^2=0.88; its value pre-modification was only equal to 0.636.

In order to introduce an empirical formula for calibration, the values of the coefficient and exponent of equation (9) were extracted for the Kut Barrage discharge calculation. The available data were used for this purpose, and the final form of equation (9) based on regression analysis is

$$C_d = 0.185\left(\frac{H}{G}\right)^{0.288} \tag{16}$$

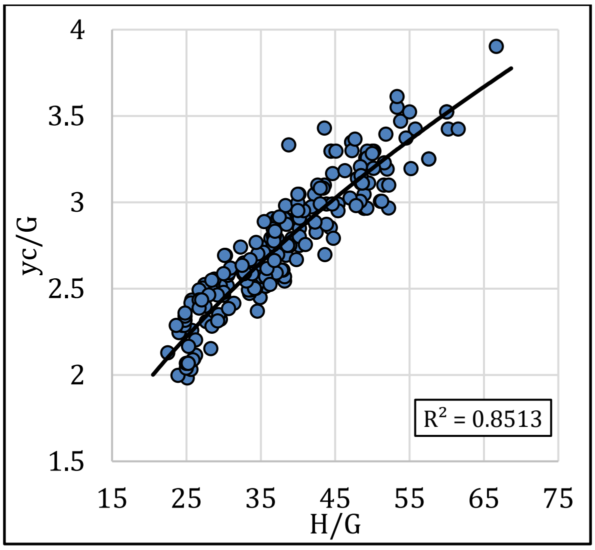


Figure 5. The calibrated values of k_o and k_o of the Ferro formula for the Kut Barrage.

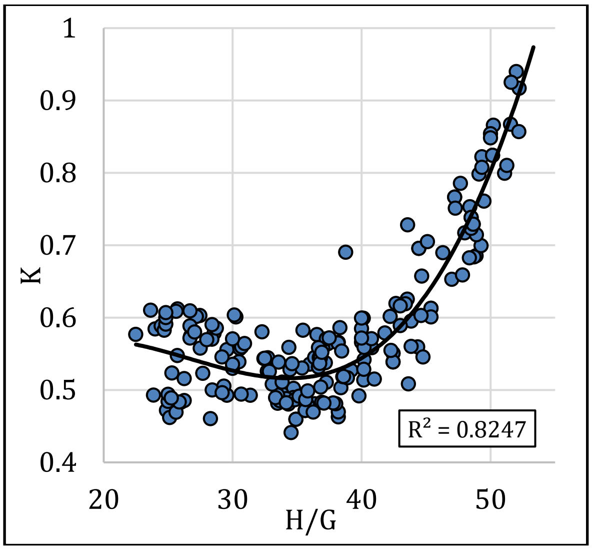


Figure 6. The modification factor for the Maatooq equation.

The determination coefficient (R^2) of equation (16) is equal to 0.4332; figure 7 shows the trend line of this equation. In the present study, an attempt was made to use another approach to calibrate the selected formulas for the discharge determination of the Kut Barrage, however, which adopted by equation (16) instead of equations (2) and (4) for the Rajaratnam and Subramanya and Swamee formulas respectively.

When the results of *Cd* based on equation (16) are substituted into equation (1), the calculated discharges show good agreement with the measurement, with R^2=0.877, while the value of R^2=0.874 appears when *K* is used with the basic formula (both equations (1) and (2)). This solution seems to allow some improvement in performance of equation (1) as compared with previous attempts using the modification factor *K*, but this is not significant. Thus, researchers can choose either method without expecting significant differences in the results.

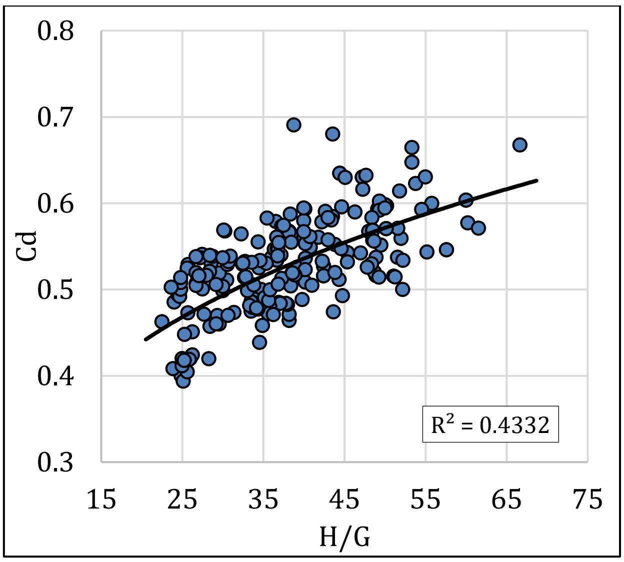


Figure 7. Empirical formula of the discharge coefficient of Kut Barrage calibration.

These results for the use of equation (16) seemed encouraging, and this procedure was thus attempted for the calibration of the Swamee formula. After replacing equation (4) with equation (16), the results obtained for the calculated discharges appeared well correlated with the measured discharges. The value of this correlation is represented by the R^2=0.878. This indicator is the same as when K is used for calibration, suggesting no difference in the results when choosing either option. However, using equation (16) to calibrate equation (1) for Rajaratnam and Subramanya and equation (3) for Swamee seems more realistic in practice.

5. Verification of Calibrated Formulas

Verification is required to show the possibility of using the calibrated equations at different flow conditions for the Kut Barrage. Some of the measured data at different operation scenarios (i.e. different head and discharge at the different gate opening) was thus selected and employed for calibration. The 28 data points chosen covered the upstream head between 3.76 m and 6.1 m and discharge between 138 m^3/s to 350 m^3/s. These flow conditions were achieved with six different gates openings: 0.09 m, 0.1 m, 0.12 m, 0.14 m, 0.16 m, and 0.17 m. The same procedures as those used for calibration were followed for verification to test the validity of the calibrated formulas of Rajaratnam and Subramanya, Swamee, Ferro, and Maatooq. The correlations between the measured and calculated discharges are represented by their R^2, which were respectively; 0.8824, 0.8823, 0.8822, and 0.871; the trend lines of these correlations as compared with the perfect line are evident in figures 8, 9, 10, and 11. All values of the RMSE as marked on the figures are close to zero, which supports the reliability of the calibrated formulas. The high values of the determination coefficients along with the low values of RMSE and convergent results suggest that any of the selected equations can be employed successfully to give satisfactory results for Kut Barrage discharge calculations, and that no fundamental differences in results are predicted, provided that the applications are within the same boundary conditions of the calibration.

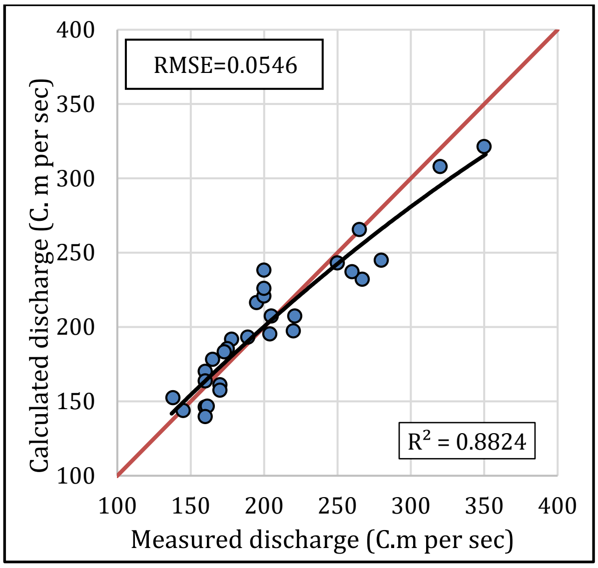


Figure 8. Verification for calibrated Rajaratnam and Subramanya formula.

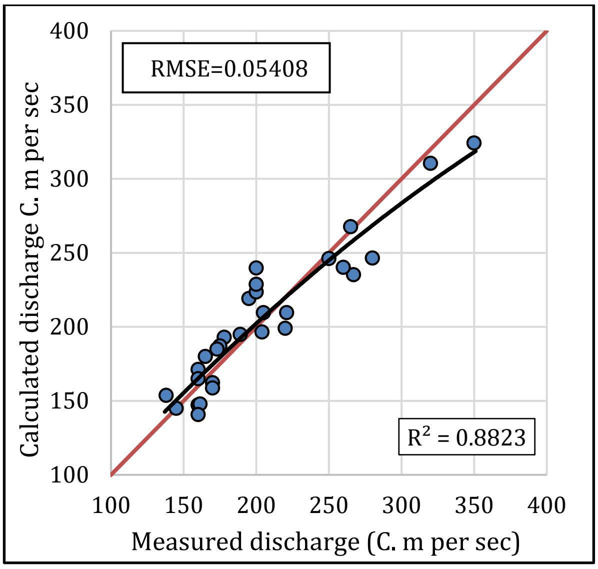
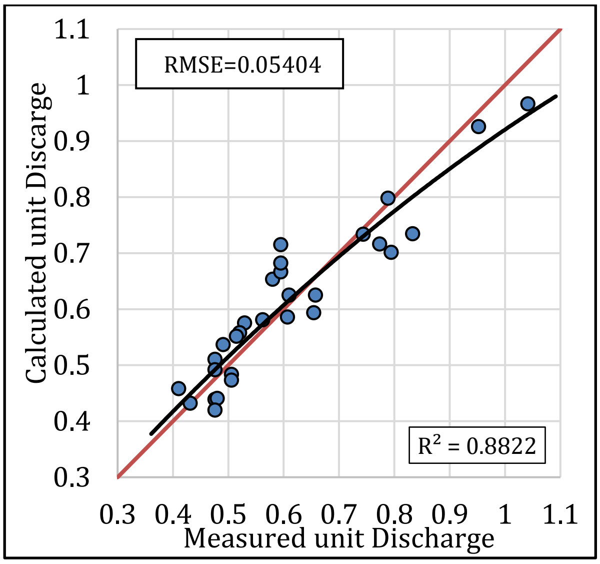


Figure 9. Verification for calibrated Swamee formula.



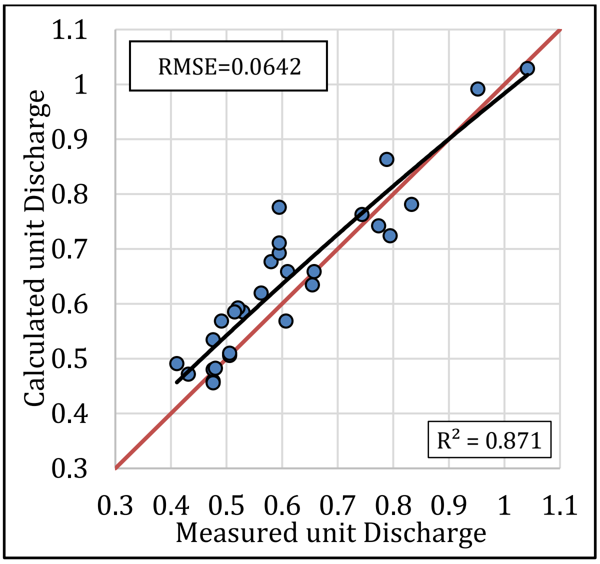


Figure 10. Verification for Ferro formula.

Figure 11. Verification for Maatooq formula.

6. Conclusions

From the results, it can be concluded that the sluice gates in barrages are usually operated at a wide range of gate openings. This means that using a fixed discharge coefficient is not advisable, because its accuracy will suffer from the abrupt changes caused by changes in gate openings; the discharge coefficient is very sensitive to such gate openings. Accordingly, the calibration of the available deterministic equations for specified flow and geometric conditions becomes essential for regulation. The selection of the first three formulas used in the present study was based on those most widely cited and recommended in the literature, while the choice of the Maatooq formula was evidence of the researchers' willingness to test the possibility of calibration to make other works more suitable for Kut Barrage discharge calculations. It should be mentioned that this formula was first proposed to simplify the action of calculation in practical situations. An empirical formula was also adopted in the present study as an attempt to offer cornerstone for calibrating the equations under considerations. The results of analysing the available data show that it is necessary to use a multiplication factor, *K*, to modify the basic equations for the Rajaratnam and Subramanya (1967), Swamee (1992), and Maatooq (2016) formulas, while for the Ferro (2000), calibration is required to extract the coefficient and exponent of equation (6) as based on the Kut Barrage database. The available measured data was also used to introduce the empirical function for the coefficient of discharge that can be used to calibrate the first two formulas to make them more suitable in direct application for Kut Barrage operations. The determined discharges using the calibrated formulas show good agreement with the measurements; the determination coefficient ranged between 0.874 using Rajaratnam and Subramanya (1967) and 0.880 using Maatooq (2016).

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7. References

[1] Belaud G, Cassan L and Baume J P 2009 Calculation of contraction coefficient under sluice gates and application to discharge measurement *Journal of Hydraulic Engineering* **135** (12) pp1086-1091

[2] Dabral P P, Pandey P K, Kumar Tr and Chakraborty S 2014 Determination of discharge coefficient and head-discharge relationships of different hydraulic structures *Journal of Indian Water Resources Society* **34** (1)

[3] Ferro V 2000 Simultaneous flow over and under a gate *Journal of Irrigation and Drainage Engineering* **126** (3) pp 190–193

[4] Henderson F M 1966 Open channel flow *MacMillan Publishing Co. Inc. New York*

[5] Henry H 1950 Discussion: diffusion of submerged jet *Transactions of the American Society of Civil Engineers* **115** pp 687–97

[6] Lozano D, Mateos L, Merkley G P and Clemmens A J 2009 Field calibration of submerged sluice gates in irrigation canals *Journal of Irrigation and Drainage Engineering* **135**(6):763–7

[7] Maatooq J S 2016 Hydraulic characteristics and discharge of canal sluice gate: practical approach *Journal of Engineering* **22** (11) pp 16-35

[8] Rajaratnam N and Subramanya K 1967 Flow equation for the sluice gate *Journal of Irrigation and Drainage Engineering* 93(3):167–86

[9] Shayan H K, Farhoudi J and Roshan R 2014 Estimation of flow discharge under sluice and radial gates based on contraction coefficient *IJST*, Transactions of Civil Engineering **38** No. C2, pp 449-463

[10] Swamee P K 1992 Sluice-gate discharge equations *Journal of Irrigation and Drainage Engineering* **118**(1) pp 56–60

[11] USBR 2001 Water measurement manual. *3rd ed. Washington, DC: U.S. Department of the Interior*

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