Analysis of the Euphrates River’s movement within Al-Hindiya, Karbala, relative to steady flow conditions using the HEC-RAS model

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Abstract. The steady flow condition is considered to be the dominant case for multiple rivers around the world. River studies thus necessarily focus on this condition, including those in Iraq, which has two rivers running from north to the south. In this study, the HEC–RAS program was applied to steady flow analysis of the Euphrates River within Al-Hindiya in Karbala. The case study was executed for the whole city of Al-Hindiya by selecting 12 km length of the river and dividing it into 30 sections. Field data for 2019 was thus used to develop three profiles for discharge at minimum, normal, and maximum magnitudes, which were 90 m$^3$/sec, 250 m$^3$/sec, and 445 m$^3$/sec, respectively. The results showed that the maximum variation ratios in velocity between sections were 80%, 70%, and 72% for the minimum, normal, and maximum profiles, respectively, with the variation ratios in water level between reach ends being 4%, 6%, and 5% and the slopes of energy grade lines were about 0.009%, 0.015%, and 0.013% for the three profiles respectively. In addition, the regression analysis of the results revealed that the relative energy losses between any two adjacent sections are linked strongly to the relative change in water level for the normal and minimum profiles, with coefficients of determination $R^2$ = 0.88 and 0.96 for these profiles, respectively; however, for maximum discharge, the relative energy losses were related to the relative change in both velocity head and water level, with $R^2 = 0.94$.

Key words. energy grade line, Euphrates River, HEC-RAS, modelling, steady flow, surface profiles.

1. Introduction
Open channel flow occurs in both natural and man-made structures in which the water flow has a free surface, due to gravitational forces. Rivers and natural streams are obvious examples of such natural channels, while irrigation canals, culverts and part-full sewer pipes, spillways, and drainage ditches are man-made channels of this type [1]. Rivers have had a great influence on human activity for many thousands of years, while in more modern eras, rivers have been the focus of multiple engineering activities, such as irrigation, water supply, power production, and flood prevention [2]. Understanding the flow dynamics of
rivers is an essential step towards satisfying human demands for water, and this concept includes utilising appropriate modelling to monitor the spatial evolution of various flow features. Using hydraulic models to support water engineering decisions helps to produce clear knowledge based on clear descriptions of flow characteristics such as flow velocity, water surface, Froude number, and slope energy [3, 4]. Most hydrodynamic river models simulate water flow in only the dominant spatial dimension, being one-dimensional models [5]. A wide range of hydraulic software packages have been developed for modelling the flow features in rivers in this manner, such as HEC-RAS, MIKE11, and BRI-Stars. Among these applications, the HEC-RAS program, developed by the U.S. Army Corps of Engineers’ Hydrological Engineering Center (HEC), is widely used by researchers to deal with the modelling of both steady and unsteady flow in rivers. For example, Mohammed et al. (2019) applied the HEC-RAS model to simulate the flood wave caused by a hypothetical failure of the Haditha Dam in Iraq [6], while Ahmad et al. (2016) assessed the suitability of the HEC-RAS model for simulating water surface profiles for the river Jhelum, which was responsible for flooding the entire valley of Kashmir [7]. Traore et al. (2015) also used the HEC-RAS model to describe the hydraulic behaviour of the Anambe River reach, located between the confluence and Kounkane dams in Senegal [3], and Bennett et al. (2004) compared the HEC-RAS model to the MIKE11 hydraulic software in terms of assessing channel roughness [2]. However, most studies have focused only on specific benefits gained from applying the HEC-RAS model, such as describing the hydraulic behaviour of river related to unsteady flow during flood waves or the shape of water surface sections. This leaves many gaps in its use to be addressed, such as the modelling of steady flow, which is the dominant case in almost every river flow case.

The main objective of this paper is thus to perform a steady flow analysis to study the hydraulic characteristics of flow, such as velocity, water surface profile and energy grade line, for a section of 12 km of the Euphrates River in Al-Hindyia City, Karbala, using the HEC-RAS program and field data recorded in 2019.

2. Materials and Methods
2.1 The Study Area
The Euphrates River is one of the longest and most significant rivers in southwest Asia, being about 2,800 km long. The river rises in Turkey and flows in a south-easterly direction toward Syria and Iraq. The Euphrates basin covers about 440,000 km², of which 47% is in Iraq, 28% in Turkey, and 22% in Syria [8, 9]. In Iraq, several important measurement stations have been constructed on the Euphrates River; these are the Husaibah, Haditha, Hit, Ramadi, and Al-Hindiya barrages. The reach of Euphrates River used for this study is about 12 km long and consists of 30 cross sections, of which the first section (beginning at 32° 37′ 46.5" N, 44°14′ 11.14" E) is 10 km downstream of the Al-Hindyia barrage and the last section (beginning at 32° 32′ 46.7" N, 44°13′ 25" E) is located directly upstream of Al-Hindiya Bridge. The general layout of study reach is shown in Figure 1, and the distance of all cross-sections upstream is illustrated in Table 1.
Figure 1. Reach of study area

Table 1. Distance of cross-sections upstream.

| No. of cross section | Distance (Km) | No. of cross section | Distance (Km) |
|----------------------|---------------|----------------------|---------------|
| 30                   | 0.0           | 15                   | 4.6           |
| 29                   | 0.4           | 14                   | 4.8           |
| 28                   | 0.7           | 13                   | 5.1           |
| 27                   | 1.0           | 12                   | 5.3           |
| 26                   | 1.0           | 11                   | 5.6           |
| 25                   | 1.8           | 10                   | 5.8           |
| 24                   | 2.3           | 9                    | 6.1           |
| 23                   | 2.6           | 8                    | 9.4           |
| 22                   | 2.8           | 7                    | 9.7           |
| 21                   | 3.1           | 6                    | 10.0          |
| 20                   | 3.3           | 5                    | 10.3          |
| 19                   | 3.6           | 4                    | 10.6          |
| 18                   | 3.8           | 3                    | 10.8          |
| 17                   | 4.1           | 2                    | 11.0          |
| 16                   | 4.3           | 1                    | 12.0          |
2.2 Theoretical background to the HEC-RAS model

In a steady one-dimensional flow simulation, the water surface profile and energy grade line of two adjacent cross sections are computed using the standard step iterative method for a one-dimensional energy equation as follows [10]:

\[ z_1 + y_1 + \frac{\alpha_1 v_1^2}{2g} = z_2 + y_2 + \frac{\alpha_2 v_2^2}{2g} + h_e \]  

where \( z_1, z_2 \) are the elevations of main channel inverts (m); \( y_1, y_2 \) are the water depths at cross sections (m); \( v_1, v_2 \) are the average velocities in m/s; \( \alpha_1, \alpha_2 \) are velocity coefficients; \( g \) is gravitational acceleration (m/s\(^2\)); and \( h_e \) is the energy head loss (m). Energy head losses between two adjacent cross-sections involve friction losses and expansion or contraction losses, giving the following energy head loss equation [11]:

\[ h_e = LS_f + C \left[ \frac{\alpha_2 v_2^2}{2g} - \frac{\alpha_1 v_1^2}{2g} \right] \]  

where \( L \) is the weighted reach length, \( S_f \) is the representative friction slope between two cross-sections, and \( C \) is the expansion or contraction coefficient. The weighted reach length is defined as follows:

\[ L = \frac{L_{rob} Q_{rob} + L_{ch} Q_{ch} + L_{lob} Q_{lob}}{Q_{rob} + Q_{ch} + Q_{lob}} \]  

where \( L_{rob}, L_{ch}, L_{lob} \) are cross section reach lengths for right over bank, main channel, and left over bank, respectively, and \( Q_{rob}, Q_{ch}, Q_{lob} \) are the arithmetic average for the discharges between sections for the right over bank, main channel, and left over-bank, respectively. The first term in Equation 2 represents the friction slope, and \( S_f \) can be computed using the average conveyance equation as

\[ S_f = \left( \frac{Q_1 + Q_2}{K_1 + K_2} \right)^{2} \]  

where \( K \) is the conveyance that can be calculated for each subdivision using the Manning Equation:

\[ k = \frac{1}{n} R^{2/3} A \]  

where \( n \) is Manning’s coefficient, \( R \) is hydraulic radius, and \( A \) is flow area.

Solving these equations requires knowledge about the river geometry, its roughness characteristics, boundary conditions, and flow rate [3], however.

3. Development of the HEC-RAS Model

The basic data required to simulate a one-dimensional steady flow using the HEC-RAS program is discussed below.

3.1 Geometric Data

Accessing an accurate river schematic is an important step in developing a HEC-RAS model, and this must be created before any other data is included. In this study, a reach of 12 km along the Euphrates River was studied, with the first station at approximately 10 km downstream of Al-Hindiya Barrage. The river reach was then divided into 30 cross-sections perpendicular to the flow direction, and these cross-section shapes were assumed to remain constant throughout the flow analysis, without erosion or sedimentation. The meandering effect of the river was also ignored, so that the distances between any two
adjacent cross-sections were deemed to be the same for the right and left banks. Contraction or expansion of flow due to change through cross-sections is a typical cause of energy losses within a reach, and for the purposes of HEC-RAS, a list of contraction and expansion coefficients values were proposed based on the degree of transition and the flow regime. For subcritical flow and gradual transition, this study took the contraction and expansion coefficient values to be 0.1 and 0.3, respectively [10].

3.2 Manning Coefficient

Selection of an appropriate value for the Manning Coefficient \( n \) is important, as this determines the accuracy of water surface profile calculation. The value of the Manning coefficient is highly variable and depends on a number of factors including: bed roughness in a channel, vegetation, channel meandering, scour and deposition, the shape of the channel, seasonal changes, and suspended material [12, 13]. The Manning coefficient value can be calibrated when information on the observed water surface profile is available. If these measured data are not available, values of Manning's \( n \) computed for identical stream conditions or values extracted from experimental data can be used as guides in the selection of \( n \) values [12].

For this study, the Manning Equation was applied to section 1 of the river to estimate the magnitude of the Manning coefficient. For this section, when the flow rate is 445 m\(^3\)/sec, the water level reaches 28 m, as shown in Figure 2. In order to apply the Manning Equation in this section, the flow area \( A \) and the wetted parameter \( P \) were calculated manually; their magnitudes were about 672 m\(^2\) and 162 m, respectively. The longitudinal slope of the Euphrates River \( S \) is known to be about 0.00005, the figure approved by Karbala Water Resources Directorate. Applying the required data to the Manning Equation for section 1, \( n = 0.0275 \). Generally, the Euphrates River can be defined as clean, straight, and full, with no rifts or deep pools; for this type of natural stream, according to Chow [12], the Manning Coefficient ranges between 0.025 to 0.033, which is in agreement with the calculated result.

![Image](image.png)

**Figure 2.** Cross section No. 1 at maximum discharge \( Q = 445 \text{ m}^3/\text{sec}, \) water elevation =28 m.
3.3 Steady flow data

Steady flow data, such as flow regime, discharge information, and boundary conditions is also necessary for executing calculations of surface water profile [4, 14]. For this study, the flow was considered to be subcritical and three profiles with discharges of 445, 250 and 90 m³/sec, respectively, were adopted. These values were selected as being the maximum, normal, and minimum discharges for the Euphrates River in 2019 ($Q_{\text{max}}, Q_{\text{norm}},$ and $Q_{\text{min}}$). Boundary conditions are necessary for the computation of the initial water surface at the river ends, though in a subcritical flow system, boundary conditions are only required at the downstream end of the river. Thus, for the selected study reach, the water surface elevation at section 1 was assumed to be the downstream boundary condition, with values of 28, 26.50, and 25.95 m for the $Q_{\text{max}}, Q_{\text{norm}},$ and $Q_{\text{min}}$ profiles, respectively.

4. Results and Discussion

The one-dimensional steady flow analysis for the Euphrates River across Al-Hindiya City was performed with results as summarised below:

4.1 Velocity distribution

The distributions of velocity along the study reach for the three profiles are shown in Figure 3; the figure indicates that the highest velocity was at section 30, with magnitudes of 1.71, 1.43, and 0.94 m/s for $Q_{\text{max}}, Q_{\text{norm}},$ and $Q_{\text{min}}$ profiles, respectively. The lowest velocity was at section 8 for the minimum discharge, at a value of 0.19 m/s, while the lowest velocity for maximum and normal profiles (0.48 and 0.43 m/s, respectively) occurred at section 15. This means that the maximum variation ratios in velocity were about 72% and 70% for the max. and normal discharge profiles, occurring between sections 30 and 15, while for the min. profile, the maximum variation ratio in velocity was 80%, between sections 30 and 8.

![Figure 3](image-url)

**Figure 3.** Distribution of velocity along the study reach for the three profiles (section 30 at 0 km and section 1 at 12 km).

Variation in the distribution of velocity within the reach is related to the differences in cross-sections shapes due to significant changes in the topography of the Euphrates River. As the velocity in section 30 is high, more soil erosion processes will occur, and the erosion material is then deposited in other areas. This
suggests that this section must be protected and the velocity reduced. In terms of specific discharge, the flow velocity increases when the cross-sectional area is small and vice versa, based on the continuity equation $Q = V \times A$. On the basis of the results produced, the high velocity in section 30 is most likely due to the fact that it has the smallest cross-sectional area ($A$) among the examined sections, with the flow areas for the $Q_{\text{max}}, Q_{\text{normal}}$, and $Q_{\text{min}}$ profiles being 260.01, 175.02, and 96.11 m$^2$, respectively. The velocity is minimised at sections 8 and 15 because they have large cross sections, with flow areas of 928.27 and 574.91 m$^2$ at section 15 for discharges of 445 and 250 m$^3$/sec, respectively and 473.49 m$^2$ at section 8 for a discharge of 90 m$^3$/sec. The shape of cross-sections w0, 15, and 8, as measured, are illustrated in Figures 4, 5, and 6, respectively.

![Figure 4. Cross section 30, 10 Km down stream of Al-Hindyia Barrage](image1)

![Figure 5. Cross section 15, 14.6 Km downstream of Al-Hindyia Barrage](image2)
4.2 Water surface profile
The distributions of water level along the study reach for the three profiles are shown in Figure 7. By analysing this figure, the highest water level is found at section 30, with values of 29.43, 28.29, and 27.00 m for $Q_{\text{max}}$, $Q_{\text{normal}}$, and $Q_{\text{min}}$; the lowest level, at section 1, showed values of 28.0, 26.5, and 25.95 m for $Q_{\text{max}}$, $Q_{\text{normal}}$, and $Q_{\text{min}}$, respectively. Thus, the variation ratios in water level ($\Delta W/L\%$) between reach ends for $Q_{\text{max}}$, $Q_{\text{normal}}$, and $Q_{\text{min}}$ profiles were about 5%, 6%, and 4%, respectively.

Figure 7. Distribution of water level along the study reach for the three profiles.
4.3 Energy grade line profile

The energy grade line elevation (E.G. Elev.) in open channel flow can be calculated by summation of the elevation of water surface and velocity head. The resultant loss in energy (\( \Delta E \)) occurs due to effects of friction, contraction, and expansion in the cross sections. In this study the slopes of the energy grade line between reach ends were about 0.013\%, 0.015\%, and 0.009\% when passing discharges of 445, 250, and 90 m\(^3\)/sec, respectively. Figure 8 illustrates the energy grade lines for the three profiles.

![Energy grade line elevation along the study reach for the three profiles.](image)

To evaluate the relationship between relative energy losses \( \left( \frac{\Delta E}{\Delta x} \right) \) and relative changes in water level \( \left( \frac{\Delta W}{\Delta x} \right) \) between adjacent sections, the scatter plots for three profiles were plotted and the coefficients of determination \( (R^2) \) and best fit equations computed, as shown in Figures 9 to 11. This shows that the \( R^2 \) magnitudes for the \( Q_{\text{max}} \), \( Q_{\text{normal}} \), and \( Q_{\text{min}} \) profiles were about 0.70, 0.88, and 0.96, respectively.
Figure 9. Relationship between relative change in energy and relative change in water level for $Q=445 \text{ m}^3/\text{sec}$.

Figure 10. Relationship between relative change in energy and relative change in water level for $Q=250 \text{ m}^3/\text{sec}$.
Figures 9 to 11 suggest that, at high discharges, the correlation between the relative change in energy and the water level decreases \( R^2 = 0.70 \) as compared to that seen for the normal and minimum discharges, as the kinetic energy effect increases with increasing discharge; thus, the energy losses between two adjacent sections depend on the changes in both water levels and velocity head. This correlation becomes stronger when the discharge is low \( R^2 = 0.96 \), as shown in Figure 11, which shows that the relative change in energy depends more on the fluctuation of the water level at that point.

Statistical analysis of the data within the \( Q_{\text{max}} \) profile was performed to find determine the equation linking the relative energy change with the relative change in velocity head and water level between any two adjacent sections. About 70% of the data was used to develop the equation (training data) and 30% was used for verification (testing data). The following equation was obtained, which is limited to the reach investigated in this study:

\[
\frac{\Delta E}{\Delta x} = 7.2 \times 10^{-6} + 1.33 \frac{\Delta H_v}{\Delta x} + 0.63 \frac{\Delta W_l}{\Delta x} \quad \ldots \ldots \ldots \ldots \ldots \ldots (6)
\]

where

\( \Delta E \): change in total energy between two adjacent sections.

\( \Delta x \): distance between two adjacent sections.

\( \Delta H_v \): change in velocity head between two adjacent sections \( (H_v = v^2 / 2g) \)

\( \Delta W_l \): change in water level between two adjacent sections.

In order to measure the accuracy of Equation (6), the coefficient of determination \( (R^2) \) and standard error (S.E) were used as criteria for error estimation [15]. The testing results indicated that for the training data, \( R^2 = 0.95 \) and S.E= 3.04E-05, while for the testing data, the relevant values were 0.94 and 2.8E-05, respectively. This agreement indicates the efficiency and strength of the developed equation. A scatter plot for observed and predicted results \( (\Delta E/\Delta X) \) for the testing data is illustrated in Figure 12.

![Figure 10. Scatter plot for observed and predicted \( \Delta E/\Delta X \) for testing data of Equation (6)](image-url)
5. Conclusions

In this study, a one-dimensional steady flow analysis was performed for the Euphrates River within Al-Hindiya in Kerbala. The study reach length was 12 km, divided into 30 cross sections. Field data were recorded during 2019, and three profiles were considered, with flow rates at maximum (445 m$^3$/s), normal (250 m$^3$/sec), and minimum (90 m$^3$/sec).

The flow regime was subcritical, and the following conclusions were drawn:

1. For all three profiles, the maximum velocity occurred in section 30, which has the smallest cross-section area. The maximum variation ratios in velocity were about 72% and 70% for max and normal discharge profiles, and these occurred between sections 30 and 15, while the relevant ratio was 80% for the $Q_{\text{min}}$ profile between sections 30 and 8.
2. High velocity in section 30 is likely to lead to soil erosion processes and thus to erosion material being deposited in other areas. This section must therefore be protected and the velocity reduced.
3. The variation ratios in water levels between section 30 and section 1 were about 5%, 6%, and 4% for the $Q_{\text{max}}$, $Q_{\text{normal}}$, and $Q_{\text{min}}$ profiles, respectively.
4. The slopes of energy grade lines for river reach were 0.013%, 0.015, and 0.009% for the $Q_{\text{max}}$, $Q_{\text{normal}}$, and $Q_{\text{min}}$ profiles, respectively.
5. For the $Q_{\text{normal}}$, and $Q_{\text{min}}$ profiles, the relative energy losses ($\frac{\Delta E}{\Delta x}$) between any two adjacent sections are strongly related to the relative change in water level ($\frac{\Delta H}{\Delta x}$), with coefficients of determination, $R^2=0.88$ and 0.96, respectively, while for the $Q_{\text{max}}$ profile the relative energy losses are linked to the relative change in both velocity head and water level, with $R^2=0.94$ and S.E= 2.8E-05.

In general, the model proposed in this study can be used to estimate the velocity of these river sections based on the released discharge from Al-Hindiya barrage. The estimated velocity is particularly useful in the assessment of the erosion and sedimentation processes that may affect river morphology over time. In addition, the model can also be used to estimate low water levels during periods of water shortages, which may have negative effects on pumping stations and on power generation projects. The hydraulic model could be further developed to perform unsteady flow analysis, by using a high discharge hydrograph as an upstream boundary condition to estimate the training line and maximum water level of waves for the area studied.

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