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Application of HEC-RAS Software for Steady and Unsteady Hydraulic Simulation of Al-Musayyab Canals

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ABSTRACT

The Al-Musayyab Canal, a vital irrigation infrastructure in the Babil Governorate of Iraq, serves numerous cultivated areas. However, it has faced frequent flooding in recent years due to increased flow rates and changes in land use. This study aims to define the hydraulic characteristics of the 49.5 km-long Al-Musayyab Canal, which extends from the head regulator at Al-Musayyab City to Jabla City and includes 13 branches that distribute water to agricultural areas. To simulate both steady and unsteady flow conditions, HEC-RAS version 6.3 software was used, incorporating 175 cross-sections distributed along the canal. Calibration and verification with flow rates ranging from 25 to 45 m³/s revealed that the optimal Manning roughness coefficient is 0.025, which minimizes the error ratio between observed and calculated water surface elevations for both steady and unsteady states. Various scenarios with gate openings ranging from quarter to fully open were simulated. The results indicated that, for the steady flow model, the water surface elevation ranged from 26.32 to 31.78 meters, and velocities ranged from 0.2 to 0.98 meters per second. For the unsteady flow condition, these values ranged from 26.58 to 33.12 meters and 0.22 to 0.89 meters per second, respectively. Risk areas were identified between stations 6750 and 24750 km, which require either cross-section training or embankment heightening to enhance the canal's discharge capacity and mitigate flooding during high flow rates.

1. INTRODUCTION

Specific software is a crucial tool in solving hydraulic problems because it allows researchers to model and simulate fluid flow behavior accurately [1-3]. These software programs provide users with the ability to set up simulations of hydraulic systems, including modeling boundary conditions, material properties, and system geometries [4-7]. They also include a range of numerical algorithms that allow for the accurate representation of complex fluid flow phenomena, such as turbulence and multiphase flow. In scientific research, the use of specific software for hydraulic problems has become increasingly important due to the growing complexity of these problems. Without this software, researchers would face significant challenges in modeling fluid flow and other associated phenomena accurately.

There are numerous computer models that can simulate hydraulic problems. One of the most common computer models is the HEC-RAS software developed by the Hydrologic Engineering Center of the US Army Corps of Engineers. The HEC-RAS software was used to specify the flow capacity and the hydraulic properties of the flow in the Al-Musayyab canal. This canal is one of the large canals that was designed to irrigate 334780 dunams within the large Al-Musayyab project, which is located 65 km south of Baghdad city and northeastern Babel Governorate. The length of this canal is 49.5 km. A number of secondary, distributary, watercourse, and field channels have been implemented in this project, which takes its water from the Al-Musayyab Canal; all these channels are unlined. This canal suffers from significant amounts of sediment that is inlet from the Euphrates River, and this has led to changes in canal cross-sections. Therefore, the Directorate of Water Resources in the Al-Musayyab project annually carries out the work of removing these sediments, and this is done by completely cutting off the water from the project, which negatively affected the production efficiency of seasonal crops.

Numerous studies have been conducted to evaluate the hydraulic properties of rivers, establish acceptable solutions during the dry period of rivers, and prevent flooding. modeling software is a powerful simulation tool that has been applied to rivers and coastal simulation for different purposes under various conditions [1, 7]. Daham and Abed [8], Daham and Abed [9] simulate the hydraulic characteristics and predict the sediment transport capacity of the Al-Gharraf River have a length of 58.2 km, in Kut city, Iraq. Also, Jassam and Abed [10], Jassam and Abed [11] studied the sediment transport and flow capacity along the Diyala River in Iraq. Asaad and Abed [12] developed a hydraulic model to simulate flow characteristics for a Tigris River within Baghdad City and suggested treatments for raising the water level in the river during drought periods. The best solution was by using inflatable weirs to raise the water levels of the Tigris River. Kayyun and Dagher [13] created a two-dimensional model of unsteady state flow to represent the Tigris River within Baghdad. The digital elevation model (DEM) was used, and the resulting mesh contained 86951 cells. Alsaadi and AL-Thamiry [14] utilized a one-dimensional model to evaluate and develop the Hilla-Daghara river system using HEC-RAS software.

Multi-scenarios were simulated to study and improve the flow capacity in the study reach. The results of the calibration show that the suitable value of Manning roughness for Al-Daghara was equal to 0.022. Abbas and Azzubaidi [15] conducted a numerical simulation in order to investigate the Tigris River's discharge capacity between Amarah Barrages and Kut, which is a length of around 250 kilometers. According to the results, the discharge capacity is a current capacity of 400 m^3/s for the main channel. They assessed that the discharge capacity has decreased by approximately half since 1988. And this is because the reach accumulated a significant amount of sediment. Hameed and Ali [16] simulated a one-dimensional unsteady analysis model in Al-Hilla River to estimate the value of Manning roughness through calibration. the model was calibrated and verified between August 20, 2008, and September 12, 2008. This period was divided into two groups, the first was for calibration, and the second was for verification. AL-Thamiry and Haider [17] developed a model to study the influence that salinity has on the Euphrates River between the cities of Ashshinnafiyah and Assamawa. The result showed that 9 m^3/s was the optimum discharge rate to minimize risk. Toombes and Chanson [18] evaluated the ability of HEC-RAS to simulate both gradually and rapidly varied flows. The results of the simulation were verified using two different physical models. The first was a streamlined weir, while the second was a channel that had gates to control its flow. It was established that HEC-RAS could model subcritical and supercritical flows and accurately forecast the location of a hydraulic jump. Ahmad et al. [19] studied the Wadi Jahlum River in Kashmir, India. The HEC-RAS software is utilized to simulate a one-dimensional steady flow to estimate flood levels. the results indicated that the river's water levels had exceeded the safe range. Chuchooklin et al. [20] created a mathematical model to estimate the Yom River's primary hydraulic characteristics using HEC-RAS software. The results of HEC-RAS, which used the approximately 400 m^3/s upstream river discharge in the Yom River into Sukhothai, showed that the water flow could be controlled if a retarding pond with a storage capacity of 32 million m^3 and a diversion channel with a capacity of 50 to 100 m^3/s were constructed. Users of HEC-RAS can simultaneously develop models for hydraulics and water quality [21]. Also, other research on water quality models was created using HEC-RAS and focused on the analysis of steady flow [22-25].

The current study aims to simulate the hydraulic characteristics of the Al-Musayyab canal, this year (2023) as a result of the recent climatic and morphological changes. Previous studies were limited to modeling models using the steady-state models, while the current study adopted both steady-state and unsteady-state models to visualize the profile and canal parts. A calibration procedure was carried out to determine the appropriate value for Manning's roughness coefficient. Moreover, the two models were carefully evaluated using HEC-RAS version 6.3 to determine the appropriate value for the Manning roughness coefficient. In the end, any issues that may occur were identified, followed by proposing possible recommendations.

The research was carried out to evaluate how the canal operated under a variety of flow scenarios, with discharge values ranging from 25 to 45 m^3/s. Multi scenarios with different gates opening were applied that varied from quarter to full gate opening. In the scenario of gates being quarter-open, the stations between 6750 and 24750 km were identified as high-risk areas necessitating measures to enhance the flowrate capacity for accommodating maximum flow rate.

Moreover, the accuracy of the two mentioned models was evaluated using HEC-RAS to determine the appropriate value of the Manning roughness coefficient. It was found that the unsteady model is more efficient in determining the optimal value of the roughness coefficient, which is shown in Figure 1.

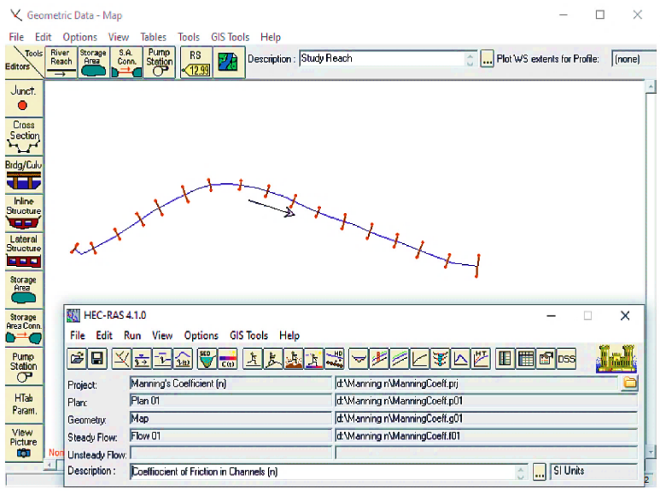


Figure 1. Unsteady manning coefficient model

2. STUDY AREA

The Al-Musayyab Canal is a vital irrigation system located in the central region of Iraq, approximately 65 kilometers to the south of Baghdad city. The canal is located entirely within the Babil Governorate and flows along the left side of the Euphrates River. The region is primarily agricultural, and the canal serves as a critical source of irrigation water for the cultivated areas in the region. The canal is 49.5 kilometers long and consists of 13 branches that divert water to various areas. The Babil Governorate, where the Al-Musayyab Canal is located, has a long history of agriculture, dating back to ancient times. The region is renowned for its fertile soil and favorable climate, which make it ideal for cultivating crops such as wheat, barley, cotton, and vegetables. The development of the canal system has been crucial to the growth and prosperity of the local agricultural sector, which has become a major source of livelihood for many rural communities in the area. Due to its strategic importance, the hydraulic characteristics of the canal must be well understood to ensure its efficient operation and maintenance. This project was bordered on the north by the main drain and on the east by the Wasit governorate, as shown in Figure 2. The project was implemented in 1951 and began operating in 1955, located between latitudes (32°18"-32°30") in the north and (44°11"-44°36") in the east [26]. The lands of this project are irrigated from the main project canal, which branches from the Euphrates River upstream of the Al-Hindiyah barrage at km 596. On the stream of this canal, a set of hydraulic structures, including head regulators, three cross regulators, and several bridges, were also constructed. These structures regulate the water flow in the canal. The Al-Musayyab project includes thirteen main irrigation branches that draw water from the main canal, six main irrigation canals that draw water from the left bank of the canal, and the remaining main irrigation canals that take water from the opposite bank of the canal.

Figure 2. Al-Musayyab project

3. BASIC EQUATION OF ONE-DIMENSIONAL MODELLING

The US Army Corps of Engineers developed the software HEC-RAS, which creates the hydraulic model by using the appropriate equations to calculate the water surface elevation and velocity. The steady-state one-dimensional flow is controlled by several basic equations, which Brunner [21] explain below. First, the energy equation is:

$$Y_1 + \frac{\alpha_1 V_1^2}{2g} + Z_1 + h_e = Y_2 + \frac{\alpha_2 V_2^2}{2g} + Z_2 \quad (1)$$

In which the energy head losses h_e in m can be expressed as follows:

$$h_e = L\, S_f + C\left(\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right) \quad (2)$$

Second, the manning equation can be expressed as follows:

$$Q = \frac{A}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \quad (3)$$

where, Y_1, Y_2=water depth in m; α_1, α_2=velocity weighting coefficients, Dimensionless; V_1, V_2=velocities in m/s; g=gravity acceleration in m/s^2; Z_1,Z_2=channel bed elevation in m; L=discharge weighted length in m; R=hydraulic radius in m; S_f=friction slope between two sections, dimensionless; Q=flowrate in m^3/s; C=expansion or contraction loss coefficient, dimensionless.

The flow of water in a stream is controlled by two physical laws, the continuity principle, and the momentum conservation principle. The unsteady state one-dimensional flow is governed by a number of fundamental equations, which will be discussed below by Brunner [21].

First, the continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_t \quad (4)$$

Second, the momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (QV)}{\partial x} + gA\left(\frac{\partial Z}{\partial x} + S_f\right) = 0 \quad (5)$$

where, A_T=total flow area in m^2; Q=total flowrate in m^3/s; q_T=flowrate in m^3/s/m; V=velocity in m/s; g=gravity acceleration in m/s^2; S_f=friction gradient, dimensionless; Z=water surface elevation in *m*.

4. BACKGROUND OF THE HEC-RAS SOFTWARE

The HEC-RAS program allows the user to perform one-dimensional and two-dimensional steady and unsteady flow hydraulics. It is an integrated system that was designed for interactive use in a network environment that allows several users to perform multiple tasks together. The system is comprised of a Graphical User Interface, data storage, and management capabilities, separate components for hydraulic analysis, graphics, and reporting facilities.

4.1 Geometric data

The geometric data consists of connecting the cross sections of all reaches to represent the canal's geometric scheme. The path of the canal reach was determined by using the topographic map that was imported into the HEC-RAS editor of geometric data as shown in Figure 3. The model was created by using 175 cross-sections that were conducted for the Al-Musayyab canal; the cross-section data were collected by the Ministry of Water Resources [27]. Utilizing an Acoustic Doppler Current Profiler, field measurements were carried out in order to obtain a flow rate measurement.

Figure 3. The river reaches the schematic system

The longitudinal surveys were carried out with the assistance of a level, a tripod, a level rod, pins, a laptop, and tapes. The distance between the surveyed cross sections ranged between 90 and 1,250 meters. The number of cross-sections utilized to understand the geometry of a reach depends on the characteristics of the site, such as the linearity of the channel, the meander degree of the channel, the longitudinal slope of the study reach, and the uniformity of the cross-section.

The canal reach schematic for the analyzed reach includes a background picture that was added. After drawing the canal schematic, the next step is to input the cross-sections of the surveyed canal, the sides of the banks, the length of the reach on the downstream side, the value of Manning roughness of the main channel, and other reach information. By using the order in the major menu these data were input as shown in Figure 4.

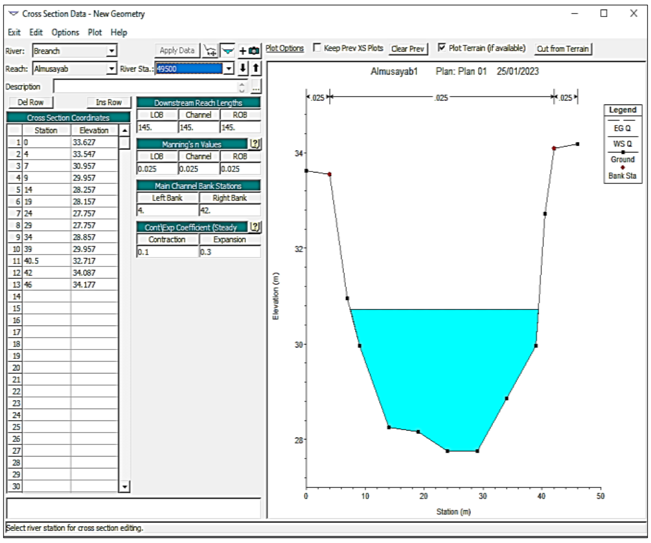


Figure 4. The cross-section geometrical data upstream cross-section

4.2 Steady flow data

A mathematical model is used to analyze the flow in the present reach in order to determine the water surface elevation and the velocity of the flow along the reach. The one-dimensional steady flow model operates based on steady flow conditions and was implemented using HEC-RAS. The steady flow data includes information on flow type and flow rate. Boundary conditions are essential for initializing the water surface elevations at both the upstream and downstream ends of the river.

To run the model, an upstream boundary with measured discharges and a range of discharges from 25 to 45 m³/s, incremented by 5 m³/s, was required. For the downstream boundary, the depth computation was constrained by the reach's longitudinal slope, with a standard flow slope of 10 cm/km selected.

4.3 Unsteady flow data

A schematic of the one-dimensional canal, extending from station 49500 meters upstream of the Musayyab Head Regulator to Jabla City, is essential input data for developing an unsteady flow model. This information, provided by the Ministry of Water Resources, includes details about the regulators and the hydraulic processes of the main canal. The flow rate, ranging from 25 to 45 m³/s with a discharge interval of 5 m³/s, is critical for simulating the hydraulic model. For each case, a gate height scenario was selected using three cross regulators in conjunction with the Al-Musayyab Head Regulator.

These scenarios included both quarter-open and fully open gates. Downstream conditions were constrained by the typical depth, while upstream conditions were defined by the flow hydrograph. The impact of the Euphrates River on the scenario of unsteady, one-dimensional flow was not examined.

5. RESULTS AND ANALYSIS

5.1 Calibration and verification of the steady and unsteady flow model

The coefficient of determination (R^2) was utilized to conduct the calibration process for both the steady and unsteady state models, aiming to identify the optimal Manning roughness coefficient (n) that minimizes the discrepancy between predicted and simulated water surface elevations (WSE) and velocities. Additionally, the results were evaluated to select the Manning roughness coefficient with the lowest root mean square error (RMSE). The unsteady state model was calibrated using hydraulic data collected by the Ministry of Water Resources (MOWR), which includes water surface levels upstream of the Al-Musayyab Head Regulator and the regulator's discharge.

The measured data from the Musayyab Head Regulator, collected by the Ministry of Water Resources (MoWR) between January and June 2019, was compared with the results obtained. In 2019, the observed discharges ranged from 15.96 to 39.19 m³/s, with water surface elevations ranging from 30.73 to 31.36 meters. The steady flow model was calibrated using observed data from 2023, which had discharges ranging from 6.15 to 17.66 m³/s and water surface elevations between 25.42 and 30.92 meters, as shown in Table 1.

Table 1. The observed data along the canal reached in 2023

Station in km	Discharge, m³/s	Water Surface Elevation, m
49.5	17.66	30.92
39	14.45	30.08
26	13	28.48
21.5	10.68	27.75
15	8.65	27.08
12.75	7.97	26.73
0	6.15	25.42

Various Manning roughness values (0.02, 0.022, 0.024, 0.025, and 0.026) were analyzed to determine the optimal value for the mainline and the bank. The results indicated that the smallest error for unsteady flow was achieved with a Manning coefficient of 0.025, yielding an RMSE of 0.1196 and an R^2 of 0.9984. Similarly, the minimal error for steady flow was obtained with a Manning coefficient of 0.025, resulting in an RMSE of 0.22 and an R^2 of 0.9921. Figures 5 and 6 illustrate the calibration of the steady and unsteady flow models for the Al-Musayyab canal's main canal and banks.

The values of manning roughness that were examined to identify the best value for both the mainstream and the bank were 0.02, 0.022, 0.024, 0.025, and 0.026. The minimum error for steady flow was determined to be Manning coefficient equal to 0.025, RMSE equal to 0.22, and R^2 equal to 0.9921, while the minimum error for unsteady flow was also determined to be Manning coefficient equal to 0.025, RMSE equal to 0.1196, and R^2 equal to 0.9984, respectively. The calibration steady and unsteady flow model in the main canal and banks of Al-Musayyab canal is shown in Figures 5 and 6.

As seen in Figure 7, the validation process was carried out to a steady state utilizing the measurement data at Al-Musayyab head regulator measured by MoWR over the period from April to August 2020 (unpublished data). The WSE varied between 31 and 31.5 meters, with discharge rates ranging from 25 to 45 m³/s in increments of 5 m³/s. A Manning roughness coefficient of 0.025 was determined to be appropriate for steady-state conditions. The R^2 was 0.9986, and the root mean square error (RMSE) was 0.171 meters.

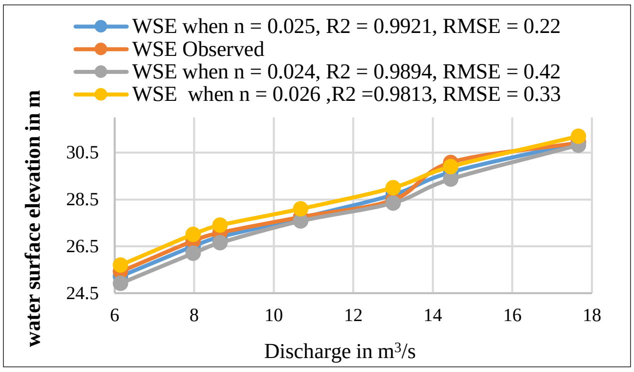


Figure 5. Calibration of steady-state flow model by the observed data

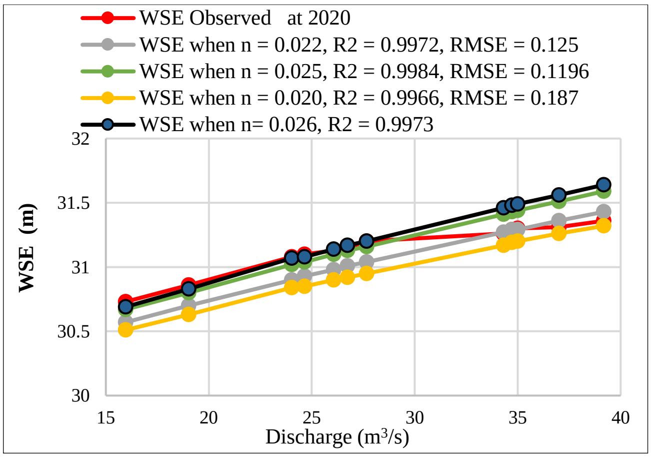


Figure 6. Calibration of unsteady-state flow model in 2020

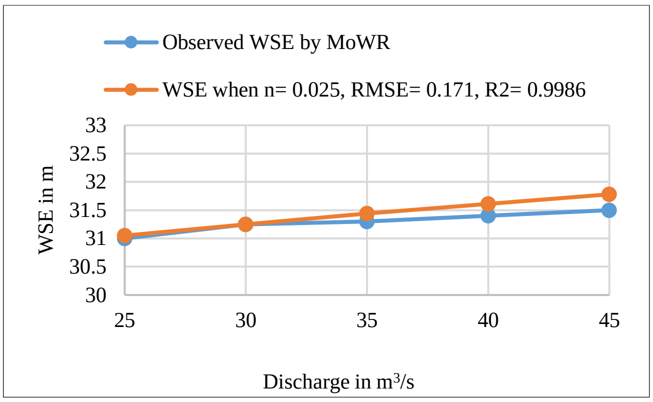


Figure 7. The study's reach validates the steady-state flow model for the April–August 2020 period

The validation of the unsteady state simulation model is illustrated in Figure 8, which employs measurement data from the Al-Musayyab head regulator for the period from February to June 2021.

The water surface elevation (WSE) varied between 30.85 and 31.4 meters, and the flow rate ranged from 20 to 40 m³/s with a discharge interval of 5 m³/s. An adequate agreement between the simulated and measured results was achieved by using the optimal Manning value of 0.025 in the simulation model.

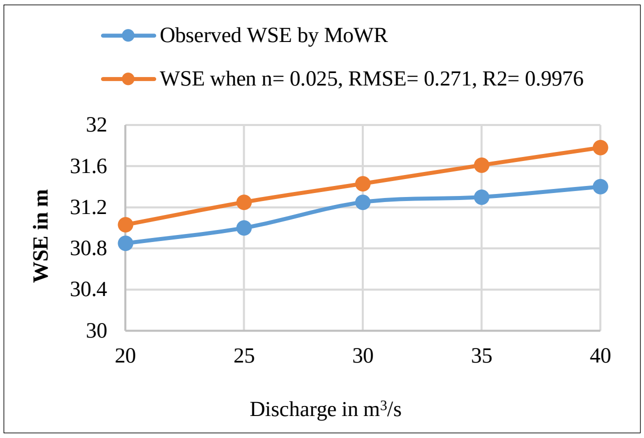
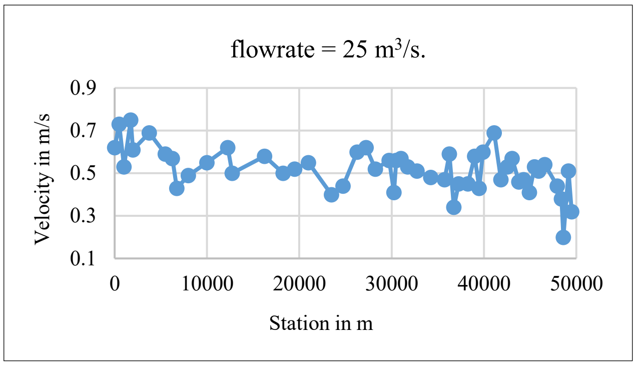


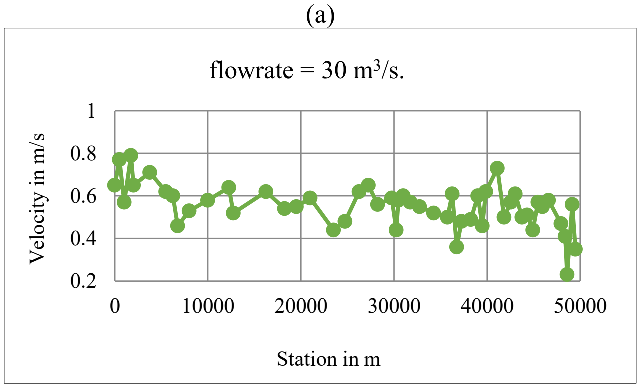
Figure 8. Validation of unsteady-state flow model in the reach of study for the period from February to June 2021 at Musayyab Head Regulator

5.2 Result of steady state

A profile of the WSE and velocity in Figures 9 and 10 illustrates the results of the steady flow modeling after the boundary condition was entered and the optimal Manning roughness value was determined. This data was then applied to the model, and various flow conditions were simulated. For a flow rate of 25 m³/s during the study reach, the WSE fluctuated from 26.32 to 31.05 meters, and the velocity ranged from 0.2 to 0.75 meters per second.



(a)



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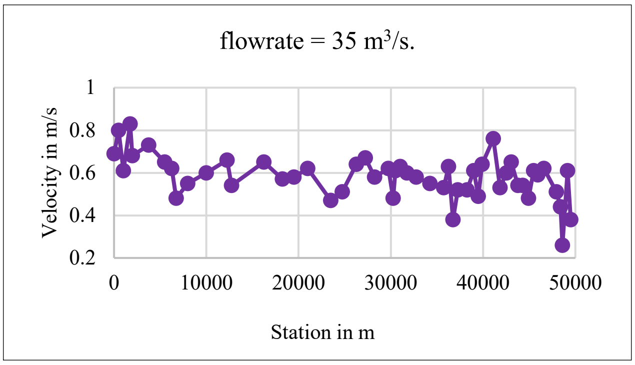

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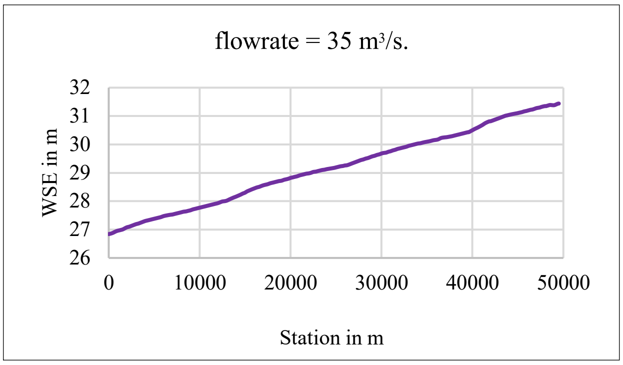

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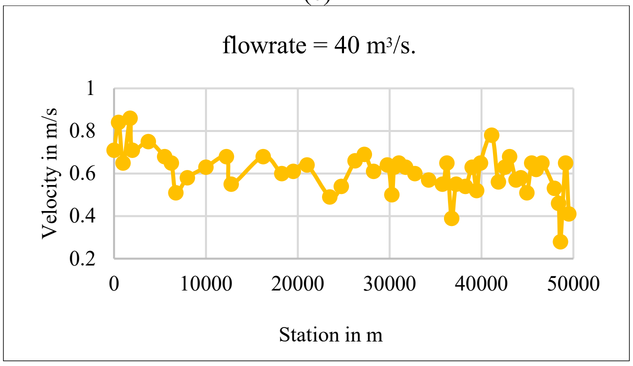

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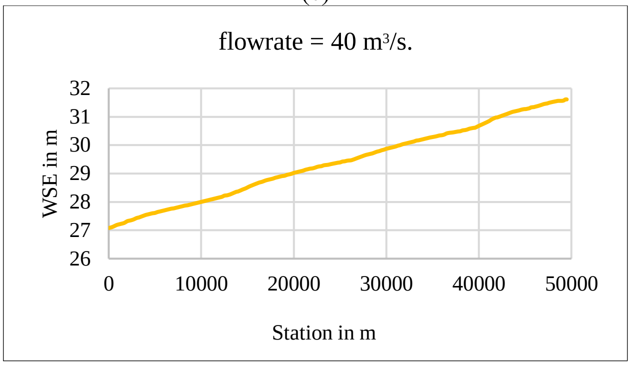

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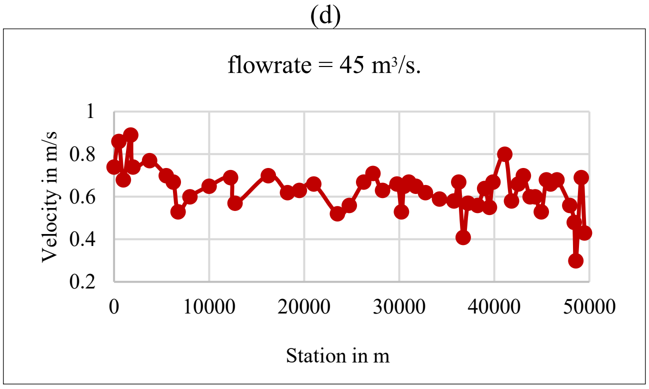
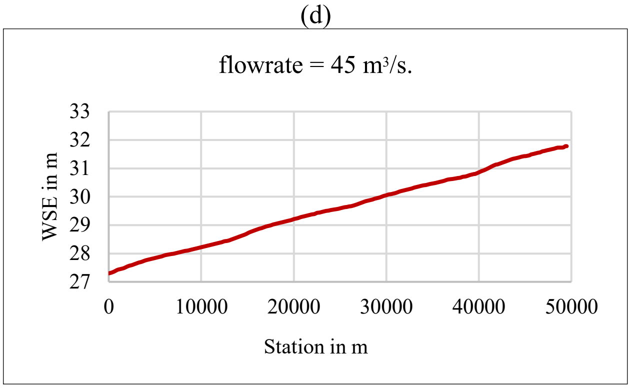


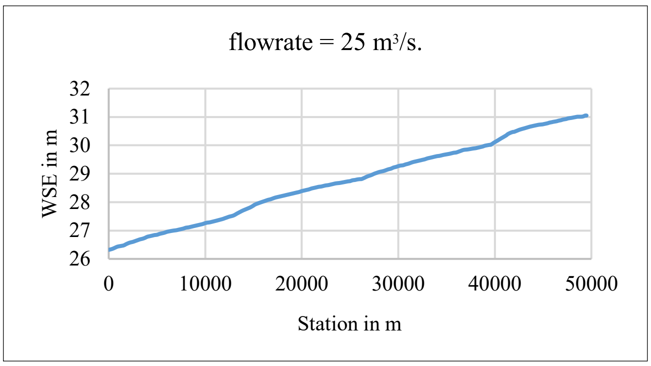
(e)

Figure 9. Velocity distribution with canal stations



(e)

Figure 10. WSE distribution with canal stations



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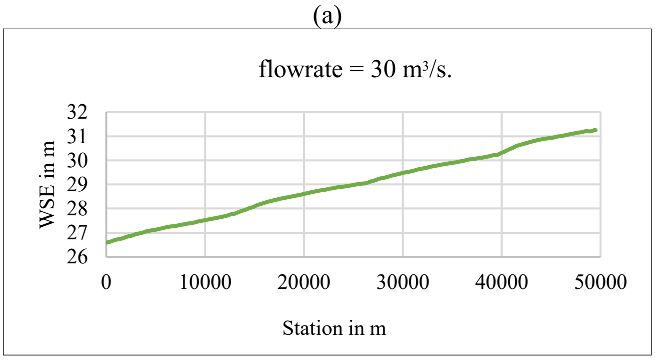


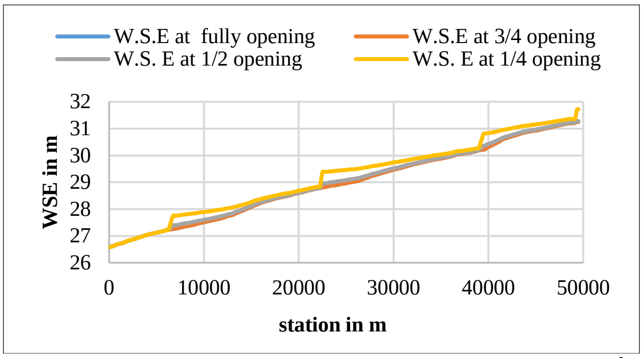
(b)

At a flow rate of 30 m³/s, the water surface elevation varied from 26.59 to 31.25 meters, while the velocity ranged between 0.23 and 0.79 meters per second. For a flow rate of 35 m³/s, the water surface elevation ranged from 26.84 to 31.44 meters, and the velocity ranged from 0.26 to 0.83 meters per second. At a flow rate of 40 m³/s, the water surface elevation and velocity ranged from 27.08 to 31.61 meters and 0.28 to 0.86 meters per second, respectively. For a discharge of 45 m³/s, the water surface elevation varied between 27.3 and 31.78 meters, while the velocity ranged from 0.3 to 0.98 meters per second.

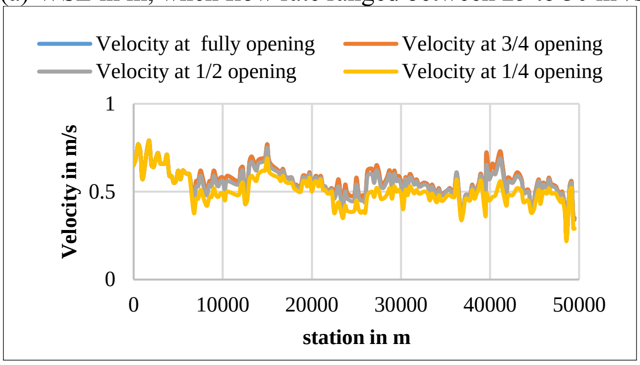
5.3 Result of unsteady state

The one-dimensional unsteady-state model was simulated after entering boundary conditions that included a flow hydrograph upstream and a normal slope downstream of the canal. This model performs the following discharge values: 25-30, 30-35, 35-40, and 40-45 m³/s with different cases of the gate opening fully, three-quarters, half, and a quarter from gate height.

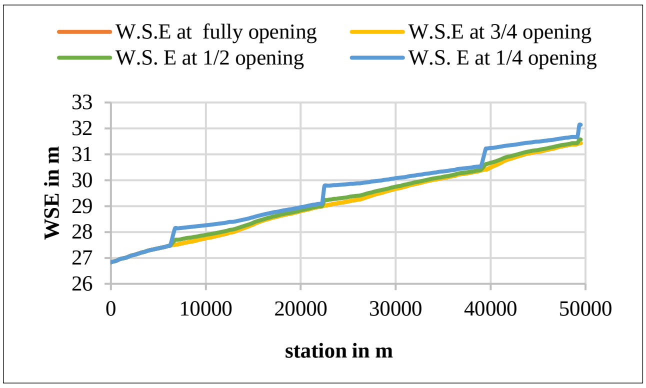
The water surface elevation fluctuated between 26.58 and 31.72 m for the discharge rate varying from 25 to 30 m³/s, with velocities between 0.22 and 0.79 meters per second. At higher discharge rates of 30 to 35 m³/s, the water surface elevation was observed to range from 26.83 to 32.14 meters, while the velocity ranged from 0.626 to 0.83 meters per second. When the discharge ranged from 35 to 40 m³/s, the water surface elevation and velocity ranged from 27.07 to 32.63 meters and 0.28 to 0.86 meters per second, respectively. For a discharge between 40 and 45 m³/s, the WSE ranged from 27.29 to 33.12 meters, with flow velocities varying between 0.3 and 0.89 meters per second. Figure 11 displays the elevation and velocity of the water surface along the study reach.



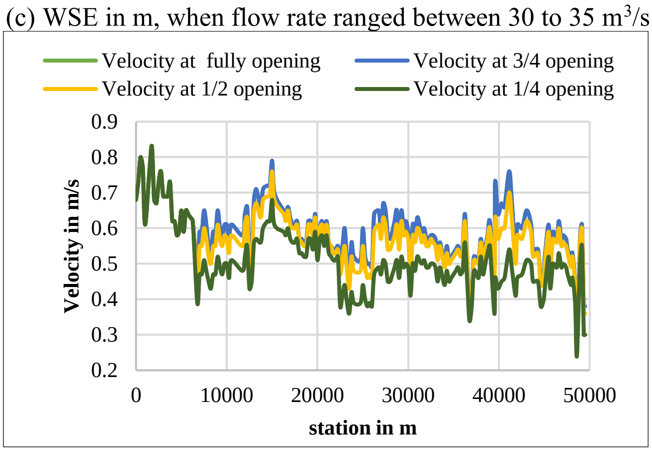
(a) WSE in m, when flow rate ranged between 25 to 30 m^3/s



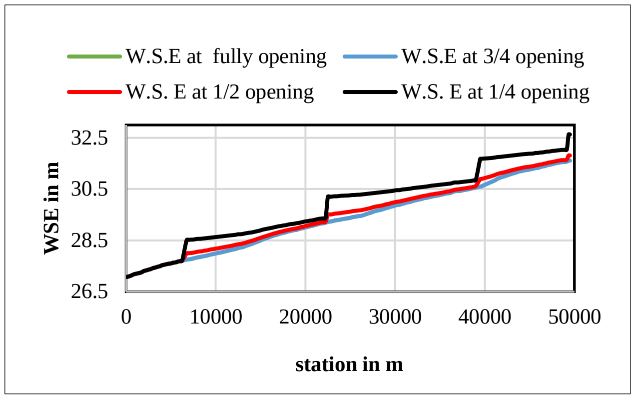
(b) Velocity in m, when flow rate ranged between 25 to 30 m^3/s



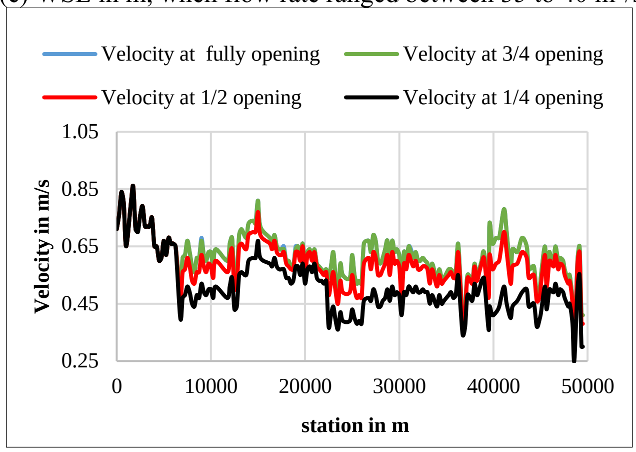
(c) WSE in m, when flow rate ranged between 30 to 35 m^3/s



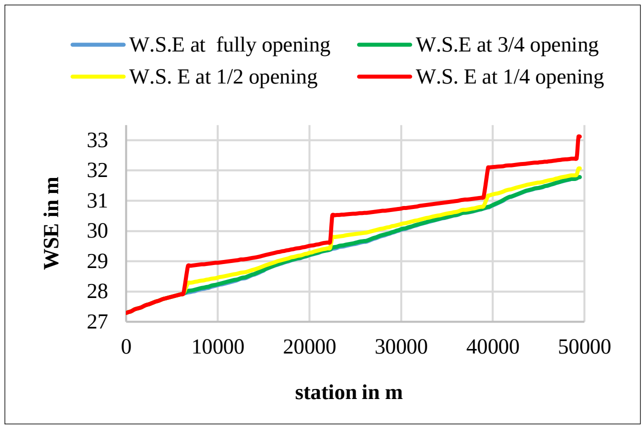
(d) Velocity in m, when flow rate ranged between 30 to 35 m^3/s



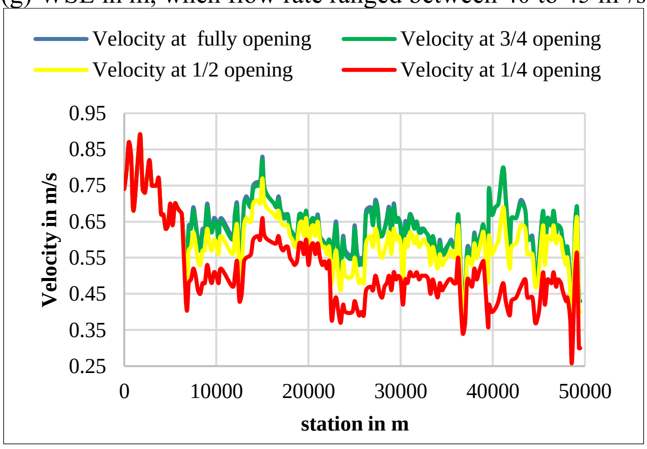
(e) WSE in m, when flow rate ranged between 35 to 40 m^3/s



(f) Velocity in m, when flowrate ranged between 35 to 40 m^3/s



(g) WSE in m, when flow rate ranged between 40 to 45 m^3/s



(h) Velocity in m, when flow rate ranged between 40 to 45 m^3/s

Figure 11. Variations in the velocity distribution and the surface water elevation across the study reach

6. CONCLUSIONS

The results gathered are analyzed here, leading to the following key conclusions:

1. The root mean square error (RMSE) achieved optimal results when the Manning roughness coefficients for both steady and unsteady states were set to 0.025. Additionally, with a high coefficient of determination (R^2), the results exhibited excellent agreement between the simulation and measurement data.
2. The water surface elevation varied between 26.32 and 31.78 meters under steady-state scenarios, with discharge values varied between 25 and 45 m^3/s. The velocities varied between 0.2 and 0.98 meters per second. In contrast, for an unsteady flow with the same discharge, the values ranged from 26.58 to 33.12 meters and 0.22 to 0.89 meters per second.
3. The values for each water surface elevation are nearly equal in the case of fully opening gates or three-quarters opening, as well as for all discharges. This is because of the reason that the gates have very little effect on the discharge values in this situation.
4. The risk areas, which required treatments to raise the flowrate capacity to pass the largest amount of flowrate, were located between stations 6750 and 24750 kilometers in the case that the gates are quarter-open.

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