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Original Research

Investigating the Current Flood Discharge Capacity of a Reach of the Tigris River From the Downstream of the Amarah Barrage to the Alqurna River

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ABSTRACT

This study examines the current flood discharge capacity of a 150-kilometer reach of the Tigris River between the Amarah Barrage and the Al-Qurna River, considering recent hydrological changes caused by upstream dams, climate variability, and increased water demand. Reductions in peak discharges, flow velocities, and water levels on the Tigris River have been observed. These changes have promoted sediment accumulation and decreased channel capacity, potentially affecting flood behavior. To evaluate the impacts of these changes, the researchers used the HEC-RAS hydrodynamic model to simulate river flow and water surface profiles over the study reach. Calibrated with data from 2010–2024, Manning's roughness coefficients of 0.031 and 0.035 were determined for the main channel and floodplain, respectively. The model calibration showed a close match between simulated and recorded water levels, confirming that the model performs well under steady-state flow conditions. For a maximum flow of 373 m^3/s, the modeled water surface remained about 0.8 m below the tops of the levees, satisfying safety standards. Model validation using data from 2020–2024 showed a strong correlation between simulated and recorded discharges, confirming that HEC-RAS can be applied at ungauged sites. Sensitivity analysis yielded high performance metrics ($R^2 = 0.998$, NSE = 0.989, RMSE = 0.042), reinforcing the robustness of the developed model. The study recommends raising levees at specific cross-sections where the water level is predicted to be less than one meter in order to reduce the risk of severe flooding.

Keywords: Flood simulation, HEC-RAS, hydraulic modelling, Manning's coefficient, Tigris River

1. Introduction

One of Iraq's two major rivers is the Tigris. Approximately 221,000 people reside in its catchment area, which is spread throughout Iran, Iraq, Turkey, and Syria. The river is around 1850 kilometers long overall. The Taurus Mountains in Turkey are where the river begins. It travels along the Turkish-Syrian border strip in southeast Turkey before entering Iraq at Fiesh Khabur City in the country's north. At Qurna City, located in southern Iraq, the river merges with the Euphrates River to form the Shatt Al Arab River. The Khabur, Adhaim, Lesser Zab, Greater Zab, and Diyala are the five principal tributaries of the rivers. The Tigris River flow pattern in Iraq was predicted using the HEC-RAS, which symbolizes a one-dimensional hydrodynamic model. The model's performance was evaluated and calibrated utilizing Manning's roughness coefficients. The Sutcliffe coefficient (NSE) and Nash-R2 values demonstrated a good degree of agreement between the simulated and real data. The HEC-RAS-built hydrodynamic model and the observed flow discharge were found to be closely related to the confirmation findings. This may help determine the discharge volume at ungagged areas along the Tigris River downstream of the Samarra Barrage [1]. The study simulates the flow of the Tigris River using the most recent HEC-RAS model, obtaining Manning's roughness coefficients of 0.026 for the Mosul site and 0.036 for the

Tikrit site. Nash-Sutcliffe Efficiency and Root Mean Square Error (RMSE) are utilized to calibrate the unsteady state flow model. For irrigation projects and water stations, the paper recommends constructing hydraulic structures, such as reservoirs and dams. Further research could include the impact of dam construction on river pollution, sediment load transfer, and TDS [2]. The flow parameters of the Tigris River within Baghdad City's borders have also been explored during this research, covering a 49 km stretch of the Tigris from Al-Muthana Bridge to the Diyala River. When there is no rainfall, water levels can be changed using a one-dimensional hydraulic model. Best results were shown using roughness coefficients of 0.032 and 0.040 for the main channel and floodplain, respectively. Possible interventions were designing and constructing embankments, barrages, and inflatable weirs. The study further examined the optimal location and the relevant expenses [3]. The study uses a numerical hydraulic model that incorporates Manning's Coefficient and HEC-RAS software to forecast the water levels of the Tigris River stretching from the north of Baghdad to Al-Aziziyah. Historical data from the 1987–1988 flood were used. The study explains how sedimentation, climate change, and dam construction contributed to the inability to cope with the flood flows of 1988. An inflatable weir is suggested to increase the water surface and provide the minimum head requirements for water stations, power turbines, and irrigation projects. Historically, the Tigris River was not fully stocked [4].

The study aimed to calculate the roughness coefficient of the Tigris River between Kut Barrage and Nu'maniyah gaging station using a one-dimensional HEC-RAS model. Twenty-two cross-sections were studied, and discharge and water level measurements were conducted on five cross-sections. Both approaches yielded comparable results with a Manning coefficient (n) of 0.027 [5]. Utilizing the HEC-RAS program, a hydraulic model for Shatt Al Rumiah in Iraq's Al-Muthanna Governorate was developed to calculate the Manning roughness coefficient (n). The analysis of projected versus measured water surface profiles from 2014 revealed a main channel roughness coefficient (n) of 0.023 and a floodplain value of 0.04, indicating strong compatibility between the data sets [6]. The study aimed to examine a 250-kilometer reach of the Tigris River, extending between the Amarah and Kut Barrages, in terms of its discharge capacity. The HEC-RAS model and data from several Kut Barrage discharges were used to simulate the capacity. To satisfy flood discharge, the principal channel's current capacity is increased from 400 m^3/s to 1800 m^3/s and 3300 m^3/s. Between 1988 and 2012, sediments reduced the reach capacity to half of its 1988 level. To reduce water levels by 20 cm on average during the reach, the research suggested reorganizing the situation by increasing the width of narrow channels, removing two sidebars and 12 islands, and extending narrow cross-sections [7]. A study assessed the hydraulic performance of the Almsharah River using a one-dimensional steady-state hydraulic model with HEC-RAS. The study found that the river's current capacity is 20-25 m^3/s, with a design discharge of 40.5 m^3/s for future agricultural and marsh projects. Manning's coefficient varied between 0.038 and 0.06 [8]. The Al-Husa'chi River in Maissan Province has been developed to improve its irrigation capacity. A one-dimensional steady-state hydraulic model was created utilizing HEC-RAS software and survey data. Although the design discharge was 84.5 m^3/s, the discharge capacity was not consistent. There is a suggestion by the researchers to increase the heights of the left and right riverbanks [9].

The Tigris River in Baghdad City has undergone significant modifications because of the creation of islands and sediment build-up in the headwater reservoirs. The river's ability to convey floodwaters has been obstructed because of the war debris, and subsequently, bridges have been rebuilt. A recent survey from the Ministry of Water Resources signifies that the river's current capacity is on a decline and is projected to drop lower than the years 1971 and 1988 [10]. One study carried out in Baghdad City utilized a HEC-RAS model that is one-dimensional to analyze the Tigris River dredging works. The study identified the presence of islands and bars that reduce the river's flood potential and water absorption efficiency. The presence of low discharges led to a drop in water levels, and water intakes should be preserved during the dredging plan [11]. The study aimed to examine the capacity of discharging of the 250-kilometer Tigris River between the Amarah and Kut Barrages. The present capacity of the reach was simulated utilizing the HEC-RAS model and data from 1988, 1995, 1993, and 1995 discharges from the Kut Barrage. Manning's coefficients attained the lowest RMSE of 0.095. The present capacity of the Tigris River's main channel is 400 m^3/s from the Kut Barrage, assuming no lateral inflows [12]. From Ali Al-Gharbi station to Amarah Barrage station, the study evaluates the 110-kilometer Tigris River's flood-carrying capability as well as the Kmait flood escape system. The current capacity is 1100 m^3/s and 280 m^3/s, respectively. The study suggests that a 2750 m^3/s flood wave can be safely accommodated in three sites by altering cross-sections and elevating bank levels [13]. The Al Butera River, a 48.8 km tributary of the Tigris River in Maysan province, has been severely impacted by sedimentation and bank encroachment, especially during the 2019 flooding. A one-dimensional hydraulic model was created utilizing hydraulic data from various sectors, and to close gaps, fieldwork was carried out. The river's current capacity is 170 m^3/s, but its long-term

capacity is 400 m³/s, limiting flood escape. To manage the design discharge, the banks would need to be raised by two meters [14]. The flow into the River Shatt Al-Arab and its branches was simulated utilizing the HEC-RAS (v.5.0.3) model, resulting in final Manning coefficients of 0.028 for the Tigris, 0.029 for the Euphrates, and 0.033 for both the Shatt Al-Arab and Gurmit Ali rivers. Coefficients of riverbank coarseness were measured at 0.06. The results indicated a strong agreement between estimated and measured phases, with maximum water speeds in critical channels not exceeding 0.8 m/s, attributed to the river's breadth and depth expansion [15].
In summary, the present study advances previous research by:

- Covering a less-studied downstream reach (Amarah–Qurna).
- Utilizing multi-year data (2010–2024) for improved temporal representation.
- Conducting comprehensive calibration and validation with high statistical accuracy.
- Including sensitivity analysis and climate change.
- Providing practical engineering recommendations for flood management. These distinctions collectively enhance the scientific robustness and applied significance of the study compared to earlier Tigris River investigations (Table 1, comparison between previous studies and the current study in terms of discharge capacity and Manning's coefficients).

Table 1. Comparison Between Previous Studies and the Current Study in Terms of Manning's Coefficients and Discharge Capacity

Study No.	River reach/length	Model used	Manning's (n)	Key findings on discharge capacity
1	Mosul – Tikrit	HEC-RAS 1D	0.026 – 0.036	Recommended construction of storage structures; analysis of dam impacts.
2	Baghdad (49 km)	HEC-RAS 1D	0.032 (main channel) – 0.040 (floodplain)	Proposed barriers, barrages, and an inflatable weir to raise water levels.
3	Kut Barrage - Nu'maniyah	HEC-RAS 1D	0.027	Good agreement between field measurements and simulated results.
4	Shatt Al-Rumitha	HEC-RAS 1D	0.023 (channel) – 0.040 (floodplain)	Strong compatibility between observed and simulated water profiles.
5	Al-Misharah River	HEC-RAS 1D	0.038 – 0.060	Current capacity: 20–25 m³/s, lower than the design discharge.
6	Shatt Al-Arab and tributaries	HEC-RAS 1D	0.028 – 0.033	High agreement between measured and predicted conditions.
Current study	Amarah – Qurna (150 km)	HEC-RAS 1D (steady)	0.031 (main channel) – 0.035 (floodplain)	Current capacity: 373 m³/s; 1 m below levee tops; excellent calibration (R^2 = 0.998, NSE = 0.989).

2. Materials and methods

2.1. Study area

The study zone incorporates the Tigris River, extending from the Amarah Barrage to the Alqurna River.

2.1.1. Study Reach Description

Examination of the Tigris River: An Extensive Synopsis. The study region is centered around the Tigris River. The study area extends from the Amarah Barrage to the Alqurna River. There are more than 150 kilometers in this part of the Tigris. Starting from a station called Downstream Amarah Barrage at UTM WGS84 coordinates [696296 E, 3529678 N], the 470 km² Tigris River basin continues to the Alqurna River station at UTM coordinates [732908E, 3433589 N]. Within the range of study, the water exhibits an average longitudinal surface slope of around 4 cm/km. Table 2 shows the location and description of gauge stations, and Fig. 1 shows the Tigris River under study.

Table 2. Location and Description of Gauge Stations

Station name	Coordinates, UTM		Station km	Measuring method
	Easting	Northing		
Amarah Barrage	3529678	696296	0 + 000	Staff and radar gauges for water level, and an acoustic device for discharge
Almajer Alkaber	706701	3507679	35 + 000	A staff gauge for water level and an acoustic device for discharge
Qalaat Saleh	3491915	715418	60 + 000	A staff gauge for water level and an acoustic device for discharge
AL Qurna River	732908	3433589	150 + 000	A staff gauge for water level and an acoustic device for discharge

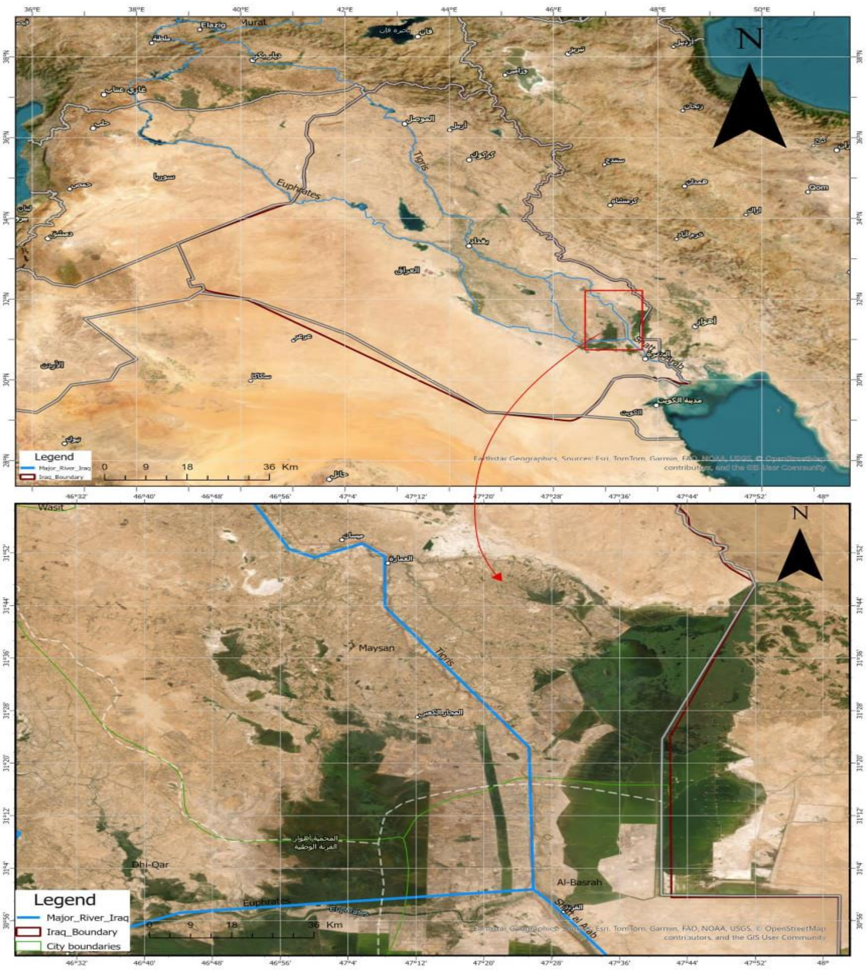

Figure 1. The Tigris River is Under Study

2.1.2. An HEC-RAS-based one-dimensional analysis of hydraulics

The world-famous HEC-RAS River Analysis System came into being at the "Hydrologic Engineering Centre" of the "US Army Corps of Engineers." When it comes to open channels, whether man-made or natural, the "US Army Corps of Engineers' Hydrologic Engineering Center" has modeled and studied sediment transport, continuous and uneven flow extensively, and several related topics. The HEC-RAS software uses a one-dimensional steady-state progressively changing flow calculation method based on the standard step methodology to find the lines of energy grade and profiles of the water's surface. This study used HEC-RAS v6 in November 2023.

2.1.3. The hydraulic model's data

There were 43 notable cross-sections documented along the route that spanned more than 150 km. Geometric data were taken from the Ministry of Water Resources and incorporated into the HEC-RAS model through 43 cross-sections. Several Tigris River cross-sections: part one is downstream of the Amarah Barrage, part two is the Alqurna River, part three is Qal'at Saleh, and part four is Almajer Alkaber. The data given in these cross-sections includes the channel across banks, the Manning coefficient, coordinates, reach lengths, contraction/expansion, and the right and left banks. Fig. 2 illustrates the cross-section downstream of the Amarah Barrage at station 0 + 000, Fig. 3 illustrates the cross-section of the Alqurna River at station 150 + 000, Fig. 4 illustrates the cross-section of Qal'at Saleh at station 60 + 00, and Fig. 5 shows the cross-section of Almajer Alkaber at station 35 + 000.

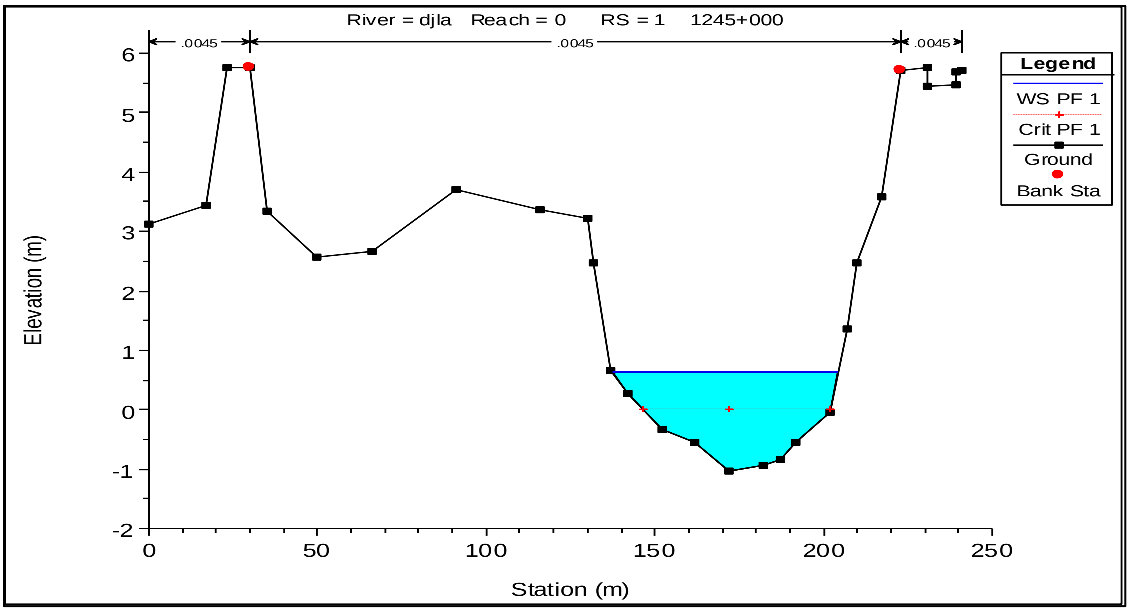

Figure 2. Cross-section downstream of the Amarah Barrage at Station 0 + 00

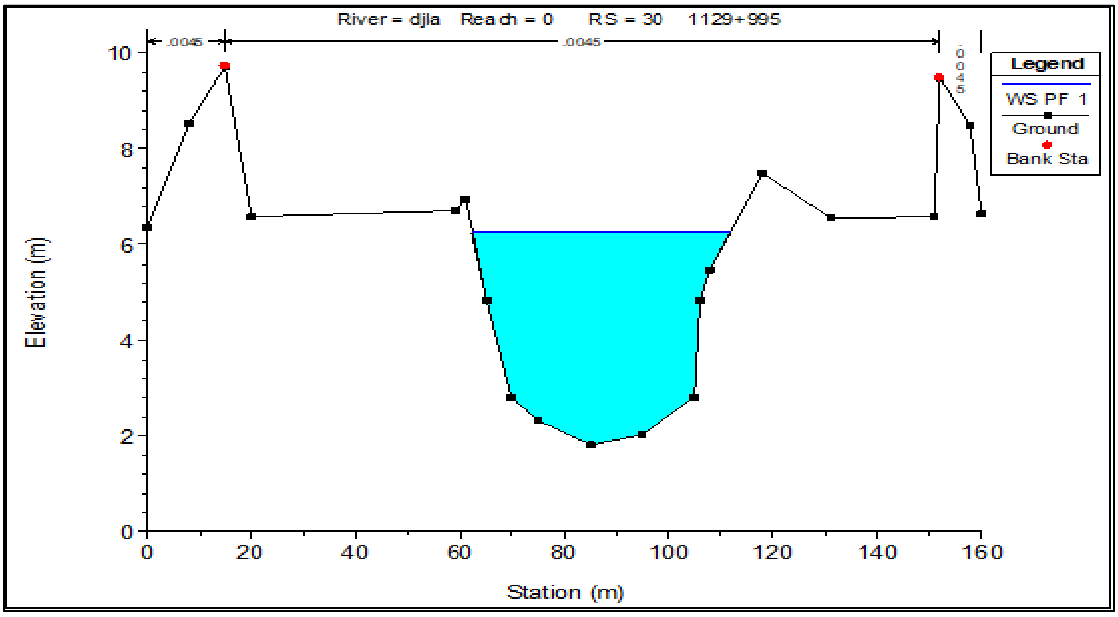

Figure 3. Cross-Section of Alqurna River at Station 150 + 000

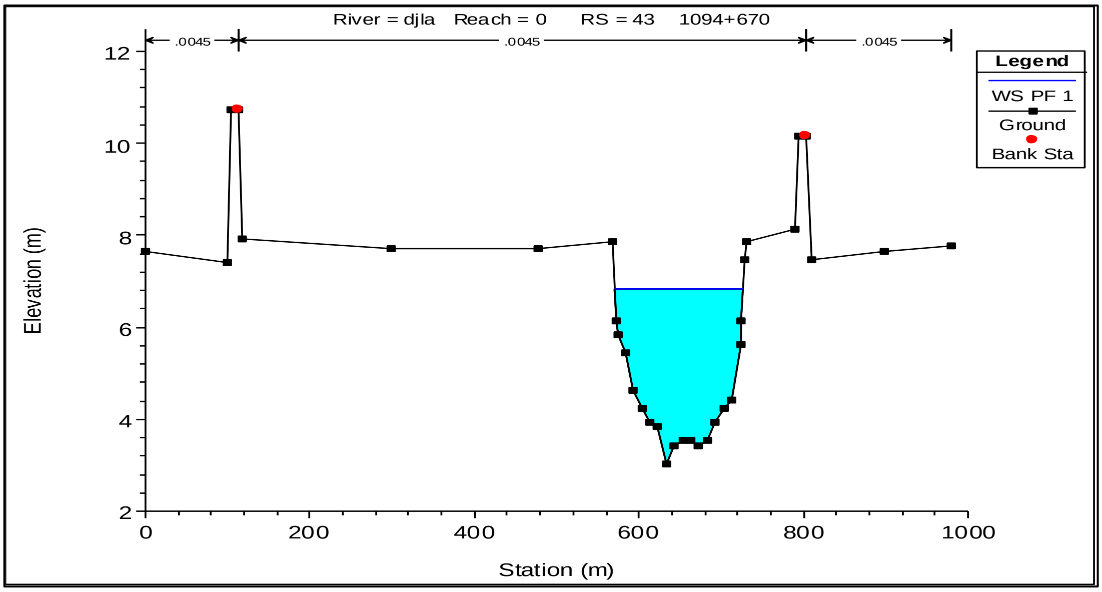

Figure 4. Cross-Section of Qal'at Saleh at Station 60 + 00

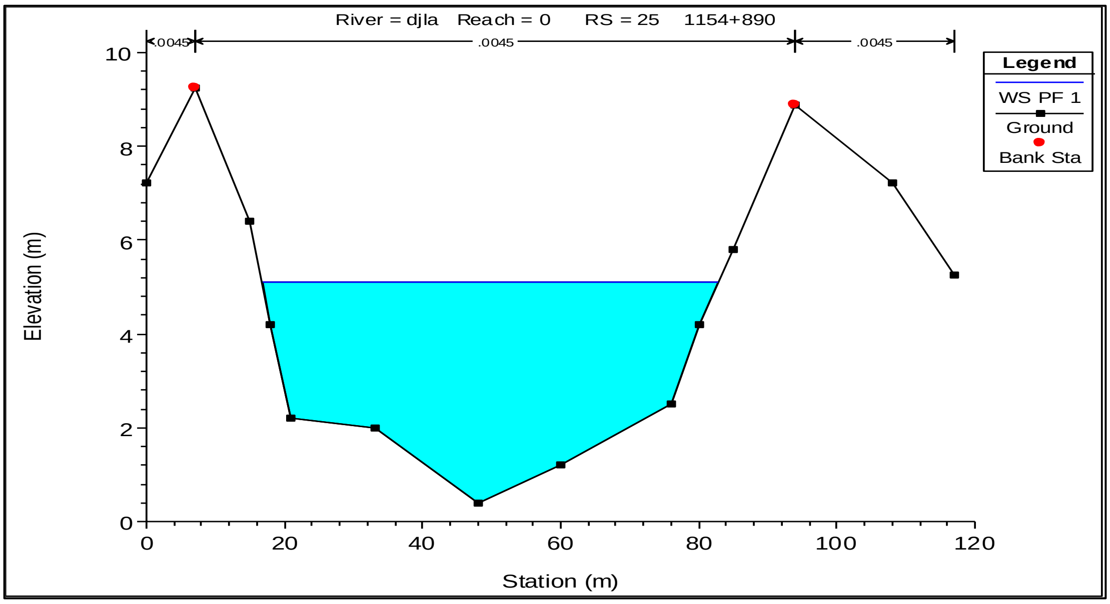

Figure 5. Cross-Section of Almajer Alkaber at Station 35 + 000

3. Results and discussion

We will show and discuss the findings of the hydraulic model for the Tigris River's flow capacity. The analysis comprises the present discharge capacity of the Tigris River from the Amarah barrage to the Alqurna River and the verification and calibration of Manning's number for the Tigris River being examined.

3.1. Developing the hydraulic model

Calibration is required to get the optimal quantity of Manning's coefficient for the researched reach about the mainline (the Tigris River reach). To get the modelling right, consider the river segment's condition and floodplain while deciding on a given Manning's number [16, 17].

Surface roughness, stage, discharge, vegetation, and river section irregularity all impact this score. Extremely high Manning's n values could indicate a rocky and grassy bank. Studies found that this coefficient usually decreased with increasing discharges [18]. The HEC-RAS model is modified for the analyzed range to determine Manning's coefficient (n) and estimate water levels. To assess how well the model can forecast river water levels for different flows, we will use data that has not been used for calibration. The findings indicate that the most accurate match between the predicted and measured water surface levels is achieved with a roughness coefficient of 0.031.

3.1.1. Tigris River model calibration

Manning's roughness coefficient was iteratively changed during the procedure of calibration until the variations between the water levels simulated and those that were observed were within allowable bounds. Various quantities of Manning's n were tested for the floodplain and the main channel to assess their influence on computed elevations of the water's surface. For the main channel, the calibration was conducted by varying Manning's n in incremental steps of + 0.002. According to previous studies on Iraqi natural rivers, plausible values of Manning's n typically range between 0.023 and 0.038 [13]. Therefore, several values within this range were evaluated, and the optimal value was selected based on achieving the minimum RMSE between simulated and measured water levels. Regarding the floodplain, the Manning's coefficient was assigned manually to HEC-RAS according to the physical characteristics of the study area, including vegetation density, bank material, and surface roughness. The process uses data collected at four gauging stations, which include daily measurements. Table 3 presents flood discharge and water level data from multiple stations along the Tigris River over several years, highlighting the importance of using multi-year, multi-season, and multi-station data. This approach improves model accuracy and provides a better understanding of flood behavior under varying hydrological conditions .Table 4 shows the sensitivity analysis of the Tigris River cross-section calibration outcomes.
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Table 3. Differences Between the Predicted and Actual Water Surface Profiles

Numbers	Station (km)	Outflow (m³/s)	The level of the water's surface m.m.a.s.l.	
			Simulated	Observed
1/2/2010	Downstream Amarah Barrage	83	4.11	4.14
	Almajer Alkaber	59	3.79	3.9
	Qala’t Saleh	64	4.90	4.93
	AL Qurna River	59.1	1.22	1.22
2/5/2013	Downstream Amarah Barrage	172	6.30	6.35
	Almajer Alkaber	95	5.3	5.5
	Qala’t Saleh	56.3	4.39	4.5
	AL Qurna River	52.7	1.29	1.29
6/3/2017	Downstream Amarah Barrage	87	4.95	4.95
	Almajer Alkaber	55	3	3
	Qala’t Saleh	45	2.84	2.85
	AL Qurna River	25	1.25	1.25
1/4/2019	Downstream Amarah Barrage	226	7.53	7.55
	Almajer Alkaber	122	6.09	6.2
	Qala’t Saleh	142	5.28	5.26
	AL Qurna River	124	1.69	1.7

Table 4. Sensitivity Analysis of the Tigris River Cross-Section Calibration Outcomes

The values of n	R.M.S.E. values	NSE values	MAE values
0.023	0.804	0.964	30.81
0.025	0.759	0.971	29.630
0.027	0.373	0.952	27.549
0.029	0.490	0.950	24.980
0.031	0.042	0.989	23.675
0.033	0.052	0.979	24.990

The calibration yielded satisfactory agreement. It shows that the difference in predicted and actual water levels for the Tigris River is 0.042. The Manning's coefficient, $n = 0.031$ falls within the typical regional range (0.025–0.035), indicating moderate channel roughness. This suggests that flow resistance and flood conveyance are physically reasonable .The selected hydrological data collected are input into the hydraulic model using Eqs. (1-3):

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (ci - oi)^2)} \tag{1}$$

Where n denotes the quantity of data, ci is the water surface that has been computed, and oi is the water surface that has been observed, m.

$$MAE = \frac{1}{N} \sum (Oi - O) \tag{2}$$

In cases where N is the total observation, the observed value is denoted as Oi, and the average of the values that have been measured is known as i.
The outcome would be zero for a perfect model, and it is a non-negative metric with no upper bound.

$$NSE = 1 - \frac{\sum (Oi - Of)^2}{\sum (Oi - O)^2} = 1 - \left(\frac{RMSE}{SD} \right)^2 \tag{3}$$

When the average of the values that have been measured is known as i. SD is a measure of the dispersion of the data points from 1 to $-\infty$, it spans.

3.1.2. Verification of the Tigris River model

The correctness of the calibrated Manning's coefficient was verified by evaluating water levels and discharges using additional data from four gauging stations for the period from 2/2/2023 to 1/3/2024.The verification process demonstrated the water surface profile of the verification set using both measured and hypothetical levels, showing good agreement (RMSE = 0.095) between experimental and theoretical water surfaces. Table 5 presents flood discharge and water surface elevation data from multiple stations along the Tigris River for the years 2023 and 2024, addressing the limitation of relying on a single dataset. Using data from multiple stations and years demonstrates the accuracy of the model within the studied area. The same approach could be applied to other river reaches; however, generalizing the results along the entire river would require additional data from different locations.

Table 5. Verify the Calibrated Manning's Coefficients by Comparing the Measured and Simulated Water Levels

Data set number	Station km	Discharge m³/s	Water surface elevation, m.a.m.s.l.	
			Simulated	Observed
2/2/2023	Downstream Amarah Barrage	105	5.95	5.97
	Almajer Alkaber	66	3.8	4
	Qala’t Saleh	80	3.63	3.68
	AL Qurna River	72	1.37	1.37
1/3/2024	Downstream Amarah Barrage	86	4.36	4.35
	Almajer Alkaber	35	2.09	2.2
	Qala’t Saleh	70.4	3.7	3.6
	AL Qurna River	63	1.55	1.55

3.2. Current capacity of the Tigris River

It has been assessing the discharge capacity of the studied reach, critical discharges that could cause floods, and lateral inflow and outflow scenarios. It was discovered that the Amarrah Barrage of the reach can sustain a design discharge of 373 m^3/s. The water surface heights approach the levee's elevation at several points. In case of a flood, this outcome was attained for the two lateral inflow scenarios. There are lateral inflows in the third scenario. Shown the heights of the water's surface along the reach for the instances at a flow rate of 373 m^3/s. The water's surface elevations reached various points in the reach's floodplain. HEC-RAS model output for this scenario is presented. The Froude number (Fr) values are less than one at each cross-section under steady-state conditions, which indicates that the flow within the considered Tigris River Reach is subcritical. The first scenario involves lateral inflows and outflows, with results shown in Table 6. A flow rate of 226 m^3/s is analyzed, and Fig. 6 illustrates surface water elevations along the reach. The freeboard being over one meter above the water surface successfully prevents overflow, confirming that water levels adhere to hydraulic safety standards.

Table 6. Presumed 226 m^3/s Outflow Due to Lateral Inflows and Outflows Along the Reach (Flood 2019)

Station km	Discharge in the Tigris River (m^3/s)	Tributary	Type	Discharge m^3/s
0 + 000	226	Downstream of the Amarah barrage	-	-
35 + 000	135	Almajer Al Kabir	Outflow	91
95 + 040	146	AL Kasara Escape	Inflow	111

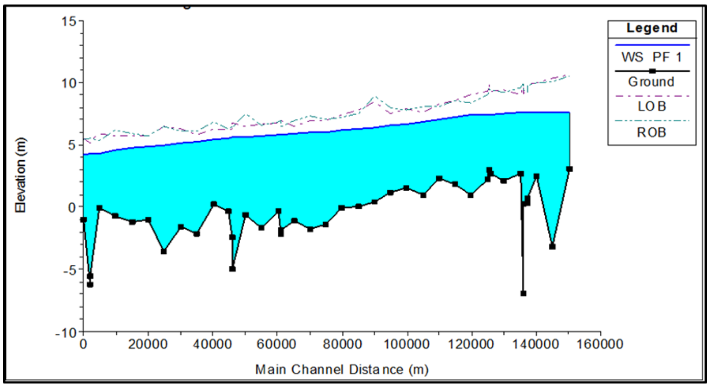

Figure 6. Throughout the stretch, the water surface elevations are changing at a rate of 226 m^3/s

In the second scenario, no lateral inflows were expected. The analysis considers the design discharge for both the Almajer Alkaber and the Amarah Barrage, illustrating the heights of the water's surface along the reach for a discharge of 373 m^3/s. Fig. 7 and Table 7 indicate that the water level remains within hydraulic safety limits.

Table 7. Presumed 373 m^3/s Discharge Due to Lateral Inflows and Outflows Along the Reach

Station km	Discharge in the Tigris River m^3/s	Tributary	Type	Discharge m^3/s
0 + 000	373	Downstream of the Amarah barrage	-	-
35 + 000	203	Almajer Al Kabir	Outflo w	170
95 + 040	203	AL Kasara Escape	Inflow	0

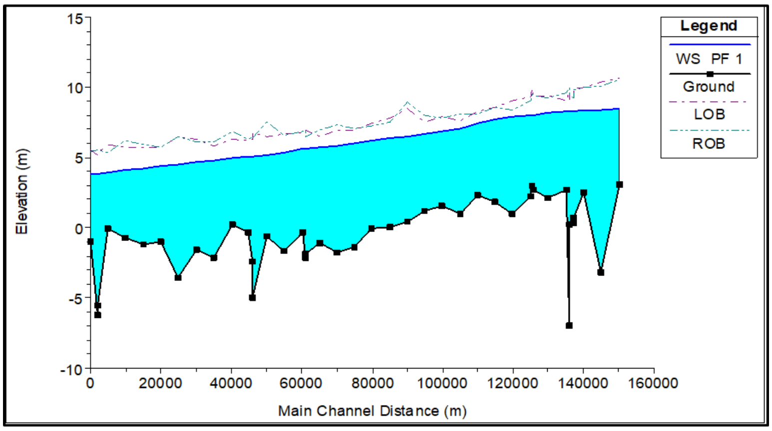

Figure 7. No Lateral Flow, and the Surface Water Levels Drop and Rise at a Rate of 373 m^3/s Along the Reach

In the third scenario, Table 8 presents lateral inflows and outflows for a discharge of 373 m^3/s, while Fig. 8 depicts river water surface heights. It is advised to raise the levees for three cross-sections (5+000, 10+000, 14+225) below one meter in elevation to ensure hydraulic safety for these cross-sections.

Table 8. The Outflow is Estimated to be 373 m^3/s, Assuming Lateral Inflows and Outflows Along the Reach

Station (km)	Discharge in the Tigris River m^3/s	Tributary	Type	Discharge m^3/s
0+000	373	Downstream of the Amarah barrage	-	-
35+000	203	Almajer Al Kaber	Outflow	170
95+040	353	Alkasara Escape	Inflow	150

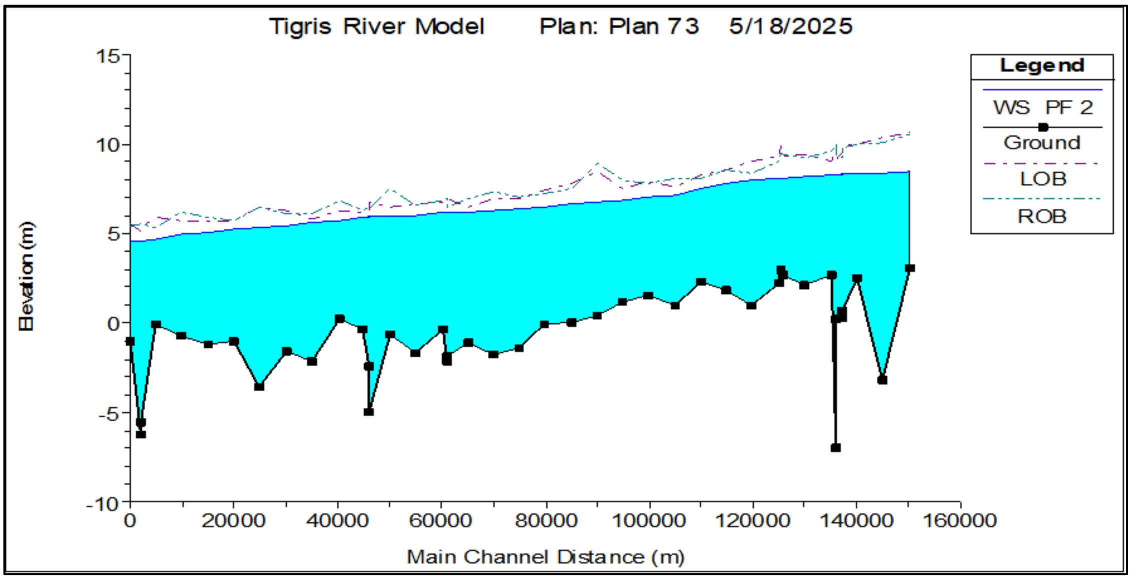

Figure 8. With Lateral Input, the Water Surface Heights Along the Reach are Increasing at an Outflow of 373 m^3/s

4. Conclusions

The present study successfully evaluated the hydraulic capacity of a 150-km Tigris River reach, spanning from the Amarah Barrage to the Al-Qurna River, using the HEC-RAS model. Optimal Manning's n values of 0.035 for the floodplain and 0.031 for the main channel were identified, minimizing water level differences between observations and simulations. The river can safely convey discharges up to 375 m^3/s. It is advised to raise levees for three cross-sections (5 + 000, 10 + 000, 14 + 225) below one meter in elevation to ensure hydraulic safety for the cross-sections, significantly reducing flood risk. Sensitivity analysis confirmed the model's reliability (R^2 = 0.998, NSE = 0.989), supporting its use for flood inundation mapping and emergency management planning. The findings provide a robust basis for practical flood mitigation and river management strategies along this critical reach.

5. Future work

Future work could include sediment transport analysis to assess the influence of sediment accumulation on flow capacity and riverbed evolution, enhancing predictive modeling, and supporting more effective river management strategies.

Declaration of Competing Interest
The authors declare no conflicts of interest regarding this manuscript.

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Author Contributions

The study problem was proposed by the author to Dr. Nezar H. Muhamed. Apart from the writer, Ranea Emad Kadhem gathered up-to-date articles and arranged them in straightforward formats. Dr. Nezar H. Muhamed was discussed by the writers. The design, findings, and completed version of this work were all suggested by Ranea Emad Kadhem.

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Notation list

Abbreviations	**Meaning**
HEC-RAS	Hydrologic Engineering Centre– River Analysis System
N	Manning's coefficient
RMSE	Root mean square error
MoWR.	Ministry of Water Resources
ci	The water surface that has been computed, and
oi	The water surface that has been observed, m.
N	Denotes the quantity of data

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