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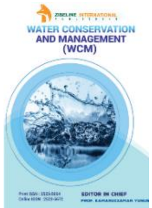

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RESEARCH ARTICLE

RIVERBED DYNAMICS OF THE TIGRIS RIVER IN BAGHDAD: IMPLICATIONS FOR HYDRAULIC OPERATIONS AND SUSTAINABLE WATER MANAGEMENT

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ABSTRACT

Understanding river flow and channel dynamics is crucial globally, especially under changing hydrological regimes driven by climate variability. In arid and semi-arid regions like Iraq, uncontrolled morphological changes in urban rivers, such as the Tigris in Baghdad, pose serious risks to infrastructure integrity, flood safety, and long-term hydraulic and ecological sustainability. This paper aims to investigate the impact of hydrological variability and sediment transport, driven by climatic fluctuations, on bed stability and channel morphology in the urban Tigris River. A one dimensional HEC-RAS model was prepared, calibrated and validated over 48.6 km of Tigris River within Baghdad Governorate. Six flow cases, for the years 1992, 2005, and 2001, were simulated under normal and controlled downstream boundary conditions (water surface elevation) using Quasi-Unsteady flow. For these cases, the sediment transport within this reach were simulated suing the Ackers–White and Toffaleti equations with field grain-size data to compute the changes in riverbed. The calibrated model with R2, RMSE, and NSE of 0.84, 0.30 m, and 0.83, was excellently validated with R2, RMSE, and NSE of 0.82, 0.39 m, and 0.81, respectively. Changes in the invert of river bed across all cases ranged from a minimum of −4.43 m with maximum flow with a downstream boundary condition of water surface fixed at 32 m.a.m.s.l (BCFS32) (Case 4) to a maximum of +4.48 m with minimum flow with BCFS32 (Case 6). Under normal flow downstream boundary conditions (BCNF), bed changes ranged between −3.83 m for maximum flow (Case 3) and +2.42 m for minimum flow (Case 5). The average invert changes were +0.23 m with average flow and BCNF (Case1) to +0.014 m with average flow and BCFS32 (Case 2), −0.27 m with Case 3, +0.44 m Case 4, +0.17 m with Case 5, and −0.03 m with Case 6. Erosion peaked at station 22+000, while peak deposition was observed at station 36+000. Flow velocities ranged from 0.12 m/s to 1.53 m/s (Cases 3 and 4), with average velocities 0.87 m/s 0.39 m/s, 1.09 m/s, 0.85 m/s, 0.67 m/s, and 0.26 m/s for the cases 1 to 6, respectively. Annual sediment deposition rates reached 7 cm/year in depositional zones, including up to 5 cm/year near intake structures. Downstream hydraulic controls are critical for maintaining channel stability and sediment balance, directly influencing the resilience of riverine infrastructure and flood safety in urban environments. Adopt adaptive sediment management strategies supported by real-time monitoring technologies to ensure hydraulic infrastructure sustainability under future climate-induced flow variability and sediment supply changes.

KEYWORDS

Tigris River, Sediment Transport, HEC-RAS Modeling, Riverbed Morphology, Hydraulic Structures, Flow Simulation, Urban River Management, Sustainable Water Resources.

1. INTRODUCTION

River Across the world, the study of river flow dynamics forms a fundamental basis for understanding how river systems interact with both natural and human-induced changes. A river is not just a watercourse: it is a living, changing system whose properties continually change as a result of interaction between water, sediment, and bed characteristics. River morphology, which includes meanders, gradients, and channel widths, directly determines it (flow patterns as well as sedimentation and erosion behavior). This understanding becomes increasingly relevant with the increasing effects of levels of climate change that have changed the time and volume of flow in many rivers particularly in arid/semiarid areas. In these locations, where water resources are characterized by natural scarcity, even minor changes in flow patterns can cause large imbalances in riverbed stability, sediment transport dynamics, and greater conflicts with flood and drought. This complicates river management and requires good models to be able to understand and respond to these dynamically changing conditions.

In arid and densely urbanized environments like Baghdad in Iraq, riverbed dynamics play a crucial role in maintaining hydraulic efficiency, ecological stability, and the safety of urban infrastructure. The lower flow velocities, coupled with the accumulation of sediments, significantly reduce the river's ability to convey floods and maintain navigable channels. Moreover,

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sedimentation near water intake structures leads to reduced operational capacity, increasing the risk of service disruption, especially during droughts or peak demands. Hence, a deeper understanding of how riverbed topography evolves under varying flow regimes is essential for designing adaptive water management strategies in Baghdad.

Iraq is water-stressed country primarily defined by arid and semi-arid climatic conditions and is one of the most countries that has been adversely affected by water stresses and river flow instability mainly as a consequence of the heightened climate variability (UN-ESCWA, 2013).

The limitations caused are multi-sectoral, and require strategic plans for maintaining the sustainability of water and regulating the morphological evolution of the river. In this regard, it is important to know the geomorphological processes that regulate river morphology because as such river dimensions (width, depth, and slope) are always modifying to the dominant geomorphological forces (Yaseen, 2018). The Tigris River, particularly as it flows through Baghdad, is highly influenced by upstream dam operations, unregulated urban development, and sediment inputs from tributaries like the Diyala River. These factors interact in complex ways that affect river depth, width, and sediment transport rates—ultimately impacting the functionality of hydraulic structures such as bridges, barrages, and intake stations. Without proper monitoring and modeling of sediment dynamics, the risks of flood damage, channel instability, and navigational failure increase significantly.As these changes continue then it gets harder to manage the Tigris River in a sustainable way. The river's health is declining, and it struggles to meet the growing demand for water in Baghdad. To deal with these problems, it is important to understand how the riverbed is changing and how these changes affect water flow. Only with this knowledge can better management and operational strategies be developed, aimed at making water use more efficient and resilient for the future (FAO, 2009). Managing the river sustainably means recognizing both hydrological shifts and changes in the river's shape, reducing the risks to important infrastructure, and helping Iraq protect its water resources over the long term.

Therefore, this research places emphasis on simulating sediment transport and bed morphology of the Tigris River through Baghdad using a calibrated HEC-RAS model under different hydrological scenarios. By identifying erosion-prone areas and depositional hotspots, especially near vital hydraulic assets, this research offers a data-driven basis for enhancing the city's resilience to future hydrological stressors.

Riverbeds change, and how sediment moves mostly depends on how water flow interacts with the sediment itself. Over the years, many researchers have tried to model this interaction to figure out where erosion and buildup happen. Software like HEC-RAS (Hydrologic Engineering Center's River Analysis System) and Delft3D helped show how water and sediment behave under different conditions. They give useful ideas about how riverbeds might change over time. Important studies by researchers pointed out how understanding where erosion and deposition happen can help in managing rivers better (Bridge, 1984; Best, 1988; Hoey, 1992; Surian, 2007; Al-Khafaji, 2008; Nama, 2011; Nama, 2015; Nama and Abdulhussain, 2015; Nama et al., 2022; Rasheed et al., 2024). But even with this research, big urban rivers like the Tigris in Baghdad haven't been studied enough. In these places, human activities and environmental factors mix and make sediment behavior harder to predict (Van Rijn, 1993).

Scholars study sediment transport in many different ways. For instance, it talked about how sediment moves theoretically (Bridge, 1984). They looked at how bedload can change, but didn't tie the study to any one place (Hoey, 1992). They worked on how rivers behave when two meet, using lab work and field studies, most likely done in the UK (Best, 1987, 1988; Boyer, 2006). They looked at how sediment moves and stays across river systems without focusing on a single spot (Lisle, 2002). They studied sediment movement and storage in the Greater Blue Earth River Basin in Minnesota, USA, and showed how river networks can control sediment behavior across large areas (Czuba, 2017). When it comes to monitoring and modeling sediment movement, different researchers have used a variety of tools and approaches. It measured bedload transport in the Missouri River, USA, by using ADCPs (Gaeuman, 2006). In the River Avon, UK, tracked sediment transport with seismic impact plates (Downs, 2016). They offered a broad review of how suspended sediment behaves over different timescales but did not focus on any specific river (Vercruysse, 2017). Built a numerical model to study sediment transport and long-term buildup in the Three Gorges Reservoir on the Yangtze River in China (Zhang, 2014). In other studies, looked at sediment movement along a 40-kilometer section of the Kabul River in Afghanistan (Raji, 2024). They studied how monsoon rains affect sediment in the Sungai Mersing in Malaysia (Nasir, 2022). They explored the impact of sediment on the Rgilewka River basin in Poland, focusing on improvements to hydraulic structures (Nowak, 2022).

Field-based research has also added valuable insights into sediment dynamics. They studied sediment flow in the Ganga River in India (Singh, 2007). They focused on how the Brenta River in Italy has changed over time, especially regarding bedload transport (Surian, 2007). They investigated how channels split and bars form in the Paraná River in Argentina (Szupiany, 2012). They analyzed how dredging has changed the riverbed in the Semois River in Belgium (Gob, 2005). On a larger scale, looked at how river temperature affects sediment transport around the world, using data from rivers in different climate zones (Syvitski, 2019).

The research included the application of SSIIM three-dimensional morphodynamic simulations to track Tigris River sediment flow by performing hydraulic calibration for water height and flow speed verification (Ali, 2016).

A 1D HEC-RAS model embracing the Toffaleti sediment transport function developed and evaluated sediment transport capacity across different discharges through field observations that matched well when hydraulic model calibration was accurate (Al-Khafaji et al., 2016). The CCHE2D model appeared in research for studying sediment behavior adjacent to Baghdad's water intakes (Al-Asadi et al., 2023). A 2D hydraulic model justified its use in sediment prediction when properly calibrated, even when lacking solid sediment data.

A combination of well-calibrated hydraulic models running HEC-RAS or CCHE2D creates a dependable means to simulate sediment transport procedures, particularly in riverine areas where data availability remains limited. Such techniques prove beneficial for the Tigris River because current sediment monitoring persists at low levels, such as (Jia, 2002; Mohammad, 2016; Razzaq, 2024; Nama, 2011). Due to the feasibility of coupling the flow and sediment transport models, HEC-RAS can prove to be essential software in riverbed dynamics.

The HEC-RAS has become a widely used tool for simulating both hydraulic and sediment transport processes. They incorporated sediment routing and sorting features into HEC-RAS, while integrated sediment yield modeling from watersheds using HEC-HMS and HEC-RAS (Brunner, 2005; Gibson, 2010). These developments were part of software-oriented studies not linked to specific river systems. They reviewed the performance of HEC-RAS in various sediment modeling applications; combined HEC-RAS with artificial neural networks to simulate sediment transport in alluvial rivers; and applied HEC-RAS to assess morphological changes and sediment deposition in the lower Tigris River system (Das, 2022; Rahman, 2020; Razzaq, 2024). These contributions demonstrate the continuing evolution and applicability of HEC-RAS in contemporary sediment transport analysis under varying hydrological and operational contexts.

They applied a 1D HEC-RAS model to assess long-term reservoir sedimentation in the Naumure Multipurpose Project in Nepal (Dahal, 2024). Using Yang's transport function, the study predicted substantial delta formation and storage loss (up to 25.65% over 50 years), highlighting the need for integrated sediment management strategies. They applied HEC-RAS 6.1 to model sediment transport and morphological changes in the Krueng Langsa River, integrating rating curves and field sampling (Azmeri, 2025). The model showed strong sediment–discharge correlations ($R^2 > 0.97$) and revealed notable bed changes, supporting its use in flood risk and sediment management. It compared sediment rating curves with an XGBoost machine learning model to forecast suspended sediment loads in Slovenia's Sora River (Bezak et al., 2025). The AI model showed reduced bias (~15%) and projected 15–20% increases in sediment loads under future climate scenarios, supporting its use in sediment and water quality management.

Different researchers have used various tools to study erosion, deposition, and sediment behavior. It used HEC-RAS 4 to examine changes along a 110-kilometer stretch of the Karun River in Iran (Haghiabi, 2012). In Iraq, studied how sediment built up in the Mosul Dam Reservoir on the Tigris River, finding that more than 80% of the sediment settled during the first five years (Mohammad, 2016). Another study looked at sediment transport along 124.4 kilometers of the Euphrates River downstream of Haditha Dam (Mustafa, 2017). Other modeling efforts focused on different rivers. They applied HEC-RAS 5.0 to the Al-Hilla River in Iraq to study sediment concentration and the types of bed material (Omran, 2017). It developed sediment transport models for the Puyallup and White Rivers in Washington, USA, emphasizing their impact on flood risks (Gibson, 2017). They analyzed sediment behavior over a 6-kilometer section of the

Euphrates River near Al-Abbasia City and found differences between straight and meandering parts of the river (Mohammed, 2018). Research also extended to reservoir management. They modeled sediment flushing in three reservoirs: Baira in India, Gebidem in Switzerland, and Gmund in Austria, showing how effective 1D sediment models can be (Chaudhry, 2018). They used HEC-RAS to study river morphology and sediment transport in the Maumee River, USA, focusing on model calibration and prediction(Joshi, 2019). In Indonesia, They evaluated different sediment flushing techniques in the Wlingi Reservoir, testing various sediment transport equations (Sisinggih, 2020).

In the south of Iraq, worked on sediment transport in the Al-Gharraf River and suggested ways to manage where sediment builds up and where it erodes (Daham, 2020). Around the same time, they used both HEC-RAS and artificial neural networks to study sediment transport, but didn't focus on a particular river (Rahman, 2020). They reviewed how HEC-RAS works for modeling sediment (Das, 2022). They talked about some new features in HEC-RAS 5.0 and 5.1, like being able to model unsteady flows and cohesive sediment, which made the software better (Gibson, 2017). Gibson's study was more about the software itself than using it on a real river.

In Malaysia, Abd Rahman looked at how city growth affected sediment transport in the Langat River (Abd Rahman, 2022). Nasir checked how monsoon rains moved sediment in Sungai Mersing (Nasir, 2022). Rahul wrote a general review about problems with sedimentation in canals and reservoirs (Rahul, 2023). Raji studied a 40-kilometer part of the Kabul River in Afghanistan and showed how urban areas are changing the river's shape (Raji, 2024).

All these changes really matter for things like dams, levees, and places where water is taken from rivers. When sediment piles up in reservoirs, they hold less water. If erosion happens around levees or other structures, it can make them weaker. Knowing how all this works and managing it right is important for keeping rivers in good shape. Even though researchers know it's smart to mix hydraulic models with real-world field data, not many have done this yet for big urban rivers like the Tigris in Baghdad (Morris, 1998).

Bratrich emphasized the necessity for enhanced green electricity certification systems to address concerns regarding river conservation (Bratrich, 2004). The study was conceptual in nature and did not focus on any specific river or country. Malekmohammadi developed a method that integrates Genetic Algorithms, GIS tools, and HEC-RAS for real-time flood management (Malekmohammadi, 2010). In Turkey, Gül investigated the flood control potential of the planned Bostanli Dam through simulations using HEC-HMS, HEC-RAS, and GIS tools (Gül, 2010). Fang examined sediment transport dynamics and morphological changes in the Yangtze River following the construction of the Three Gorges Dam (Fang, 2012). In Italy, Grimaldi introduced advanced hydroinformatic tools developed by the National Research Council (CNR) for managing hydropower infrastructure along the Rhône River, including the SYSSIH platform for integrated hydraulic modeling (Grimaldi, 2014). Mikhailov adopted a global perspective in analyzing the long-term impacts of large-scale hydraulic projects on river deltas, advocating for a systems-based approach in delta infrastructure design (Mikhailov, 2015).

Che proposed a real-time model to enhance reservoir and river management during flood events, utilizing HEC-HMS, HEC-RAS, and Genetic Algorithms, though the model was not tested on a specific location (Che, 2015). Zhang addressed the challenge of balancing hydropower generation with ecological water requirements in the You-shui River, China, through an optimization model targeting both energy and environmental objectives (Zhang, 2016). Revetria worked on developing methodologies to support integrated water management and improve reservoir operations, without focusing on a particular river basin (Revetria, 2017). Han analyzed the effects of long-term engineering interventions on water levels and channel morphology in the Yangtze River, highlighting significant changes resulting from dam construction and river straightening (Han, 2017). In Bangladesh, van Staveren evaluated various flood management strategies in coastal deltas, emphasizing the value of historical and indigenous knowledge in selecting between open and closed flood management systems (van Staveren, 2017). Tadda reviewed the design and operational principles of hydraulic structures, particularly in the context of resource development and risk mitigation, without reference to a specific site (Tadda, 2020). Lastly, Nowak investigated the rehabilitation of hydraulic structures in the Rgilewka River basin, Poland, demonstrating improvements in water storage and management performance (Nowak, 2022). PC and Thomas used HEC-RAS to perform detailed steady-flow analysis along 67.85 km of the Periyar River in India (PC and Thomas, 2024). Their study identified high-velocity zones critical for flood risk reduction and restoration planning, supporting sustainable river basin management.

Despite the widespread global application of HEC-RAS for sedimentation analysis, its utilization in the Tigris River context remains limited. Further research is necessary to explore its potential effectiveness in this specific river system (Edwards, 2021). There is a clear research gap when it comes to studying how sediment moves and how the riverbed changes in the Tigris River inside Baghdad. Many models have tried but have not been able to show the complicated ways that sediment, hydraulic operations, and city infrastructure affect each other, especially with climate change and fast development happening at the same time. Even though HEC-RAS is used a lot in different parts of the world for sediment studies, it has not been used much for Baghdad. Past research mostly did not mix hydrodynamic modeling with other important parts like checking water quality, making sure boats can still move, or looking at the social and economic effects of changes in the riverbed where lots of people live.

In this paper, a HEC-RAS-based river simulation model was used to check where sediment builds up, where the riverbed gets worn down, and how these things change the river's shape and how well it moves water. Also, the study looked at how sediment changes over time and under different conditions to see how it affects the way the river functions. The goal is to give ideas and plans that can help engineers, environmental workers, and government officials make better decisions. What is learned from this work should help Baghdad keep its water systems working better, lower problems from sediment, and make sure the river is ready for future needs. In light of the above, the aim of this paper is to evaluate the morphological changes and sediment transport dynamics of the Tigris River as it flows through the urbane center of Baghdad, with a particular focus on the impacts of hydraulic structures, climatic variability, and downstream operational conditions. The overarching goal is to provide a scientifically grounded framework for improving the efficiency and sustainability of hydraulic operations and sediment management strategies in urban river systems. To this end,

To achieve this aim, the paper is guided by the following specific objectives: Preparing, calibrating and validating one-dimensional steady and quasi unsteady HEC-RAS-based simulation model to simulate both hydraulic flow and sediment transport over a 48.6 km reach of the Tigris River in Baghdad; To simulate river behavior under six distinct hydrological cases encompassing maximum, average, and minimum discharge conditions with both normal and controlled downstream boundary settings; To quantify bed level changes and identify zones of erosion and sedimentation, especially near critical infrastructure such as bridges and water intakes;

To assess the influence of sediment dynamics on the operational reliability of hydraulic structures and to evaluate the implications for flood risk, navigability, and sustainable river management; To offer data-driven recommendations for adaptive sediment management and flow regulation strategies under varying climate-induced flow conditions.
By addressing these objectives, this paper contributes to bridging the knowledge gap concerning sediment transport and riverbed evolution in the urban reaches of the Tigris River—an area that has received limited attention despite its strategic importance for water security and infrastructure resilience in Iraq.

2. Materials And Methods

2.1 Study Area

2.1.1 Location and Geometry

The Tigris River is one of the main rivers in the Middle East. It flows through Iraq and is a major source of fresh water for the country. In Baghdad, the river flows from north to south, defining the water supply in the city as well as the city' layout. This study examines a 48.6 km length of the Tigris River within the confines of Baghdad, beginning at the Al-Muthanna Bridge and ending where it merges with the Diyala River, Figure 1. In this part of the river there is key infrastructure such as bridges and water intake points that determines how water moves and how Sediment moves. How the river interfaces with the city's infrastructure in this area is very significant for the volume of water supply, for navigation, and to determine the efficiency of the hydraulic system.

This section of the river is particularly important, not only because it traverses densely populated urban areas, but also, it has buildings, which change the flow of water the sediment movement. The detailed hydrological map of the study area is mapped in Figure 2 from information found in the Directorate of Baghdad Water Resources (DBWR, 2024). It highlights three main parts: the central portion between the Al-Muthanna bridge and the confluence point, the upstream point at the bridge and downstream point where flow and sediment changes considerably. This map helps explain how the land features and man-made structures work together to shape the river's behavior inside the city.

Hydrological and morphological variability presents various conditions within the river channel, such as altering sediment accumulation patterns in response to Diyala River confluence. The area needs sustainable management because urbanization, combined with dredging activities and environmental changes due to climate have impacted the region historically. Data Availability occurs because monitoring stations like Saray station create opportunities to access historical and real-time hydrological and sediment data for precise modeling and analysis.

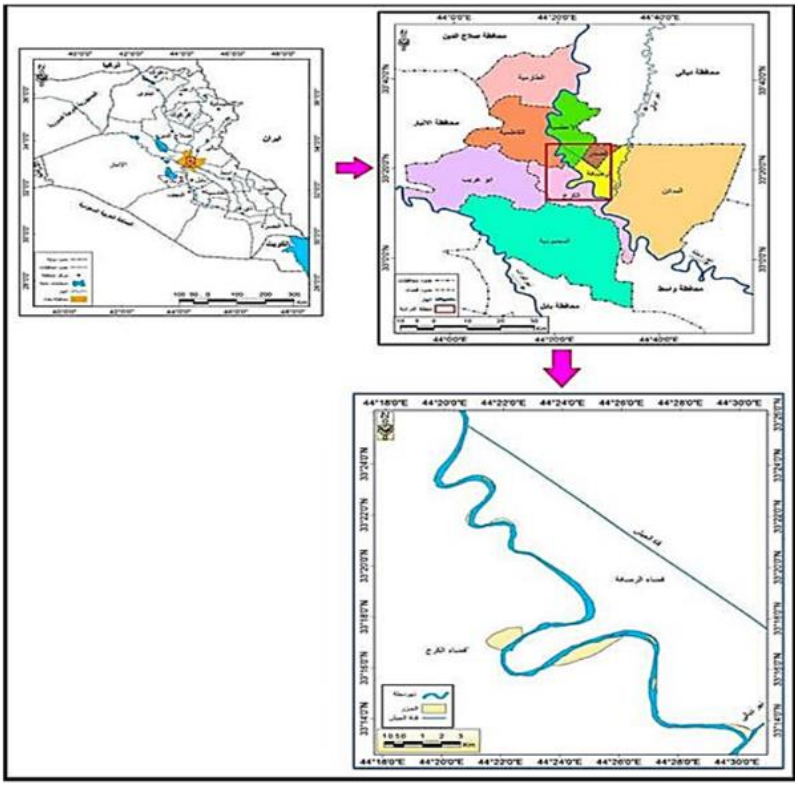

Figure 1: Location of the study area: Ministry of Water Resources, General Authority for Survey, Administrative Map of Iraq, Scale: 1:1,000,000.

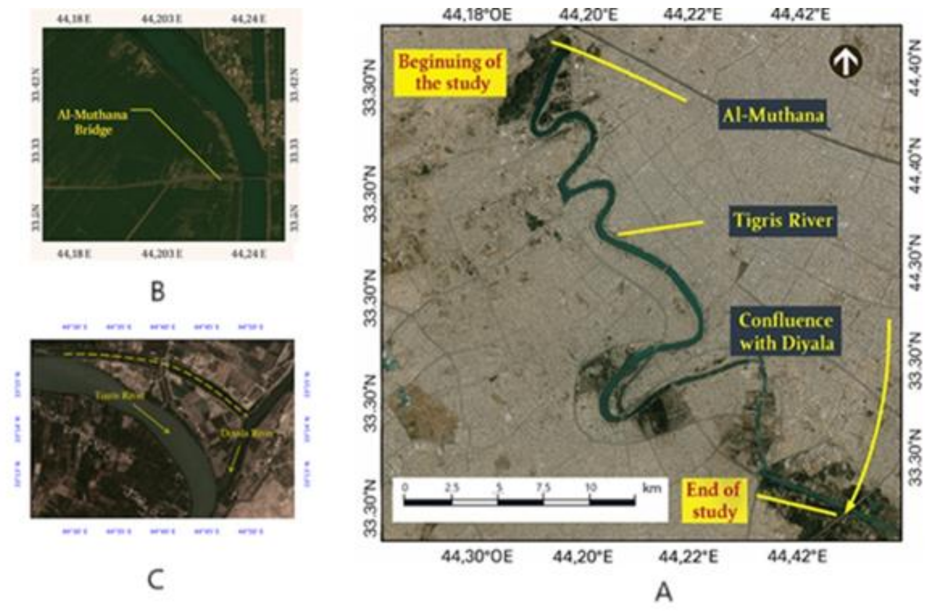

Figure 2: hydrological locations within the study area based on DBWR maps (2024): (A) Tigris River reach between Al-Muthanna Bridge and its confluence with the Diyala River, (B) location of Al-Muthanna Bridge, (C) depicts the confluence point of the Tigris and Diyala Rivers.

The cross-sections of the river in the city of Baghdad were studied for the year 2024 at a rate of five to seven cross-section for every 1 km, with a total of 314 cross-sections (Ministry of Water Resources / General Authority Figure 3 shows sample of cross-sections locations (Survey, 2024). The Tigris River in Baghdad has a meandering pattern, influenced by natural and anthropogenic activities that alter its course and sediment deposition.

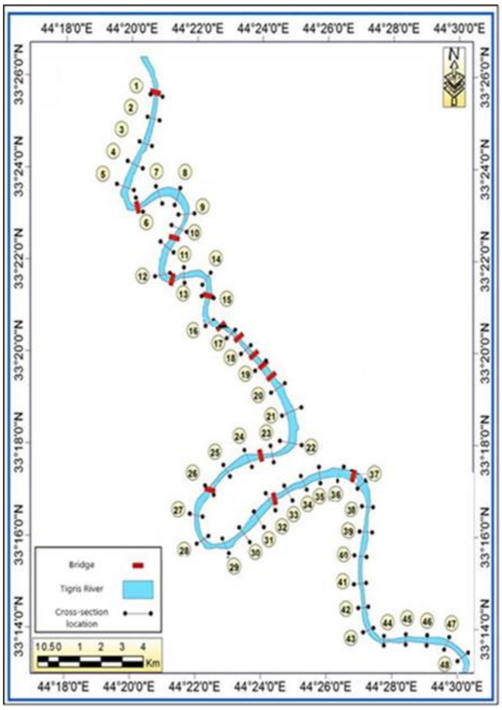

Figure 3: Sample of cross-section locations of the Tigris River in Baghdad.

2.1.2 Hydraulic Data

Discharge measurements from the Saray Station in Baghdad for the period 1989 to 2024 show that the highest flood flow reaches about 2,257 m3/sec. During the same period, the average flow was 625 m^3/s, while the lowest recorded discharge was 289 m^3/s. These historical records were used as boundary conditions for the HEC-RAS model simulations. They reflect the typical extremes seen over a long period of monitoring and match the official data from the (DBWR, 2024) . As for water levels, the water surface elevation of the Tigris River in Baghdad ranges from 27.23 meters above mean sea level (m.a.m.s.l) at station 22+000 to 35.84 m.a.m.s.l at station 0+000. River depth usually ranges from 2 to 8 meters during normal seasons and can get deeper during floods. Depth also varies depending on the location, often getting deeper near bridges and river bends because of sediment movement and scouring effects.

Between 5 and 10 cm/km the slope of the Tigris is so gentle that the water moves slowly in many places. Such slow movement facilitates deposition in certain areas leading to reduced permeability of water. The shape of the river's cross-section also varies: In urban areas, it's more regular due to reinforced banks, and in open areas, it's typically more irregular due to erosion and sediment. The river retains some natural bends especially along Al-A'dhamiya and Al-Karrada where the bends reflect changes in flow speed, a process in which sediment settles on one side and erodes the other. In due course, engineering projects have modified other parts of the river as well. Activities which human beings engage in such as widening of the channel, dredging and construction of bridges such as Al-Jumhuriya, Al-Sinak and Al-Ahrar have influenced the flow of water and sediment accumulation. Several of such structures have reduced the rate of flow, or increased sediment deposition in particular areas.

The Tigris River's flow in Baghdad shows clear seasonal changes, mainly driven by rain and snowmelt from the mountains in Turkey and northern Iraq. The river's average flow is about 625 cubic meters per second, with highs reaching around 2,257 m^3/s and lows down to 289 m^3/s. Peak flows usually happen during spring, from March to May, when snowmelt increases the river's discharge, while lower flows are common in the summer and fall months.

Figure 4 shows the time series of the water surface elevation at Saray Station for the period 1989 and 2024. The data captures how the river's level shifts over time because of natural patterns, changes in the climate, and human actions like dam operations and water management across the basin.

Between 1989 and 1998, river levels stayed fairly high, with the highest points recorded in 1992 and 1993, when elevations went over 32 m.a.m.s.l. During these years, the average elevation ranged from about 29.5 to 30.5 m.a.m.s.l, suggesting good water availability. After that, from 1999 to 2004, there was a noticeable drop. The lowest levels appeared in 2000 and 2001, falling between 27.5 and 28.5 m.a.m.s.l, pointing to lower inflows or dry conditions.

From 2005 to 2010, water levels stayed low but steady, with small rises noticed in 2004 and 2009. Between 2011 and 2018, there were a few jumps, especially in 2015 and 2018, probably because of unexpected water releases upstream. Still, the general average didn't change much during that period.

In the most recent years, from 2019 to 2024, the river's behavior became more unstable. Water levels rose sharply in 2021, reaching above 31 m.a.m.s.l, but then dropped again in 2022 and 2023, where they hit the lowest point across the whole record, near 26.7 m.a.m.s.l. This sharp decline was likely due to stronger droughts and climate pressures. In 2024, there was a slight recovery, with the water surface going back up to around 29.5 m.a.m.s.l.

Looking at the entire record, the average water surface elevation ranged between 28.5 and 29.2 m.a.m.s.l. These shifts highlight how much the river's condition can vary over time and show why it's important to manage water resources carefully using flexible, data-driven approaches.

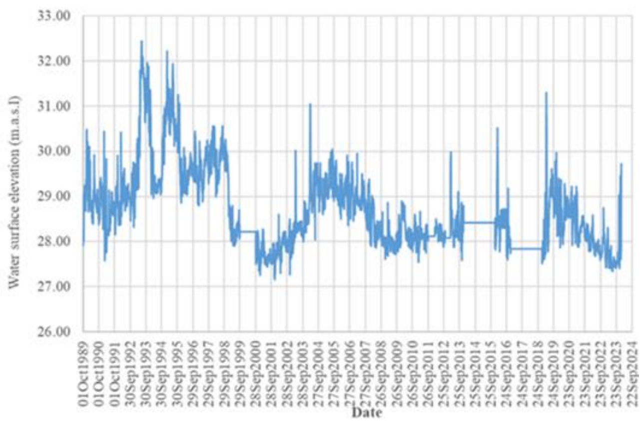

Figure 4: Time Series of Tigris River water surface elevation at Saray Station, in Baghdad, for the period 1989 to 2024 (Based on DBWR, 2024, unpublished data).

2.1.3 Observed water surface elevation

Observed water surface elevation measurements were recorded at Saray Station in Baghdad under two distinct flow conditions: the first at 425

m^3/s, and the second at 700 m^3/s, as shown in Table (1) below. These data were collected by the, Ministry of Water Resources (Unpublished data Ministry of Water Resources, 2014) and reflect changes in water surface elevation at the same locations within Baghdad's river stretch in response to varying discharge rates. This dataset serves as a valuable reference for model calibration and validation processes.

Table 1: Observed water surface elevation at Saray Station in Baghdad under two flow conditions (Q = 425 m^3/s and Q = 700 m^3/s) (Unpublished data Ministry of Water Resources, 2014).

Station(m)	Water Surface Elevation (m.a.m.s.l) at Q=425 m^3/sec.	Water Surface Elevation (m.a.m.s.l) at Q=700 m^3/sec.
0	28.96	29.30
2000	28.75	29.30
2750	28.93	29.42
4000	28.85	29.10
9500	28.85	29.21
11500	28.73	29.23
11750	27.60	29.24
12000	28.72	29.30
12250	27.74	28.32
12500	27.62	28.62
12750	27.66	28.61
14250	27.73	28.53
15500	27.85	28.51
22000	27.45	28.53
22750	27.35	28.57
23750	27.29	28.64
35750	27.32	27.88
36750	27.05	27.56
38000	27.12	27.51
38750	26.64	27.40
39750	26.36	27.24
40000	26.54	27.73
40500	26.60	27.62
40750	26.56	27.34
47000	26.51	27.26

2.1.4 Bed material and sediment data

The discharge levels of the Tigris River in Baghdad, together with sediment transport rates, experience substantial modifications through flow regulation performed by upstream projects, including the Mosul Dam and the Samarra Barrage. The study found that downstream sediment transport capacity showed significant reduction because of flow regulation at Baghdad Station where both mean annual discharge reached 953.41 m^3/s and inflow exceeded 30.05 km^3, but showed notable seasonal variations in sediment transportation (Issa, 2013). This analysis suspended sediment concentrations in Baghdad measured between 1.52 mg/L and 1.72 mg/L due to processes such as silting and suspended organic matter alongside biological activity (Hassan, 2013). The continuous movement of silt and clay together with sand and gravel sediments modifies the riverbed shape while influencing hydraulic structures and water standards according to (Issa, 2013; Hassan, 2013).

Riverbed shape transformation occurs through the regular movement of silt-clay sediments alongside sand-gravel sediments as per (Issa, 2013: Hassan, 2013). The studied reach of the Tigris River in Baghdad reveals bed material composed of fine to medium sand with gravel along with sand-gravel mixtures, primarily located near bridges, water intakes, and where the Diyala River joins. Non-cohesive sediment properties are reflected in the field-measured grain sizes d_{50}, which usually range from 0.120 mm to 0.300 mm according to observations by (Al-Ansari, 2015). For instance, near the Saray Station, the bed consists of well-graded fine sand with d_{50} around 0.178 mm, while in the downstream reaches, such as near Al-Ahrar Bridge, coarse gravel layers were recorded with d_{50} values approaching 8.0 mm, The summarized sediment characteristics, including particle size distribution d_{50} and sediment classification at selected locations along the Tigris River in Baghdad, are presented in Table (2), based on both field observations and interpretations from previous studies by (Al-Ansari, 2015). Indicative of higher flow energy and sediment transport potential. The southernmost segment of the study area typically displays mixed sediments consisting of sand and gravel particles, which coexist near the Diyala River junction. The analysis of grain size across various cross-sections supports generally fine sand dominance since d_{50} values remain between 0.143 mm to 0.210 mm while d_{90} values span 0.213 mm until 0.278 mm. These values directly control sediment mobility together with transport methods during different flow conditions.

The bed material characteristics were determined based on reports provided by the General Authority for Survey and Water Resources, indicating that the riverbed consists primarily of fine sand and medium gravel (Al-Ansari, 2015). The distribution of grain sizes is detailed in Table 2 and Figure 5.

Table 2: Bed Material Characteristics of the Tigris River in Baghdad (Based on Al-Ansari, 2015).

River Section ID	Location Description	Bed Material Type	Dominant Grain Size (mm)	Classification	Sand/Gravel Ratio or Sediment Depth	Source
BGD-01	Near Saray Station	Fine Sand	0.178	Well-graded sand	90% Sand / 10% Silt	Al-Ansari et al., 2015
BGD-02	Al-Shuhada Bridge Area	Fine Sand	0.200	Poorly graded sand	80% Sand / 20% Gravel	Al-Ansari et al., 2015
BGD-03	Confluence with Diyala River	Sand-Gravel Mixture	2.000	Mixed composition	60% Sand / 40% Gravel	Al-Ansari et al., 2015

The bed material percentages from different sections are depicted through Figure 6 using charts for selected cross-sections (BGD-01 to BGD-03). Data presented shows the expansion of gravel abundance throughout the stream direction specifically near bridge foundations and at Diyala River confluence points (Al-Ansari, 2015). Knowledge of sediment composition distribution aids the selection of suitable sediment transport models and aids local hydraulic modeling.

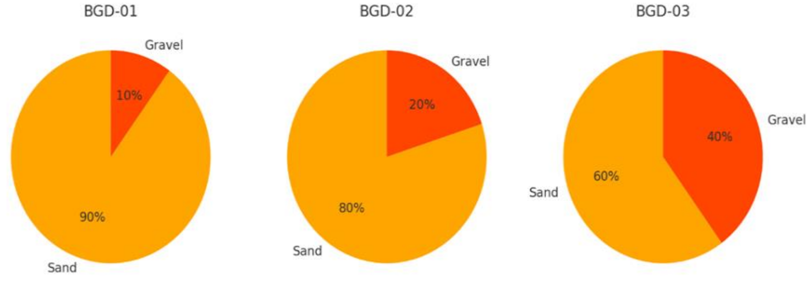

Figure 5: Sand and Gravel Distribution in Bed Material Across Tigris River Cross-Sections (BGD-01 to BGD-03) (Based on Al-Ansari et al., 2015).

Ali (2016) investigated the Tigris River bed sediment, Figure 6 and found that the cumulative size distribution graphs at locations CS2-L and CS7-C were as shown in Figure 7. The riverbed dominantly contains fine-grained sediments according to the sharp increase of particles in the smaller diameter range down to 0.25 mm. Analysis of the distribution curves reveals that CS2-L depicts superior sorted sediment distribution compared to CS7-C, which exhibits more distribution variation in the upper part of the curves.

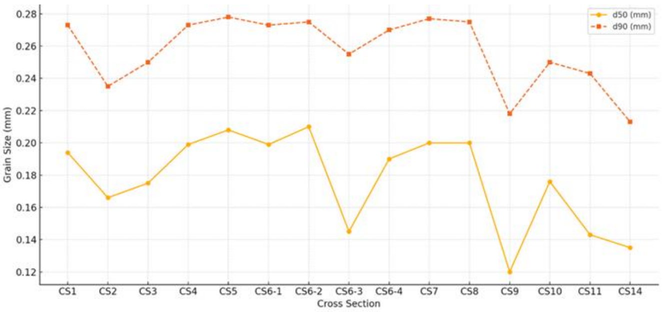

Figure 6: longitudinal profile of d50 and d90 for the riverbed sediments of Tigris River reach in Baghdad (Ali, 2016).

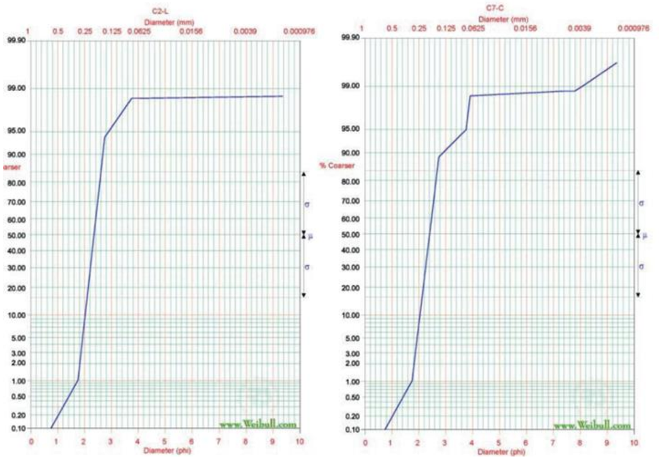

Figure 7: Cumulative curves of the bed sediment of the Tigris River for the sampling points CS2- L and CS7-C, respectively (Ali, 2016).

2.1.5 Discharge and water level requirements

The hydraulic operation of the Tigris River within the city of Baghdad depends on achieving a careful balance between the inflowing discharges and required water surface elevations to ensure continuous operation of water intake facilities, support river navigation, and maintain water quality standards. Records from the Saray Station showed that the highest recorded water level in Baghdad was 35.04 m.a.m.s.l during the 1988 flood, and similar high levels between 34 to 35 m.a.m.s.l were observed again in 2014. These high stages correspond to major flood events and reflect the river's capacity to carry flood discharges of 5800 to6000 m^3/s. Conversely, during periods of severe drought such as in 1991 and 2018, the water level fell as low as 27.16 m.a.m.s.l, with associated discharges often falling below 350 m^3/s, resulting in significant operational disruptions and increased ecological stress.

As illustrated in Figure 4, annual variations in the water surface elevation at Saray Station between 1989 and 2024 reveal an average range of 28.5 to 29.5 m.a.m.s.l, which corresponds to typical flow rates of 400 to 900 m^3/s. For the reliable operation of Baghdad's major water intake stations, such as Al-Rasheed, Al-Qadisiyah, and Al-Wahda, a minimum water level of 28.25 m.a.m.s.l must be maintained to ensure at least 1.5 m of submergence depth for the intake pipes. Any drop below this elevation causes cavitation, sediment intrusion, and eventual shutdown of the pumping systems (DBWR, 2024). Seasonally, the river reaches its highest levels during February, March, and April due to snowmelt from upstream basins in Turkey and Iran and concurrent spring rainfall, while the lowest levels are commonly observed in June through September, caused by reduced rainfall and high evaporation (Al-Ansari, 2015). From the perspective of navigation, the General Company for River Transport recommends maintaining river water levels between 30 and 32 m.a.m.s.l to provide minimum safe depths ranging from 2.5 to 3.0 m for boat and barge movement. Navigability is impaired during flood periods when high flow velocities occur, and during low water periods when sedimentation leads to the formation of shallow zones (Ministry of Transport, 2023) . Additionally, maintaining a sufficient environmental base flow is essential to dilute pollutants and sustain ecological balance. Several studies confirm that 650–700 m^3/s is the minimum flow required to achieve adequate dilution during the dry season and mitigate pollution from untreated wastewater discharges. Once discharges drop below 400 m^3/s, the river's own ability to deal with the quality of the river becomes active and conditions are conducive for eutrophication and accumulation of sediments to enhance risks to aquatic health and downstream users (Al-Suhail and Hassan, 2017).

Sedimentation in the Tigris River negatively impacts navigation because sandbars shift, while shallow spots emerge that complicate navigation and thereby justify more dredging. It also creates problems for hydraulic work resulting in water intake structures and irrigation systems having reduced efficiency. Climate change and human activity have exacerbated the problem, and there is a real need for sustainable uses of the river and protection of the environment. Operating the Tigris in Baghdad well involves a combination of hydraulic engineering, sediment control work, and good water governance. It is important to overcome these challenges to ensure that the river is still a robust source of life for the people and economy of Baghdad (Al-Obaidy, 2015).

2.2 Hydrodynamic and Sediment Transport Simulation Model

This study uses a simple one-dimensional model to investigate the dynamics of flow and sediment transport in the Tigris River within Baghdad. HEC-RAS was used in the construction of the model. HEC-RAS was chosen because it works well for simulating river flow and sediment transport. It also links easily with GIS maps and is used a lot in river studies and flood planning.

The water flow part of the model used steady flow. That means it assumed the river's discharge stayed the same during the simulation. This method made it easier to study how the river behaves under maximum, average, and minimum flow conditions. It helped to check water levels, flow depths, and water speeds for different cases, which shows how well structures like bridges and intakes can work.

To study how sediment moves, the quasi-unsteady flow option in HEC-RAS was used. This method runs several steady flow simulations in a row to guess how the river changes over time. It was a good choice because it keeps the calculations simple but still shows erosion, sediment build-up, and changes to the riverbed. This fits the Tigris River, which has flow changes depending on the season.

HEC-RAS was not picked only because of its technical features. It was also a good match for the river itself. The Tigris in Baghdad mostly changes along its length, not across its width, so a one-dimensional model made sense. After the water flow model was adjusted and checked, it became possible to use it for studying sediment transport and seeing how changes in flow can affect the riverbed and the performance of hydraulic structures.

2.2.1 Hydrodynamic Simulation Methodology

At first, a steady flow model was implemented to figure out basic hydraulic properties like the Manning roughness value and the shape of the river channel. After that, a quasi-unsteady flow was implemented to simulate the sediment movement and the riverbed changes over time during the simulation period. This approach mixes steady and unsteady methods to keep the calculations simple while still capturing the main patterns of water flow and sediment movement.

The hydrodynamic part of the simulation is based on the one-dimensional shallow water equations, often called the Saint-Venant equations. These describe how water flows in open channels when the flow is not steady, and they form the math behind how HEC-RAS models river behavior (U.S. Army Corps of Engineers, 2021). To simulate how sediment moves, the model uses a set of formulas that estimate both bedload and total load movement, depending on the sediment size and the flow conditions. In this study, functions like Ackers–White, Engelund–Hansen, Meyer–Peter and Müller, and Toffaleti were chosen because they fit the local sediment types and flow patterns well (Brunner, 2021). Also, the Exner equation was used to model how the riverbed itself changes over time as erosion and deposition happen. Together, these formulas make it possible to simulate how sediment and riverbed shapes shift under different flow conditions.

The model runs in a one-dimensional setup because the Tigris River in Baghdad mostly changes along its length and not much across its width.

The flow simulations move forward using different steady flow steps to handle varying discharge conditions. In this setup, sediment is mostly treated as bedload and suspended load, without looking at cohesive sediment effects. The river's shape and the boundary conditions help keep the model stable. Overall, the flow and sediment simulations were done inside a 1D HEC-RAS model that was adapted to fit the real hydraulic and morphological features of the Tigris in Baghdad. Since the river mainly flows in one direction with little side-to-side change, using a one-dimensional model was the best choice for this study.

The simulation started by running steady flow simulations that allowed the confirmation of hydraulic parameters and modeling parameters through validation and calibration against measured water surface elevation and discharge data. Steady flow simulations during this phase achieved proper alignment of experimental and modeled flow configurations inside established hydrologic conditions. The Quasi-Unsteady Flow modeling method served to simulate long-term sediment transport and morphological system evolution because it provides efficient computation with precise dynamic process simulation. Such computational technique maintains higher model stability and sediment dynamic tracking as well as flow time variation precision while using larger simulation time steps than complete unsteady techniques.

The Quasi-Unsteady Flow Model received selection because researchers identified it as an effective tool to display complete discharge variation together with sediment transport dynamics and control through gates and barrages. The model showed excellent performance for modeling the operational conditions in the Tigris River because it could represent flow regulation at dams alongside the seasonal changes in climate.

Representative hydraulic and sediment transport conditions along the Tigris River in Baghdad were defined through an analysis of historical time series data from Saray Station, covering 1989 to 2024. This analysis identified 1992 as the year of maximum discharge and water surface elevation, 2005 as representing average flow conditions, and 2001 as showing minimum discharge levels. These characteristic years formed the basis for developing modeling scenarios. All data were sourced from the ensuring alignment with field observations and operational standards(DBWR, 2024).

Six modeling cases were designed segregated into two groups according to downstream boundary conditions. Group A (Cases 1-3) modeled maximum, average and minimum flows under the normal depth boundary condition. Group B (Cases 4-6) used the same flow conditions but with a controlled downstream boundary condition, a fixed water surface elevation of 32.0 m.a.m.s.l, indicative of operational control levels. This design has enabled analysis of river response to floods, droughts, and operations while covering dynamic flow and sediment transport processes, hydraulic structures' impact and hazard under such extreme discharge conditions. These six modeling cases were used for the analysis of how riverbeds transform while examining hydraulic potentials in real field operational conditions. The model simulations were split into two separate groups where Group A (Case1, Case 2, and Case 3): contained variable downstream boundary conditions of normal depth, at the year of maximum, average and minimum flow rate, while Group B (Case 4, Case 5 and Case 6): used the same flow rate conditions with fixed downstream water surface elevation of 32 m.a.m.s.l., which represents the typical controlled operational stage for the urban river sector. The model structure enabled it to analyze how the river responded to different hydrological conditions ranging from floods and droughts to standard operational procedures.

The flow control boundary established at 32 m.a.m.s.l. matches observed field measurements as well as industry literature since it maintains a favorable environment for water intake and navigation purposes. The modeling approach also addressed. Dynamic flow and sediment transport: capturing seasonal fluctuations, dam releases, and sedimentation events that influence river morphology. Hydraulic Structure Operations: Simulating how flow-control structures affect water levels and sediment movement. Flood and Low-Flow Risk Analysis: Evaluating the system's performance under extreme discharge events and drought conditions. This methodology ensures that the model remains both computationally feasible and capable of delivering reliable results that support sediment management planning, infrastructure resilience, and sustainable hydraulic operations along the Tigris River in Baghdad.

2.2.2 Sediment Transport Simulation

The sediment transport part of this study was done using the sediment transport tool in HEC-RAS. It took flow results from the quasi-unsteady model, which had already been calibrated, and used them to run the sediment simulations. These flow results were mixed with sediment data collected from the river, based on samples and lab tests. Some of this information was shown earlier in Figure 5. This helped in picking the right sediment transport equations for the model. Where the river had coarse material, the sediment movement was modeled with the Meyer-Peter and Müller equation because it fits larger sediment sizes. In places with finer materials, equations like Engelund-Hansen and Van Rijn were used instead. The Exner equation was used to keep track of how the riverbed changed over time with erosion and deposition. Choosing which transport equations to use was based on the sediment types found, how steep the riverbed was, and how strong the flow was. Field measurements also contributed to verifying whether the model was sensible. In this way, the sediment model could display what the Tigris River in Baghdad actually does over time.

2.3 Calibration and Validation

Model calibration was performed by altering parameters of the HEC-RAS model to correspond to available historical flow discharges of rivers. After calibration, the model was validated using field observations and experimental data that were not used during calibration. This validation step guaranteed that the model was capable of accurately measuring river flow dynamics and sediment transport depending on the circumstances.
The calibration process was developed to reduce the discrepancy between simulated and observed water surface elevations under known hydraulic conditions. A representative discharge event taken from historical data was chosen as an example of the normal flow characteristics in the Tigris River, and measured water surface elevations were utilized as reference points. A systematic variation of the Manning's roughness coefficient (n) was applied to a reasonable range of values depending on the channel geometry, bed material, and floodplain characteristics.

In this study, the one-dimensional HEC-RAS model was implemented under steady state conditions to perform the calibration and validation processes. The calibration performance was evaluated using statistical indicators comparing computed and observed water surface elevation along the river reach. The adopted statistical indicators were the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Nash–Sutcliffe Efficiency (NSE).

The calibration and validation processes were conducted using an independent dataset corresponding to a different set of measured water surface elevation with a discharge of 700 m^3/s and 425 m^3/s, (unpublished data Ministry of Water Resources, 2014), respectively. As shown in Table (1(, which serves as the reference dataset to evaluate the prediction accuracy of the HEC-RAS model across various operational scenarios.

3. Results And Discussions

3.1 Model Calibration and Validation

The calibrations operated using steady-state flow at 700 m^3/s discharge and validation executed with a different dataset at 425 m^3/s discharge. The optimal match between observed and simulated water surface elevations was achieved through repetitive Manning's roughness coefficient adjustment that yielded n = 0.030 for the best results in both model phases. The model performance evaluation during steady-state flow conditions was established by statistical metrics that consisted of R^2 and RMSE and NSE. The model performed exceptionally well with observed data during calibration through its R^2 value of 0.84 and RMSE of 0.30 m and NSE of 0.83. These metrics indicated excellent match between observed and simulated water surface elevations.

The validation results indicated that the model retained high performance through R^2 of 0.82 and RMSE of 0.39 m as well as NSE of 0.81. The model displays acceptable hydrologic and hydraulic performance as per study because the stated values lie within recommended ranges (Moriasi et al., 2007). The model's capability to accurately predict water levels demonstrates its quality design which makes it suitable for studying sediment transport and riverbed changes in Baghdad's urban Tigris River stretch under diverse hydraulic conditions.

The Tigris River runs through Baghdad from the northwest to the southeast and is characterized by significant morphological and hydraulic variability. Based on simulation results under three discharge conditions: minimum flow (289 m^3/s), average flow (625 m^3/s), and Maximum flow (2275 m^3/s). The water surface profiles for these flow conditions are shown in Figure 8. From the figure, it's clear that water levels drop gradually from upstream at Station 0+000 to downstream at Station

48+000. The highest elevations reach around 35.9 m.a.m.s.l near the upstream point and fall to about 32.55 m.a.m.s.l downstream. The average and minimum water levels follow a similar pattern, dropping from about 30 to 27.4 m.a.m.s.l, and from 28.9 to 26.3 m.a.m.s.l, respectively. This steady drop reflects the natural riverbed slope and shows how flow rates and boundary settings control the water surface profile, affecting things like hydraulic energy, sediment transport, and navigability.

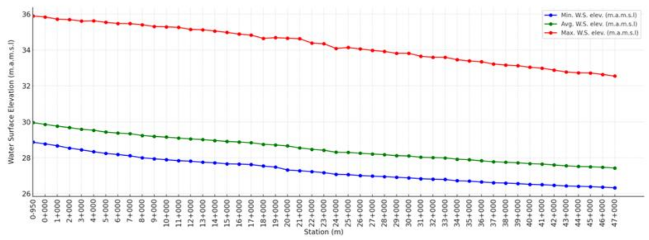

Figure 8: Water surface elevation of Tigris River reach in Baghdad for the cases of, minimum (289 m^3/s), average (625 m^3/s), and maximum (2257 m^3/s) flow.

The river width exhibits notable spatial variation. At the average discharge (625 m^3/s), it ranges from 131.22 m at station 22+000, the narrowest section, to 398 m at station 36+000, the widest. Under the maximum discharge scenario (2275 m^3/s), the width spans from 130.32 m at station 22+000 to 410.38 m at station 36+000. Meanwhile, during minimum flow conditions (289 m^3/s), it narrows to 108.21 m at station 43+000 and reaches a maximum of 365.83 m at station 7+000, as illustrated in Figure 9. These measurements were obtained from the geometric output of the HEC-RAS model developed for this study. The average longitudinal slope of the river course is approximately 6.9 cm/km. The river begins to curve westward, forming a series of meanders passing through Al-Krayat, Al-Kadhimiya, Al-Adhamiya, Al-Atifiya, and Bab Al-Muadham. It then straightens until reaching Al-Karrada, where it forms the notable Al-Jadriya bend, followed by the Al-Dawra bend—the last major bend within Baghdad.

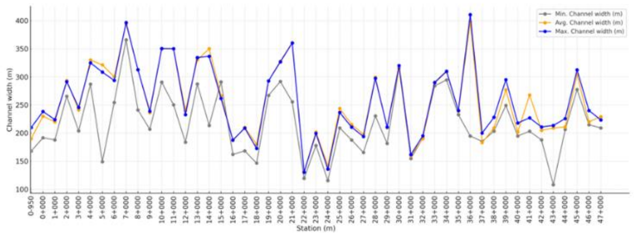

Figure 9: Width of the Tigris River reach in Baghdad for the cases of, minimum, average, and maximum flow.

3.2 Analysis of Flow Time Series

To specify the year of minimum, average and maximum flow rate, analysis of the recorded historical flow at Saray Station in Baghdad, Figure 4, shows that the minimum, average and maximum flow rate were occurs during the years 2001, 2005, and 1992, respectively, see Figure 10.

In 1992, the river had the highest flows, with discharge going over 2000 m3/sec. between days 240 and 300. These high flows were mainly due to snowmelt and big releases from upstream reservoirs.

The 1992 graph shows strong and steady high flows that stayed above the flows seen in the other years, making it clear why strong flood management was needed during that time. However, the year 2005 represents a more typical year, where daily discharge stayed mostly between 500 and 700 m^3/s. This moderate but steady pattern is a common standard to which strange years of flow are compared, and normal river operations are planned. In contrast 2001 had the lowest flows. Most of the daily discharges were within 400 and 500 m^3/s, with no significant peaks. This implies it was a dry year or a short supply of water from upstream which demonstrates how subject the river is to drought and why it is crucial to plan for dry periods. In the overall, the figure shows how critical it is to monitor river flows on a daily basis for accessing how Tigris responds when the climate and water availability change. Such information is essential for managing dams, making equitable decisions regarding water use and development of better plans to cope with floods and drought simultaneously.

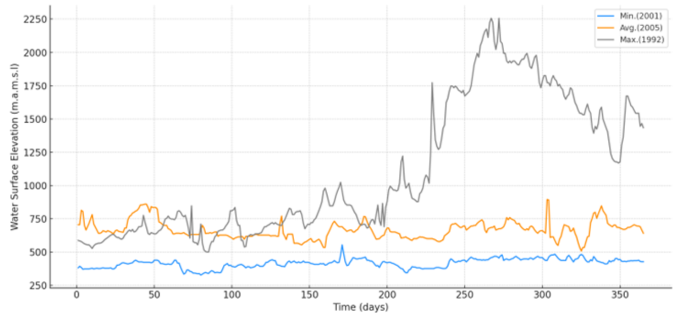

Figure 10: Minimum, average and maximum flow rate (1992, 2001 and 2005); Time Series of Tigris River Discharge at Baghdad Saray Station.

Flow Cases: In order to study the dynamic interactions of flow conditions, sediment transport as well as riverbed morphology, on the river-beds of Tigris river at Baghdad a comprehensive set of six simulation situations were designed. These scenarios were based on historical flow records (1989 - 2024) from the Saray station that reflect both climatic variability, and upstream hydraulic actions. The scenarios define three main flow regimes that are characterized by the river's extreme hydrology: maximum flow conditions, linked with flood events, or large dam releases, in 2001 (exceeding 2250 m^3/s), average flow conditions, corresponding to normal seasonal behavior, or ordinary releases, in 2005 (actual discharge ca. 625 m^3/s, depth 5.45 m), and minimum flow conditions, associated with drought periods or extreme low-flow events, in 1992 (discharge 289 m^3/s, depth 1.76 m).

Each of these flow regimes was simulated under two distinct downstream boundary conditions: one allowing for natural variation in the downstream stage and another imposing a fixed stage elevation of 32 m.a.m.s.l, simulating the influence of potential downstream controls or flow restrictions. The water level of 32 m.a.m.s.l was selected as the downstream boundary condition in the HEC-RAS model because it represents the typical and natural water surface elevation of the Tigris River within the city of Baghdad under normal flow conditions.

The hydrodynamic behavior of the Tigris River in Baghdad was analyzed using the HEC-RAS model employing the Quasi-Unsteady Flow simulation option. To characterize the total range of hydraulic conditions observed in the river, six different scenarios were developed. Three primary discharge levels (average, maximum, and minimum) were included, each which was modeled under two boundary conditions. one when assuming normal downstream depth and the other one at a downstream water surface elevation of 32.0 m.a.m.s.l. In particular, Case 1 was representative of average flow rate during normal water depth, and case 2 investigated identical average discharges but with a fixed downstream stage. Case 3 and Case 4 then tested the river response at its maximum flow, in both normal and fixed downstream stage, respectively. Finally, Case 5 was modelled for minimum flow but normal depth and Case 6 was modelled for the same low flow discharge, but fixed stage boundary. This layout enabled a petaled answer to the question of how changes in flow magnitudes and downstream control strategies affect the water surface profiles and the nature of the flow in the river reach.

Each pair of scenarios supports comparison of free-surface profiles versus those limited to a fixed downstream boundary condition 32.0m.a.m.s.l, thus showing the difference between controlled and natural flow behaviors. In order to obtain an integrative picture of the system's response a seventh scenario was elaborated averaging hydraulic output of all 6 scenarios. Data in the field feature that the water surface elevation in the city of Baghdad typically varies between 28 and 32 m.a.m.s.l.

The upper limit of 32 m.a.m.s.l was selected to correct the drawing for a safe navigational depth and reflection of the common stable hydraulic conditions observed in the Tigris River. This choice increases the accuracy and stability of the model during simulation especially while modeling flow dynamics in downstream reaches. The importance of this elevation involved in object location selection was dictated partly by the historical water level records in Saray monitoring station, on the one hand, and partly by the modeling practices that were introduced by means of researches which took place beforeistance that this level turned out to be representative of stable flow condition (Issa, 2013). Moreover, it offers the necessary depth for navigation and helps in maintaining operational effectiveness of hydraulic structures on the urban section of Tigris River in Baghdad.

Table 3 presents the summary of distribution for these scenarios with classification of flow (maximum, average and minimum), type of downstream boundary (variable or fixed) and respective discharge values. This regimented scenario framework outlines the subsequent simulation and analysis which provides an indication of how riverbed responses and sediment transport processes in the study reach are affected by different levels of hydraulic discharges.

To provide a comprehensive perspective, a composite case also referred to as "Average_All_Cases" or Case 6 was formulated by producing an average of the outcome results of all 6 cases to aggregate the river response under various hydrology and sediment transport condition. The objective of this case framework is to determine how different discharge magnitudes affect transport capacity of sediment, what the patterns of erosion/ deposition are within the river reach, how morphological changes under natural and controlled conditions occur, and where the sediment accumulation/scouring can threaten the hydraulic infrastructure of infrastructure or affect the flow efficiency. Such cases, in turn, constitute a background for risk estimation, guide sediment management approaches, and underpin long-term planning for sustainable river management in the existing and projected hydrological regimes.

Table 3: Summary of Simulation cases for flow and boundary conditions in the Tigris River.

Case	Flow Type	Flow year	Downstream Condition
Case 1	Average year	2005	Normal flow
Case 2	Average year	2005	Fixed Stage (32 m.a.m.s.l)
Case 3	Maximum year	1992	Normal flow
Case 4	Maximum year	1992	Fixed Stage (32 m.a.m.s.l)
Case 5	Minimum year	2001	Normal flow
Case 6	Minimum year	2001	Fixed Stage (32 m.a.m.s.l)

3.3 Hydrodynamic Analysis

The simulation results for the six cases shown in Table 4 revealed significant spatial and temporal variations in both water surface elevation and flow velocity profiles across the study reach. Particularly, areas with steeper bed slopes exhibited pronounced drops in water surface elevation and correspondingly higher velocities, indicating zones of accelerated flow and potential instability. Conversely, segments influenced by widening channel geometry or backwater conditions displayed markedly reduced velocities, with near-stagnant flow in some zones—suggesting sedimentation-prone areas and operational challenges during low-flow periods.

The computed water surface elevation and flow velocity along the Tigris River for the six cases of flow conditions, minimum (2001), average (2005), and maximum (1992), is shown in Figures 11 and 12 . Together, these figures highlight the combined effect of discharge variability and downstream boundary control on the river's hydraulic behavior, providing critical insights for infrastructure design, sediment management, and sustainable flow regulation.

For natural depth conditions, Case 1 (Average flow with normal depth) exhibits water surface elevation values ranging from 26.18 m.a.m.s.l to 29.87 m.a.m.s.l, with an average of 27.62 m.a.m.s.l, reflecting moderate hydraulic gradients consistent with average discharge scenarios. Under Case 3 (Maximum flow with normal depth), water levels rise significantly, achieving a maximum of 32.53 m.a.m.s.l and an average of 30.07 m.a.m.s.l, highlighting the increased energy input and steeper surface profiles associated with flood conditions.

Conversely, Case 5 (Minimum flow with normal depth) shows the lowest surface elevations among natural conditions, ranging between 26.32 m.a.m.s.l and 28.94 m.a.m.s.l, with a mean water surface elevation of 27.10 m, indicating potential risks for navigation and operational reliability during dry periods.

In the fixed downstream stage cases, the results emphasize the controlling influence of boundary conditions. Case 2 (Average flow with fixed 32 m.a.m.s.l stage) maintains water levels narrowly around 32.00 m to 32.54 m.a.m.s.l, averaging m.a.m.s.l.11 m, demonstrating a stabilized backwater effect. Similarly, Case 4 (Maximum flow with fixed 32 m stage) displays water surface elevation from 32 m.a.m.s.l up to 33.94 m.a.m.s.l, with an average of 32.47 m.a.m.s.l, reflecting significant flow impoundment during high discharge. Case 6 (Minimum flow with fixed stage) maintains the most stable profile, with water surface elevation varying only between 32 m.a.m.s.l and 32.23 m.a.m.s.l, and an average of 32.05 m.a.m.s.l, illustrating the pronounced attenuation under low-energy, fixed-boundary conditions.

Overall, the profiles captured in Figure 11 highlight the combined effects of discharge magnitude and downstream control strategies on the river's hydraulic response, offering essential insights for sustainable management of navigation, sediment transport, and hydraulic infrastructure operations along the Tigris River.

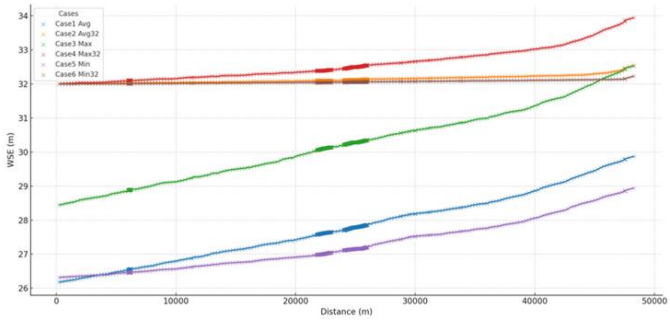

Figure 11: Longitudinal profiles of computed water surface elevation along the Tigris River reach in Baghdad for cases of minimum, average and maximum flow years (1992, 2001, and 2005, respectively).

Under natural depth conditions, Case 1 presents velocities ranging between 0.68 m/s and 1.10 m/s, with an average velocity of 0.87 m/s, indicating a moderately energetic hydraulic regime suitable for stable sediment transport and navigability. In Case 3, velocities increase substantially, achieving a maximum of 1.53 m/s and averaging 1.09 m/s, reflecting high flow energy conditions typically associated with flood events and increased bed mobility. Conversely, Case 5 demonstrates lower velocities, ranging from 0.42 m/s to 0.94 m/s, with a mean velocity of 0.67 m/s, indicating reduced sediment transport capacity and a higher risk of sediment deposition in slower-moving sections. In controlled downstream stage cases, the results underscore the damping effect of fixed boundary conditions. Case 2 exhibits velocities varying from 0.17 m/s to 1.08 m/s, with an average of 0.39 m/s, signifying flow attenuation and backwater influences. Similarly, Case 4, despite having a relatively high maximum velocity of 1.53 m/s, shows an average velocity of only 0.85 m/s, indicating the moderating influence of downstream control even under peak flow conditions. The lowest velocities overall are observed in Case 6, where speeds range between 0.12 m/s and 0.8638 m/s, with a mean of 0.26 m/s, highlighting critical conditions prone to sedimentation and operational challenges during low-flow periods. Collectively, the profiles captured in Figure 12 emphasize the pronounced impact of both flow magnitude and boundary conditions on the river's hydraulic behavior, providing essential insights for optimizing sediment management strategies and maintaining hydraulic efficiency along the Tigris River.

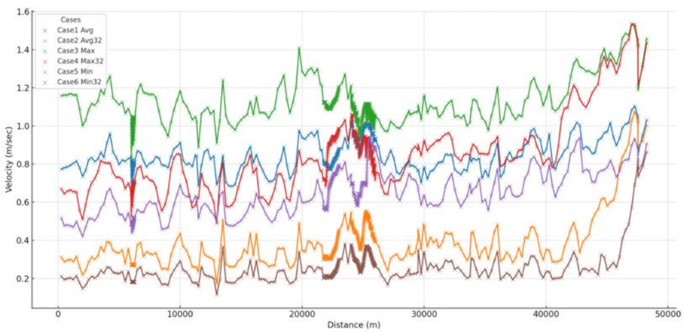

Figure 12: Computed Longitudinal Flow Velocity Profiles along the Tigris River under Six Operational Scenarios Using (HEC-RAS Output)

3.4 Sediment Transport and Riverbed Changes

The sediment transport and morphological evolution of the Tigris River in Baghdad were analyzed using a calibrated HEC-RAS model configured for quasi-unsteady flow simulations. Seven cases were developed: six covering combinations of maximum, average, and minimum discharge conditions under both natural and fixed downstream stages (32 m.a.m.s.l), and a seventh case (Average_All_Cases) synthesizing the outcomes to present a representative sediment behavior pattern across varying hydrological regimes.

Simulation results revealed that significant morphological changes occurred along the riverbed as a result of sediment mobility. Upstream reaches and the outer banks of meander bends experienced pronounced erosion due to elevated flow velocities and shear stresses, which triggered lateral channel shifts and bed scouring. Erosion hotspots were particularly noticeable near narrow cross-sections (e.g., Station 22+000), where velocities exceeded 1.5 m/s. Conversely, deposition was dominant in wider, slower-moving zones, such as those near Stations 36+000 and 45+000, where velocities fell below 0.8 m/s. Sediment accumulation was often concentrated along the inner meander bends and channel expansions, reducing local flow depth and navigational capacity. Modeling projections estimate an average deposition rate of 2.5 cm/year, with localized siltation reaching up to 7 cm in some areas.

Under minimum discharge scenarios, sediment transport capacity decreased significantly, resulting in aggradation near hydraulic structures and low-slope reaches. These depositional conditions risk obstructing water intakes and diminishing flood conveyance efficiency. However, scenarios involving a fixed downstream water surface elevation (32 m.a.m.s.l) produced more uniform gradients and improved sediment flushing, thereby stabilizing sediment deposition patterns.

Due to the limited availability of sediment field measurements, the sediment transport model was not fully calibrated against observed sediment data. However, the hydraulic calibration showed strong predicting abilities, which corresponded well with sediment behavior trends observed in previous studies.The analysis, calibrated a 3D SSIIM model by using flow depth and velocity measurements so that the sediment movement was simulated successfully (Ali, 2016). Researchers demonstrated that one-dimensional HEC-RAS model using Toffaleti function made reliable sediment transport predictions for hydraulic-only calibration (Al-Khafaji et al., 2016). The study also confirmed the applicability of the CCHE2D model on sediment near water intakes implying that hydrodynamic calibration alone can produce valuable results in data-scarce environments such as the Tigris River (Al-Asadi et al., 2023). Generalizing, the observed sediment transport dynamics highlight the crucial importance of the hydraulic setting and boundary assumptions in the further formation of river morphology. The quasi-unsteady HEC-RAS model turned out to be successful in describing the spatial variation in erosion and deposition and provides useful information on sediment management planning, protection of infrastructure and, sustainable operation of the Tigris River system in Baghdad.

Bed change results for all six cases.

Table 4, shows simulated longitudinal profiles of invert changes along the Tigris river for six cases based on sediment transport and morphological model using HEC-RAS. The results reveal substantial spatial variability in riverbed response influenced by discharge magnitude and downstream boundary control strategies.

Under natural depth conditions, Case 1, the bed level changes ranging from a minimum of −2.056 m to a maximum of +1.64 m, with an average change of +0.23 m, indicating moderate alternations between localized erosion and deposition. However, Case 3 reveals more pronounced bed degradation, with invert changes reaching −3.83 m at their lowest and +2.42 m at their highest, and a negative average of −0.27 m, reflecting high-energy conditions and enhanced sediment mobility. Furthermore, Case 5 displays relatively limited bed alterations, with invert changes between −1.58 m and +1.37 m, and a moderate positive average of +0.17 m, indicating low sediment transport rates under reduced hydraulic energy.
In cases involving fixed downstream water surface elevation at 32.0 m.a.m.s.l, a distinctive bed response is observed. Case 2 exhibits invert changes ranging from −1.38 to +4.27 m, with an almost neutral mean change of +0.02 m, highlighting the stabilizing influence of downstream control. Case 4 demonstrates substantial deposition, with values between −4.43 m and +3.92 m, and a relatively higher average of +0.44 m, reflecting strong backwater effects and energy dissipation during flood conditions. Finally, Case 6 indicates minimal bed disturbance, with changes varying from −0.24 m to +4.48 m, and a slightly negative average of −0.03 m, suggesting sediment accumulation in localized areas but overall bed stability under low-flow, controlled conditions.

Collectively, the profiles captured in Table 4 highlight the complex interplay between discharge magnitudes, boundary conditions, and sediment transport processes, providing critical insights for designing effective riverbed management and sediment mitigation strategies along the Tigris River.

3.5 Impact of Sedimentation on Hydraulic Operations

Sedimentation processes along the Tigris River in Baghdad have considerable implications for hydraulic operations, including water intake reliability, flood control efficiency, and navigation channel stability. Model simulations and field observations confirm that zones of reduced flow velocity, particularly where flow velocities fall below 0.5 m/s, act as sediment deposition hotspots. These deposits progressively narrow the river cross-section, lowering conveyance capacity and increasing water surface elevations under the same discharge conditions, thus raising flood risks during high-flow events.

Water intake structures, such as Al-Rasheed, Al-Qadisiyah, and Al-Wahda stations, are particularly vulnerable to sediment accumulation during low-flow periods (discharges below 400 m^3/s). Sediment deposition around intake mouths reduces submergence depth, promoting cavitation risks and decreasing operational efficiency. Simulation results show that aggradation rates near intake zones can reach up to 5 cm/year under minimum flow conditions, risking intake blockage if not periodically dredged or flushed.

Table 4: Simulated Longitudinal Invert Changes under Six cases of flow conditions along the Tigris River reach in Baghdad.

Cases	Minimum Invert Change (m)	Average Invert Change (m)	Maximum Invert Change (m)
Case 1: Average Flow with Normal Depth	-2.0571	0.2318	1.6381
Case 2: Average Flow with Fixed 32 m Stage	-1.3759	0.0143	4.2698
Case 3: Maximum Flow with Normal Depth	-3.8313	-0.2731	2.4252
Case 4: Maximum Flow with Fixed 32 m Stage	-4.4322	0.439	3.9169
Case 5: Minimum Flow with Normal Depth	-1.5831	0.1693	1.3746
Case 6: Minimum Flow with Fixed 32 m Stage	-0.239	-0.0273	4.4835

Flood control infrastructure is also adversely affected by sedimentation patterns. The accumulation of bed material along channel expansions and meander bends reduces the river's effective cross-sectional area, leading to higher localized water levels during flood peaks. During maximum discharge simulations (Case 3 and Case 4), critical sections downstream of Al-Jadriya bend and near the Diyala River confluence exhibited water surface elevation increases of up to 1.2 m compared to initial baseline conditions, significantly stressing urban flood defenses.

For navigation, sedimentation causes the formation of shifting sandbars and shallow shoals, particularly near hydraulic constrictions and river bends where velocities drop below the sediment transport threshold. Under minimum discharge scenarios, navigable depth decreased by up to 0.8 m in critical zones, notably between Stations 36+000 and 45+000, which impairs river transportation and necessitates intensified dredging operations to maintain minimum channel requirements.

Overall, the study emphasizes that sedimentation dynamics in the Tigris River are tightly coupled to hydraulic operational performance. Ensuring sustainable river management requires integrated sediment control strategies, including adaptive downstream boundary management, targeted dredging, and real-time monitoring to mitigate risks to water supply, flood protection, and navigation reliability

3.6 Sensitivity Analysis

To evaluate the robustness of the hydrodynamic and sediment transport model, a sensitivity analysis was conducted focusing on the effects of varying sediment loads, flow conditions, and key model parameters on simulation outcomes. The analysis was conducted to determine the effects of modification in input assumptions on predictions of riverbed morphology and hydraulic operations.

First, sensitivity of sediment load was determined by changing the inflow sediment concentration at the upstream boundary, varying by ± 20% to baseline values. Results indicated that a 20% increase in sediment load led to intensified deposition, especially in low-velocity zones such as downstream of Station 36+000, where sediment thickness increased by approximately 1.8 cm over the simulation period. On the other hand, lowering 20% of sediment load reduced deposition rate by approximately 1.5 cm, delivering a relatively more stable bed profile.

Second, flow condition sensitivity was evaluated by altering the discharge rate from all cases by ± 15%. Greater stream velocity and floods resulted after discharge was increased by 15% with maximum additional scouring of 0.5 m observed at Station 22+000 in narrow sections. A reduction in the discharge by 15% led to extensive deposition of sediments, especially on wider sections, under low-flow situations highlighting the vulnerability of the river to siltation. Third, model parameter sensitivity was based on various variations of Manning's roughness coefficient (n), ranged +/− 10% from the calibrated value of 0.030. While roughness increase caused relatively lower flows and greater sediment deposition by +7 % and the reduction of roughness allowed for greater velocities and enhanced erosion, primarily around bridges and bends.

In general, the sensitivity analysis reveals that sediment transport and riverbed evolution in the Tigris River are very sensitive to variations in sediment supply, magnitude of discharge, and hydraulic resistance parameters. The outcomes underscore the necessity of accurate calibration of these inputs for the successful generation of model forecasts and the planning of sediment management and hydraulic operations. By incorporating such sensitivity assessment, it enhances the robustness of river management strategies under vulnerable future hydrologic and sedimentary environment.

4. Conclusions

- This study has applied hydrodynamic simulation models to study the behavior of Tigris riverbed under several flow hypotheses and control regimes of operation for the Baghdad Governorate. The simulations showed important features of sediment transport and morphological transformation, indicating that fixed downstream water levels result in significant fluvial erosion at high discharge zones, whereas low flow without downstream control causes sediment deposition especially in slow moving regions like bends or water intakes operating below 0.6 m/s. These modifications have practical management problems, such as instability of bridges and banks, inefficiencies of pumping stations and navigation hindrances.

- Stabilizing effect of downstream water level regulation was established; however, mismanagement can enhance unnatural sediment accumulation. The results underscore the need for equilibrium between flow control and sediment stability. Although the study employed a one-dimensional model and included simplifying assumptions, the simulated outcomes aligned well with field observations and prior research findings. This validates the approach and affirms the role of hydrodynamic modeling as a vital planning tool for sustainable river operations.

- The findings further recommend enhancing simulation accuracy through the development of three-dimensional modeling techniques, especially in complex urban environments. Future studies should prioritize the integration of comprehensive field data—particularly sediment size distribution—to improve model performance. Moreover, there is a pressing need to implement real-time monitoring systems and adaptive infrastructure control protocols. These advancements, supported by improved modeling platforms, will be essential for addressing the evolving hydrological and operational conditions of the Tigris River in Baghdad, and for ensuring effective and sustainable river management strategies.

Overall, the results of this paper underscore the critical importance of coupling hydraulic modeling with sediment transport analysis to inform decision-making in urban river systems. For Baghdad, where the river serves multiple functions—navigation, municipal supply, and ecological balance—such integrated approaches are essential to address the compounded effects of climate change, urban expansion, and sediment dynamics.

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