

Sediment Transport Simulation under Flood Propagation by 2D HEC-RAS for Tigris River, Iraq

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ABSTRACT

Changes in the hydrological regime significantly affect water quality and sediment delivery in all river systems. Sediment transport analysis aids in better understanding fluvial dynamics. This paper focuses on river dynamics, which maintain the environment and support low-cost training activities and flood control constructions. The work aims to evaluate the total load sediment transport rate in the case of unsteady non-equilibrium under the condition of flood in 2D waves adopted within the 2D HEC-RAS model. The Tigris River, between the Mosul Dam and Samarra Barrage, was selected as the case study. In addition, advection and diffusion formulas are applied to simulate the rate of sediment transport based on the length of the adaptation parameter. Manning's roughness coefficient corresponding to the land cover has been calibrated. The outputs represented the obtained maps that were incorporated with the Digital Elevation Model (DEM) with a 100 m grid size, which describes the regions exposed to erosion and deposition in 2D. The average length of adaptation was 80.1 m. Furthermore, high variation in the sediment transport rate due to flood waves near Mosul Dam, where the sediment transport rate is $8100 \text{ kg m}^{-1} \text{ s}^{-1}$ at 5 km, which corresponds to a flood flow of $205000 \text{ m}^3/\text{s}$, then decreases to $1600 \text{ kg m}^{-1} \text{ s}^{-1}$ at km 422. The Laursen-Copeland model provides more precise results in simulating sediment transport, riverbed elevation changes, and sedimentation patterns. Finally, the study enhanced the control plan by providing details about a critical risk in inundation areas.

Keywords: Deposition, Length of adaptation, Sediment transport, Tigris River, 2D HEC-RAS.

1. INTRODUCTION

Reservoirs are integral to water resources management, especially in addressing water deficit, sediment regulation, and flood control. Therefore, accurate simulation of the downstream flood-wave propagation resulting from dam failures plays a crucial role in

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mitigation planning and cost-related decision-making (**Pratama et al., 2025**). Sedimentation is the deposition of solid materials transported by water, usually as a result of soil erosion. High rainfall directly contributes to increased soil erosion, exacerbating the phenomenon (**Kardhana et al., 2024**). The sedimentation process is inherently complex, as it potentially involves mechanisms for the absorption and removal of pollutants in suspension and influences biochemistry and biodegradation processes (**Patriadi et al., 2021**). Furthermore, the sedimentation process is affected by the soil type in the area and the presence of natural binders like vegetation and trees (**Kardhana et al., 2024**).

Sedimentation is a natural part of the hydrological cycle. However, excessive precipitation in lakes can pose significant technical and operational challenges, negatively impact on the life of the reservoir and significantly reduce storage capacity and operating efficiency (**Perera et al., 2023**). The current water storage capacity of global reservoirs is approximately 6,000 cubic kilometers. However, this capacity is declining at a rate of 0.52% per year due to precipitation, which accumulates at a rate of 31 cubic km/year. If this trend continues, global reservoir capacity is expected to decline by 50% by 2100, significantly impacting long-term storage potential and operational efficiency (**Beça et al., 2023**).

Recent developments, like the integration of machine learning ML models with hydrological simulations, offer encouraging methods for capturing this variability to improve hydrological forecasting, making them suitable for modelling long-term variability in sediment transport (**Marshall et al., 2025**). LSTM (long-short-term memory) ML models have demonstrated superior predictive accuracy in hydrological forecasting and can be trained on historical data of flood discharge and sediment transport to identify complex, nonlinear interactions between sedimentation dynamics and climate variables (**Chaplot and Birbal, 2022; Kisi et al., 2024**). Accurate predictions of high discharges enhance decision-making. Incorporating past land use changes and future projections can enhance understanding of sedimentation-land cover interactions, and addressing these upstream land cover drivers contributes to improving modelling.

The modelling of morphological processes under an unsteady free surface is a complex and open issue, so all physical phenomena are required to represent the mutual impact between flow, particle transport, and bed change (**Magdalena et al., 2020**). Overtopping, structural or foundational flaws, and piping are the main reasons for dam failure that result in turbulent flow (**Zhong et al., 2019**). Most of the sediment-transport equations have been developed to predict equilibrium sediment-transport rates in steady uniform flow. The "nonequilibrium transport effect" refers to the spatial delay between flow characteristics and sediment-transport rate derived from fluvial systems instantaneously responding to varying flow circumstances (**Iradukunda and Bwambale, 2021**).

Numerous numerical models were utilized a length of adaptation was built into the non-equilibrium sediment transport algorithm to account for this spatial lag effect for bed load transport. To overcome these issues, several attempts were conducted by (**Chen et al., 2010**) to demonstrate that, in extremely erratic flows like dam-break flow or catastrophic floods, the results of these models are sensitive to non-equilibrium characteristics. In order to accurately simulate the non-equilibrium sediment transport process, it is crucial to evaluate the adaptation length with a numerical model activity. (**Harsanto et al., 2021**) studied the effect of a flood wave on the bed and bank of the Winongo River (Indonesia) by using riverbed erosion analysis in 1D-HEC-RAS. The study results showed that the maximum depth of erosion reached 0.96m. Moreover, damage to the retaining wall occurs due to erosion, which is critical for effective river management/mitigation of erosion. On the other



hand, **(Abd Rahman et al., 2022)** utilized the 1D HEC-RAS model to simulate the sediment transport capacity in the Langat stream. The research concluded that the Langat River's capacity was determined to help the appropriate authorities manage the river.

(Kosaj et al., 2022) examined the incipient motion of sediment transport based on laboratory data and a numerical model (computational fluid dynamics). The values of the slope in the physical model range from 0.001 to 0.003. The conclusion is that when the bed slope of the channel is larger, the laboratory results are closer to those of the Flow3D model, and vice versa when the slope is lower. **(Nama et al., 2022)** implemented 2D HEC-RAS to simulate the total sediment capacity downstream in the case of steady uniform flow based on the Toffaleti formula. The Tigris River downstream of the expected Makhool Dam was adopted in this study. According to the total sediment capacity calculations, the bed material makes up less than 0.002% of the total sediment capacity of the overall load, with suspended sediment making up the majority of the total sediment capacity.

(Pratama et al., 2025) studied sedimentation and its effects on reservoir performance in the Pare Reservoir, Indonesia, which was analyzed using the 2D HEC-RAS model to simulate sediment accumulation, transport, and deposition over ten years. Furthermore, the study incorporated field data such as topography, reservoir bed bathymetry, discharge, and sediment samples. Results from the model indicated sediment accumulation of 6,847 m³, corresponding to an average annual reservoir storage reduction of 1.3%. Contrary to the typical applications for sediment transportation under flood propagation in rivers, this particular module implemented in the new 2D HEC-RAS 6.3 has lacked studies in literature. The program's straightforward structure, user-friendly application, and compatible software specifications make it a compelling choice. Additionally, the accuracy of the modelling results can be evaluated by analyzing the weighting factor of the implemented numerical scheme.

Most research focuses on the transportation of sediment in one dimension. Moreover, a few papers reported the application of length of adaptation, advection, and diffusion equations that included (erosion and deposition) depths. In addition, to the best of our knowledge, based on the reviewed literature, on applying this model to simulate sediment transport during dam failure-induced floods for (erosion and deposition) depth and total load sediment transport visualizations in two dimensions in the case of fully unsteady flow.

In this article, the conventional two-dimensional hydraulic engineering center-river analysis system (2D HEC-RAS) technique is employed for the following goals: Producing maps in two dimensions that explain the depth of erosion and deposition; furthermore, evaluating the total load sediment transport rate and producing maps that describe the diffusion of the sediment. Both aims are implemented under unsteady, non-uniform, and non-equilibrium conditions due to the waves of the flood resulting from a theoretical failure in the Mosul Dam along the Tigris River in the region between the Mosul Dam and Samarra Barrage. Therefore, this study plays a pivotal role in advancing approaches to riverbed morphology modelling, thereby broadening the tools available for sediment transport analysis. Beyond its significance for scientific and technological progress, the findings can also serve as a valuable reference for managing riverbed morphology at the study site.

2. METHODS

2.1 Study Area

The Tigris River represents an important source of water in Iraq that stems from Turkish areas and runs into Iraqi land to join the first tributary, the Khabur River **(Khadim and**

Olewi, 2021). The average annual discharge at Mosul city is $668 \text{ m}^3/\text{s}$, while the maximum and minimum annual discharges are $7,740 \text{ m}^3/\text{s}$ (recorded in 1972) and $85 \text{ m}^3/\text{s}$ (observed in 1935), respectively (**Dina, 2010**). The Tigris River is joined by two tributaries: the Greater Zab, which lies south of Shirqat City, approximately 50 km, with a total length of 437 km and an average discharge rate of $450 \text{ m}^3/\text{s}$ (**Al-Ansari et al., 2020**). It feeds the Tigris River with about 28.7% of its water.

The second tributary is called the Lesser Zab River, which conflues with the Tigris River nearly 30 km north of Fatha city. The maximum discharge rate was recorded in 1954 with about $3420 \text{ m}^3/\text{s}$ (**Al-Ansari et al., 2020**). The area of the case study region extends from Mosul Dam in northern Iraq, located at latitude ($36^\circ 37' \text{ N}$) and longitude ($43^\circ 44' \text{ E}$), and extends south along the Tigris River, ending at the Samarra Barrage, located at latitude ($34^\circ 9' \text{ N}$) and longitude ($42^\circ 1' \text{ E}$), as described in **Fig. 1**. Furthermore, it was recorded that the maximum discharge at km 360 at Fatha city reached nearly $1365 \text{ m}^3/\text{s}$. The study area includes Bars, braids, islands, and meanders, which affected the characteristics of the flow.

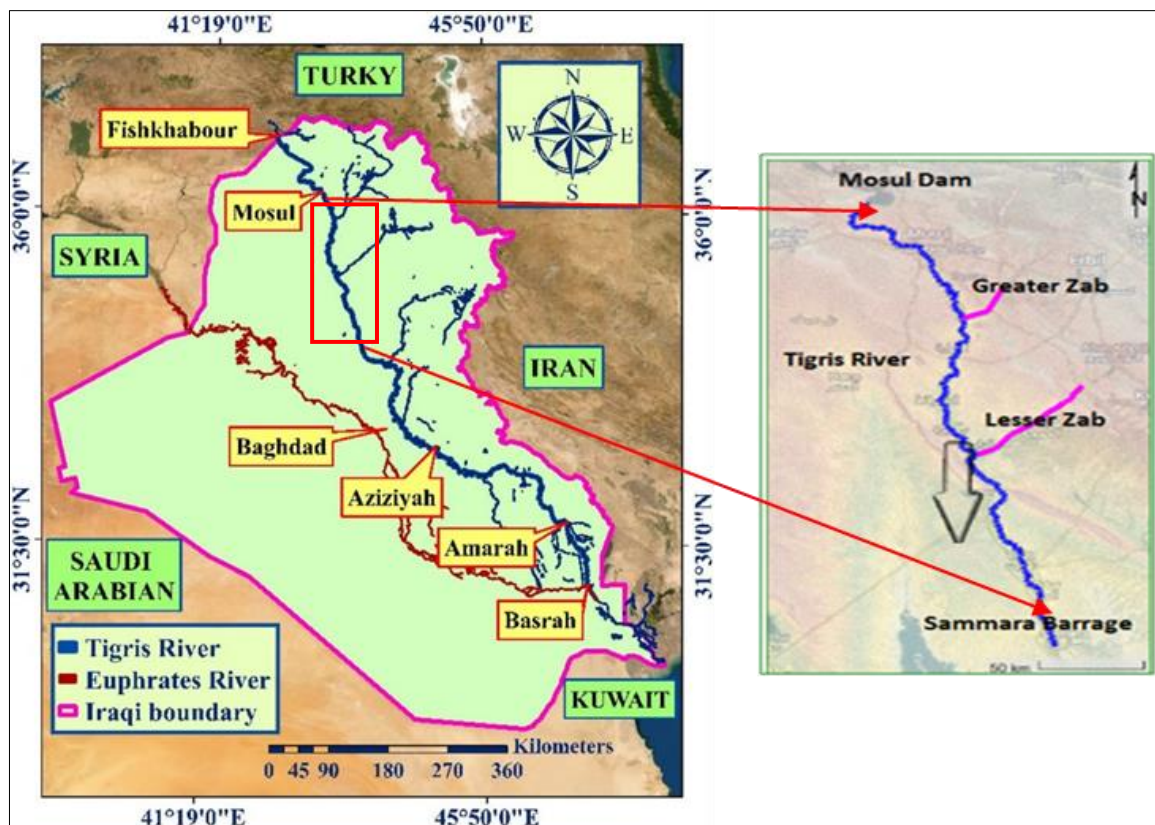


Figure 1. The map of the study area.

Mosul Dam is one of the largest hydraulic structures in Iraq, located 80 km south of the Iraq-Turkey border. Mosul Dam is an earth-fill dam with a clay core and does not have a rock material, the dam stretches 3,600 meters in length and rises to a height of 113 meters, with a crest elevation of 341 meters above the water surface. The Mosul reservoir has a design storage capacity of 1.1 million hectare meters at the normal operating level (**Mohamed et al., 2023**). The dam was built on highly karstified beds of the Fatha Formation. Consequently, grouting operations were carried out during construction to fill cavities, fissures, joints, and cracks in the karstified layers. Despite these efforts, seepage beneath the dam's foundation could not be prevented (**Al-Ansari et al., 2020**).

Several studies have been carried out to identify an effective grout or technique to address this issue. The seepage caused by the dissolution of gypsum and anhydrite beds has raised significant concerns about the dam's safety and the potential risk of its failure. Between June 2004 and July 2007, the US Army Corps of Engineers conducted an in-depth study on Mosul Dam, emphasizing the likelihood of its failure (**Wakeley et al., 2007**). In 2014, this concern gained widespread attention when news media reported on the issue after ISIS took control of the dam site. **Fig. 2** shows the Mosul Dam location and the main design details.

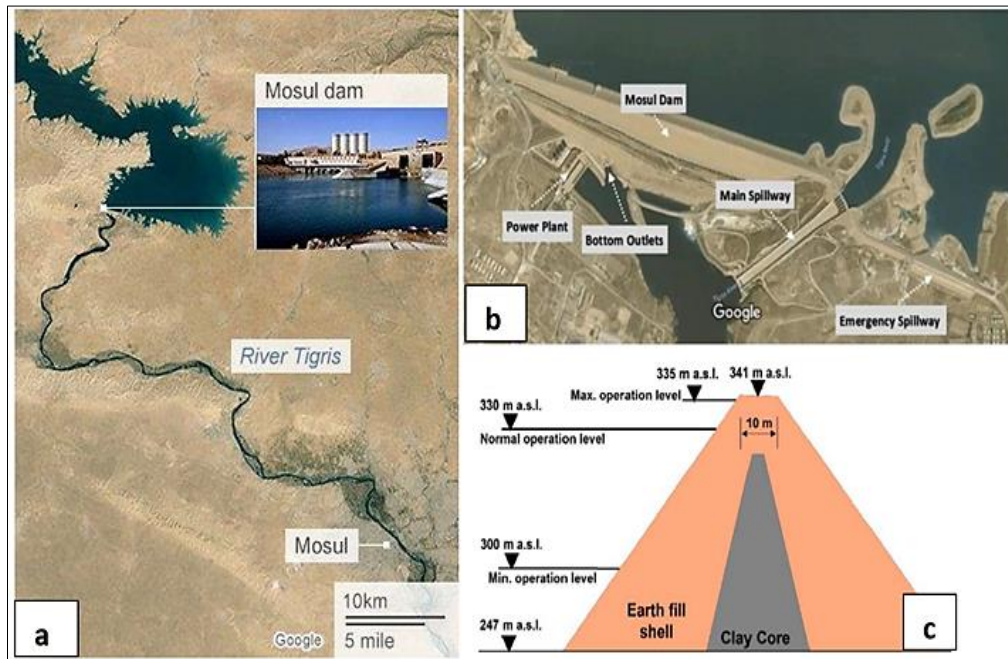


Figure 2. Mosul dam location: (a) Satellite image of the reservoir and Mosul dam, (b) Main dam, bottom outlet, spillways, and power plant, (c) Cross section of Mosul dam (**Mohamed et al., 2023**)

2.2 Data Collection and Methodology

The methodology of this study is workflow illustrated in **Fig. 3**. The flood hydrograph resulting from the Mosul Dam failure was obtained from the (**Ministry of Water Resources in Iraq, 2019**) and was utilized in the model as a boundary condition, as shown in **Fig. 4**. Moreover, the layer of the land cover that was used to classify the study area was obtained from the Ministry of Agriculture in Iraq. Besides the Digital Elevation Model (DEM) available from SRTM (Shuttle Radar Topography Mission) in WGS 1984 UTM Zone, with 14m grid cell resolution, the terrain north of Mosul Dam features elevated landscapes near the Iraqi-Turkish border, transitioning from extensive mountainous regions to flat plains as it extends southward, as illustrated in **Fig. 5 (USGS, 2016)**.

Soil classification in the examined vicinity varies in intensity along the river. In Mosul City, the soil ranges from very stiff to reasonably hard gypsum layers, with dark sandy silt and rock fragments. Downstream towards Tikrit City, the soil steadily changes from gravel to sand, after which it becomes silty sand, loose silt, and coarse silt. Based on the FAO soil database, the reach is classified as Hydrologic Soil Group D and was adopted in the HEC-RAS model, indicating soils with fairly low infiltration capability and excessive ability for surface runoff.

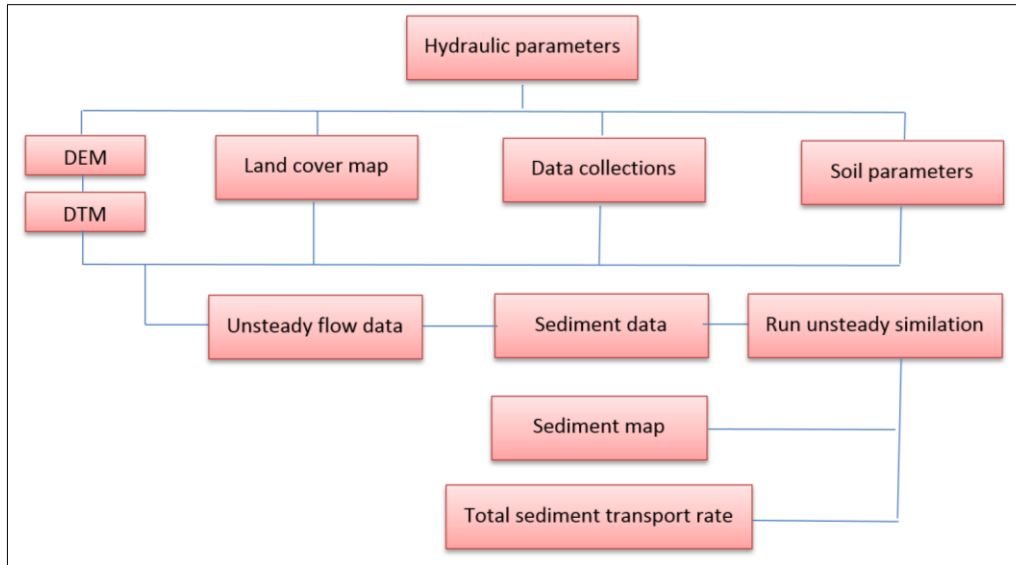


Figure 3. Workflow of sediment simulation in the Tigris River using 2D HEC-RAS.

2.3 Hydraulic Model

In this study, the HEC-RAS model is employed. The model has been broadly implemented for performing one-dimensional steady and unsteady flow, two-dimensional unsteady flows, the transport of sediment, and the modelling of water quality (**Zainal and Abu Talib, 2024**). Utilizes refers to water flow characterized by the average depth and velocity in two dimensions, and the height of the water according to the gravity forces and friction forces. These formulae show how mass and momentum are conserved in space. The feature of the Finite Volume Method that is associated with the 2D HEC-RAS model has geometric flexibility and is used to solve the unstructured mesh. The study area is discretized into a network of cells, all of which utilize the fundamental topography data. HEC-RAS creates a thorough hydraulic property table for each cell and cell face, including information on the relationship between elevation, area, and volume (**USACE, 2023**). When the water level in a lake suddenly rises, it flows through fissures, weakening the bonds between soil components (**Mohamed et al., 2023**). Larger cells are created as a result, which can use higher time steps and retain topographical information. The resistance to flow is controlled by the type of land use and Manning's roughness coefficient, and the given topography allows the water to flow in any direction. The mathematical equations of Navier-Stokes used to route the flood wave downstream from the dam, presented in the 2D HEC-RAS model, are momentum and diffusion equations that are simplified by a combination of the momentum and continuity principles. These formulas are given as stated below (**Haltas et al., 2016**):

$$\frac{\partial H}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} + q = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + \frac{u}{\partial x} \frac{\partial u}{\partial x} + \frac{v}{\partial y} \frac{\partial u}{\partial y} = -g \frac{\partial H}{\partial x} + vt \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - C_f u + fv \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{u}{\partial x} \frac{\partial v}{\partial x} + \frac{v}{\partial y} \frac{\partial v}{\partial y} = -g \frac{\partial H}{\partial y} + vt \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - C_f v + fu \quad (3)$$

Where: H: elevation of water (L), h: the depth of water (L), u and v: the components of velocity in two dimensions (LT⁻¹), q: a flux (source or sink) (L²T⁻¹), g: gravity (LT⁻²), vt: the

horizontal coefficient of eddy viscosity L^2/T , C_f : the coefficient of bottom friction, and f : the parameter of Coriolis T^{-1} .

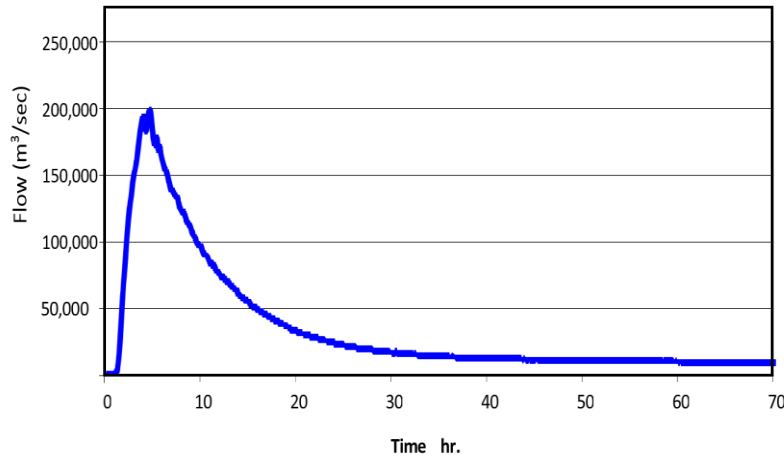


Figure 4. Outflow hydrograph of Mosul dam during failure

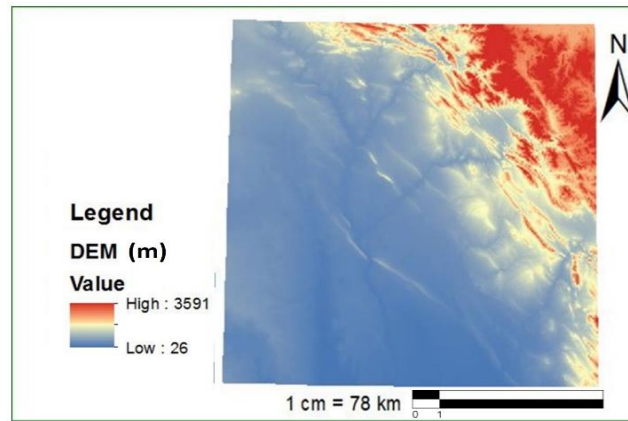


Figure 5. DEM of the case study (USGS, 2016)

2.4 Sediment Model

The common formula for sediment is based on the conservation formula of total mass and momentum. Therefore, to account for the impact of fluctuating silt concentration, the density of the flow is handled as a variable. The mass conservation equation takes bed aggradation or degradation into account when calculating the variation in sediment mass and flow. The total load transportation formula is mentioned by Brunner and defined in Eq. (4) (Tajima et al., 2026).

$$\frac{\partial}{\partial t} \left(\frac{h C_{tk}}{\beta_{tk}} \right) + \nabla \cdot (h U C_{tk}) = \nabla \cdot (\varepsilon_{tk} h \nabla C_{tk}) + E_{tk}^{HF} - D_{tk}^{HF} + S_{tk} \quad (4)$$

Where: C_{tk} : total load non-cohesive sediment concentration of the grain class k_{th} (M/L^3), β_{tk} : factor of the total load correction for the grain class k_{th} , U : depth-averaged velocity (L/T), h : the depth of water (L), ε_{tk} : coefficient of the total load diffusion L^2/T , E_{tk}^{HF} the rate of the total-load erosion ($M/L^2.T$), D_{tk}^{HF} : the rate of the total load deposition ($M/L^2.T$), and S_{tk} : total load sink-source ($M/L^2.T$). On the other hand, the erosion calculation depends on the wet and dry conditions, which are affected by shear stress and precipitation splash on the form of the sheet surface. Therefore, the fraction of sediment in suspension was represented as

the ratio between the suspension load transport rates and the total sediment transport rates. It is approximated by the transport mode parameter **(Tunas et al., 2025)**.

$$r_{sk} \approx f_{sk} = \frac{q_{sk}^*}{q_{tk}^*} \quad (5)$$

Where: f_{sk} : Transport mode parameter (fraction of sediments in suspension), q_{sk}^* : rate of potential suspended load transport (M/L.T), and q_{tk}^* : rate of potential total load transport (M/L.T). It is an important factor used to separate the contribution from bed and suspension, different factors that represent advection and the horizontal mixing coefficient. Rouse factor is one of the methods that can be used to estimate the transport mode parameter **(Greimann et al., 2008)**:

$$R = \frac{w_s}{u_* \times 0.4} \quad (6)$$

Where: R is the Rouse number, w_s is the sediment settling velocity, and u_* denotes the bed shear velocity. These values are used in **Fig. 6** to determine the transport mode parameter.

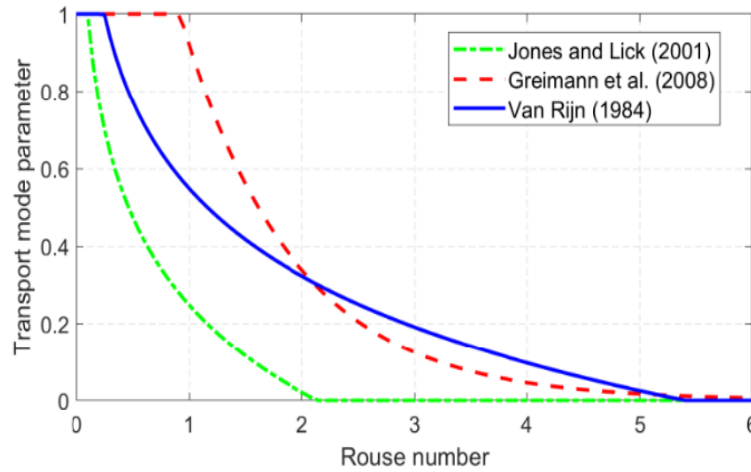


Figure 6. Relationship between transport mode parameter curves and Rouse number

The total horizontal diffusion (mixing) coefficients ε_{tk} can be divided into two parts: suspension load and bed load, which are related to (eddy viscosity, grain diameters d_k , etc.) as stated in Eq. (7):

$$\varepsilon_{tk} = r_{sk} \varepsilon_{sk} + (1 - r_{sk}) \varepsilon_{bk} \quad \text{for } k = 1, \dots, N \quad (7)$$

The dispersion generated via the mixture on the bed is generally greater than the diffusion of the bed load in the horizontal direction. Consequently, the coefficient of diffusion of the bed load is generally disregarded. The coefficient of the total load correction advection β_{tk} represents the distribution of the suspended sediment concentration in the vertical direction **(Greimann et al., 2008)**. Classification of grain size in which coarse-grained materials, mainly sands or gravels, are either well-graded or poorly graded. The process of grading soil falls under the Unified Soil Classification System. The classification of the sediment particles

within the 2DHEC-RAS model is adopted from **(Brunner, 2016)** for all grain-size classes k . On the other hand, the profile of the velocity and velocity at the bed load are generally slower compared with the average depth velocity **(Lai, 2020)**. It should be noted that the

transportation of sediments is supposed to be on a similar path, as the flow suspended-load correction factor β_{sk} is 1 in cohesive sediment and 0.5-0.7, while the advection coefficient for bed load is the ratio between the velocity bed load and the depth-averaged velocity. The total load adaptation length is an important factor that is used for estimating the adaptation coefficient that determines the erosion and deposition rate. It was evaluated as a function of unit discharge and sediment fall velocity. Various approaches for determining the total load adaptation length like the weight average of the bed, constant adaptation length, and suspension load adaptation length (**Greimann et al., 2008**). In this study, the constant-adaptation length method was adopted to determine the total load adaptation length. Excess shear and the ratio of shear velocity to fall velocity serve as fundamental factors. This concept was later expanded and adapted for application to graded beds (**Sisinggih et al., 2020**). This study employed the Laursen-Copeland formula, capitalizing on the applicability of silts to gravel (**Balouchi et al., 2024**):

$$q_{tk}^* = 0.01\rho_w U h \left(\frac{d_k}{h}\right)^{7/6} \left(\frac{\theta_b'}{0.039} - 1\right) f_{tk} \left(\frac{u_*'}{\omega_{sk}}\right) \quad (8)$$

Where, q_{tk}^* : capacity of sediment transport (M/L.T), θ_b' : grain-related Shields number and $(\theta_b')/(0.039)$ Present bed shear stress ratio, U : the magnitude of the current velocity (L/T), h : depth of water (L), ρ_w : density of water (M/L³), f_{tk} : active fractions of grain class by weight ω_{sk} : fall velocity of the sediment (L/T), and d_k : the mean diameter of the grain class (L).

2.5 Model Generation

The primary goal of mesh discretization is to obtain the best level of accuracy for a specific calculation. Smaller grid sizes allow higher accuracy in a longer time. On the other hand, coarser grids provide lower accuracy in a shorter time. The flood hydrograph due to the failure of the Mosul Dam is considered a boundary condition upstream. The normal depth is considered a boundary condition downstream. The Courant-Friedrichs-Lewy conditions have been employed to create a stable model (**Miao and Zhang, 2025**). Similarly, due to the quick computation and high stability, the Diffusion Wave equation was selected using a grid size (100 m) where the floodplains are relatively flat and extensive, which is generally appropriate for the flood inundation state and for calibrating of roughness coefficients to utilize it in the simulation of sediment transport (**Alwan et al., 2018**).

3. RESULTS AND DISCUSSION

3.1 Model Calibration and Verification

Based on the appropriate coefficient of roughness (n) values that are associated with each type of land cover. The 2D HEC-RAS model is implemented as a technique that depends on repeatedly iterating different values of " n ". Based on the annual discharge values observed in Mosul city during the period 2009-2019 (**Ndaka, 2025**), this technique is used to calibrate and validate " n " values. Nine flow rates have been employed, varying (500-9260) m³/s applied for the calibration process, and the results of these calibrations have shown good agreement among the calculated and recorded water levels along the river reach with coefficients of determination R^2 equal to 0.845 and RMSE 0.831, as illustrated in **Fig. 7a**. **Table 1** summarizes the calibrated values of " n " for different land cover types. Likewise, seven Tigris River flow rates, which vary between 500 and 6926 m³/s, are applied to validate the model that gives coefficients of determination R^2 of 0.840 (**Fig. 7b**).

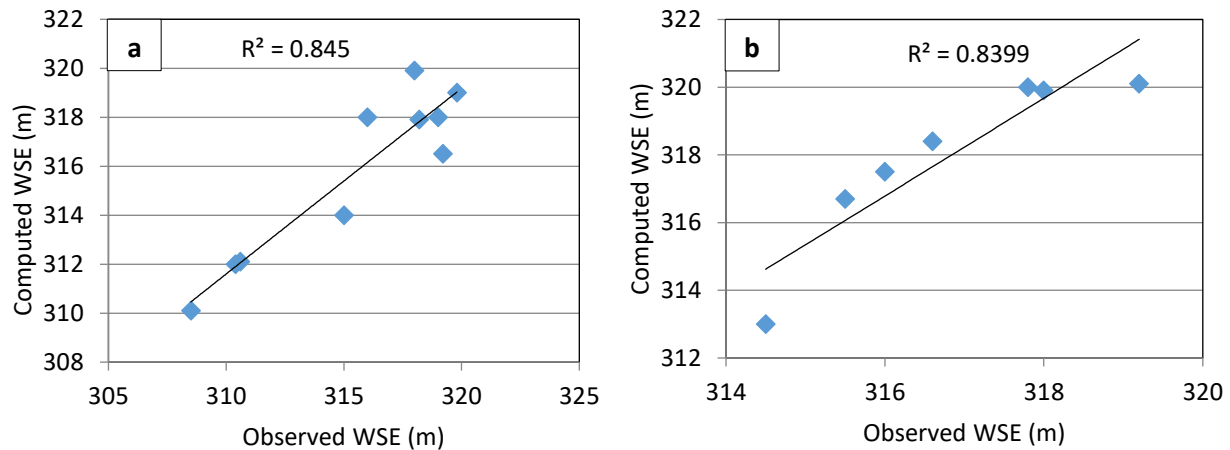


Figure 7. (a) Model calibration, (b) Model validation

Table 1. Calibrate Manning's roughness coefficient values.

Land use type	Barren land	Open water	Shrub	Open space	High intensity	Cultivated crops	Pastures
Area (ha)	27566	7576	436	1072	390	703	369
valuesn	0.023-0.03	0.025-0.05	0.07-0.16	0.03-0.05	0.12-0.2	0.02-0.05	0.025-0.05
Calibrated n	0.027	0.033	0.087	0.036	0.12	0.03	0.031

3.2 Length of Adaptation

In the first phase, the 2D HEC-RAS is utilized to simulate the sediment interaction with the flood flow due to dam failure for the case study. In this phase, the time series addressed upstream boundary condition, and the average normal depth of about 0.0005 was considered as the downstream boundary conditions. The bed gradation data is subsequently added as the second phase for all the areas of the case study. The information is entered using the percent finer approach because it has the option of having various bed gradations; each 2D region must be assigned the exact bed gradation. A three-average-bed gradation is applied in this scenario; then the sorting technique, the fall velocity technique, and the transport function have been selected. The Laursen-Copeland formula (defined in equation 8) and Ruby approaches are all used in this situation. After that, the sediment data is full and ready to be used in the simulation of 2D sediment transportation due to flood waves. The bed materials of the Tigris River study area extending from the Mosul dam body to the Samarra Barrage (479 km) were divided into three sizes in three zones: the average ratios are 3% for fine sand (0.125 to 0.26 mm), 30% for medium sand (0.26 to 0.64 mm), and 67% for coarse sand (0.64-2 mm), respectively (Nama et al., 2022).

The considered average value of the river slope is 0.0005, mass density ρ_s is 2650 kg/m³, and the average particle diameter d_{50} is 0.018 m. The variation of the values of U_b with the depth of water has been computed and then applied to determine the fall velocity. ω_{sd} was found to be 0.32 m/s and the shield parameter θ_{crk} is 0.16. Grain shear stress and bed shear stress. Hence, it appears that the average value of the Schmidt number is 0.71. Rouse number has been calculated and then combined with Fig. 6 to determine the value of the transport mode parameter f_{sk} as 0.3, which is applied for determining the horizontal diffusion; total load correction factors and then computed the average total load adaptation associated with the depth of flood, which is 80.1 m. This parameter is more impacted by the depth of water and velocities. The values of median grain size (d_{50}) are considered important factors that

directly impact the fall velocity and critical bed shear stress, as shown in **Figs. 8 and 9**. Both the coefficient of suspension diffusion and the total length of adaptation parameters are represented based on the height of the flood wave as displayed in **Fig. 10**. The average total length of adaptation was computed 80.1 m (**Fig. 11**). **Table 2** shows the results of important parameters related to grain size and length of adaptation. A comparison was made between these findings and the values obtained from the (**Zhang, 2013**) study, which showed a slight difference between them. Hence, these parameters are more affected by the depth of water and velocity.

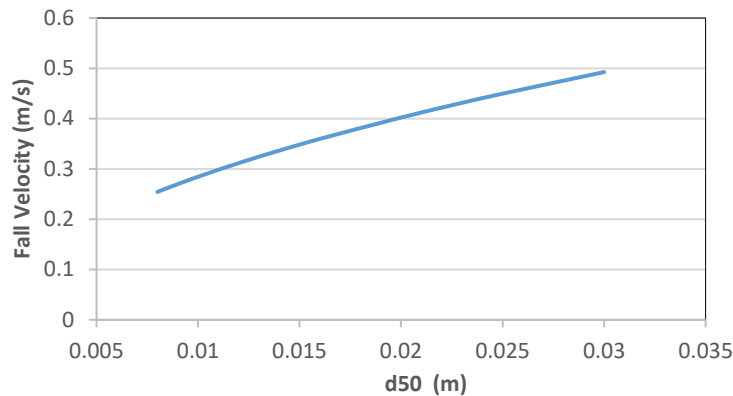


Figure 8. Relationship between the grain size of sediment and fall velocity

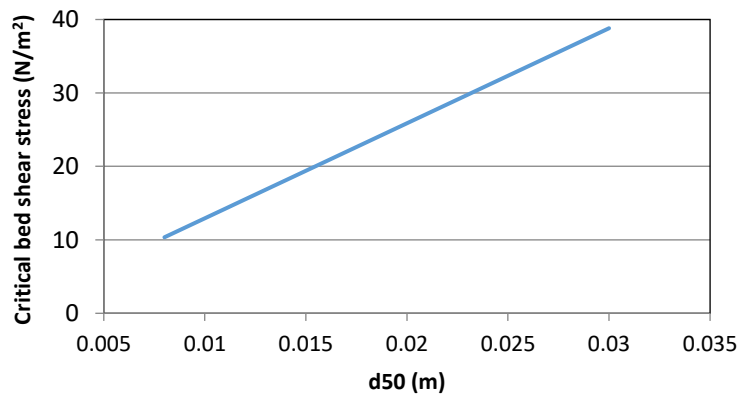


Figure 9. Relationship between the grain size of sediment and critical bed shear stress.

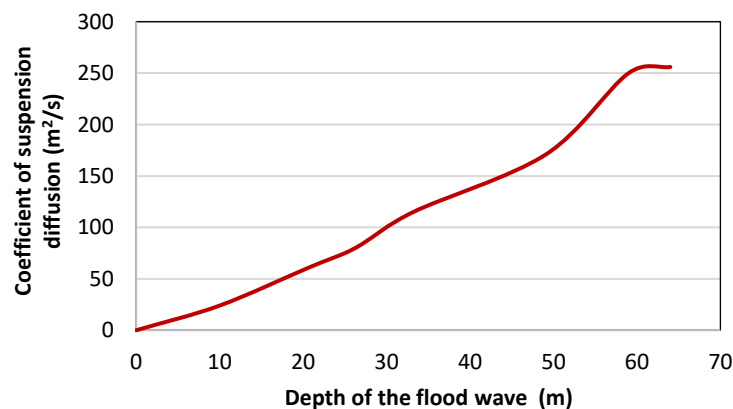


Figure 10. Relationship between the depth of the flood wave and the coefficient of suspension diffusion.

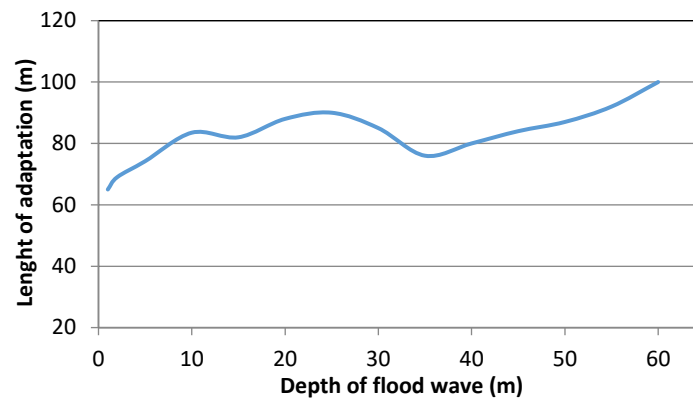


Figure 11. Relationship between flood wave depth and length of adaptation

Table 2. Results of grain size, depth of flood wave, fall velocity, shear stress and length of adaptation

Grain size d_{50} (m)	Depth of flood wave (m)	Length of adaptation (m)	Fall velocity (m/s)	Shear stress (N/m ²)	Coefficient of suspension diffusion (m ² /s)
0.03	60	100	0.492	38.808	294
0.025	55	92	0.450	32.340	294
0.023	50	87	0.431	29.753	269.5
0.02	45	84	0.402	25.872	245
0.016	40	80	0.360	20.698	220.5
0.015	35	76	0.348	19.404	196
0.014	30	85	0.336	18.110	171.5
0.013	25	90	0.324	16.817	147
0.012	20	88	0.311	15.523	122.5
0.011	15	82	0.298	14.230	98
0.011	10	83.5	0.298	14.230	73.5
0.01	5	74.2	0.284	12.936	49
0.009	2	69	0.270	11.642	24.5
0.008	1	65	0.254	10.349	9.8

3.3 Erosion and Deposition

The model produced maps that explained the distribution of erosion and sedimentation rates of the river during the flood wave in two dimensions, as shown in **Fig. 12**. The central zero values on the profile line indicate the boundary. Deposition occurs when the invert change exceeds the initial bed level, while erosion dominates when new invert level below the initial bed level. A high variation in bed changes due to flood waves near Mosul dam, in which the average value of erosion is 1.9 m and deposition 1.3 m at 5 km, as act in **Fig. 13a**. In km 255, there is no considerable variation along the area in the bed change except for a very small region that is confined between 0.64 m erosion and 0.47 m deposition, **Fig. 13c**. However, in km 422, the bed change is affected by a flood wave in different regions along the Tigris River, with nearly 3.5 m for erosion and a high rate of deposition of approximately 0.54 m, as illustrated in **Fig. 13e**, where the erosion and deposition processes, respectively, are represented by the negative and positive values. Erosion is influenced by the "characteristic flow length". However, the deposition depends on settling velocity. The maximum value of the depth of erosion is noted upstream of the river, while the maximum

deposition is found downstream of the river reach, especially at the meandering section. Therefore, a high difference between the depth of erosion and deposition occurs at km 422 when the velocity reduces and the cross-section expands. Also, the slope of the river becomes milder in this location, impacting the behavior of the flow. In general, the high density of widespread erosion and deposition in the study area is due to high discharges.

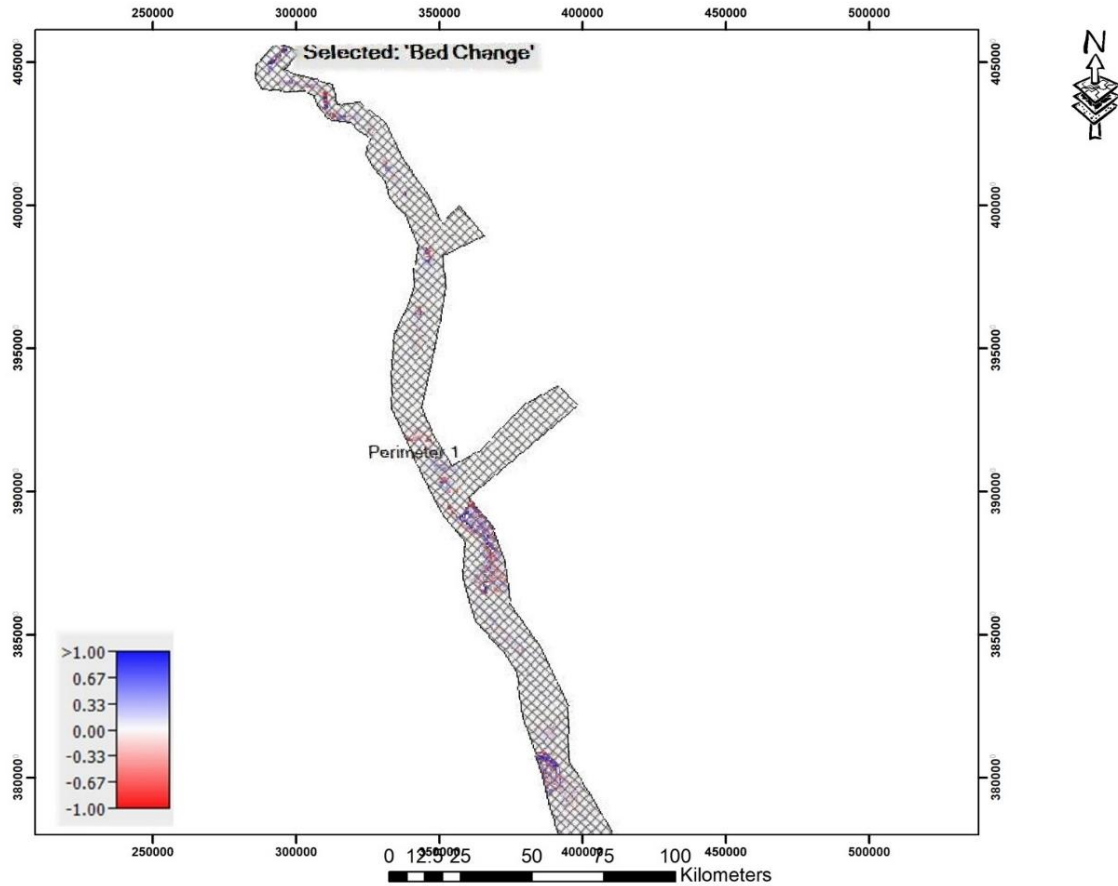


Figure 12. 2D Sediment map for deposition and erosion due to flood waves.

3.4 Total Load Sediment Transport Rate

An additional map was obtained from the model that explained the distribution of the sediment transport rate of the river during the flood wave in two dimensions, as shown in **Fig. 14**. A high variation in the sediment transport rate due to flood waves near Mosul dam, in which the average value of the sediment transport rate is $8100 \text{ kg m}^{-1} \text{ s}^{-1}$ at 5 km, as stated in **Fig. 15a**. The rate is slightly decreased in the sediment transport rate that reaches $4000 \text{ kg m}^{-1} \text{ s}^{-1}$ at km 255, as act in **Fig. 15b**. However, it showed that the rate of sediment transport continues to decrease, with the peak value at km 422 being $1600 \text{ kg m}^{-1} \text{ s}^{-1}$ as displayed in **Fig. 15c**. One of the most important factors influencing the amount of sediment transported is flood discharge. In general, the quantity of sediment reached a maximum value somewhat upstream and then declined when transported downstream of the river. The total adaptation length is calculated by (Zhang et al., 2013) at 74 m, and they noted that the average value comparison of the value with the study showed a slight difference between the values. (Ali, 2016) examined the sediment transport capacity of reaches in the Tigris River (in one dimension). The calculated outcomes of the rating curve for the total

sediment transport rate use the Laursen method, whereas the 2DHEC-RAS model for this work is in two dimensions.

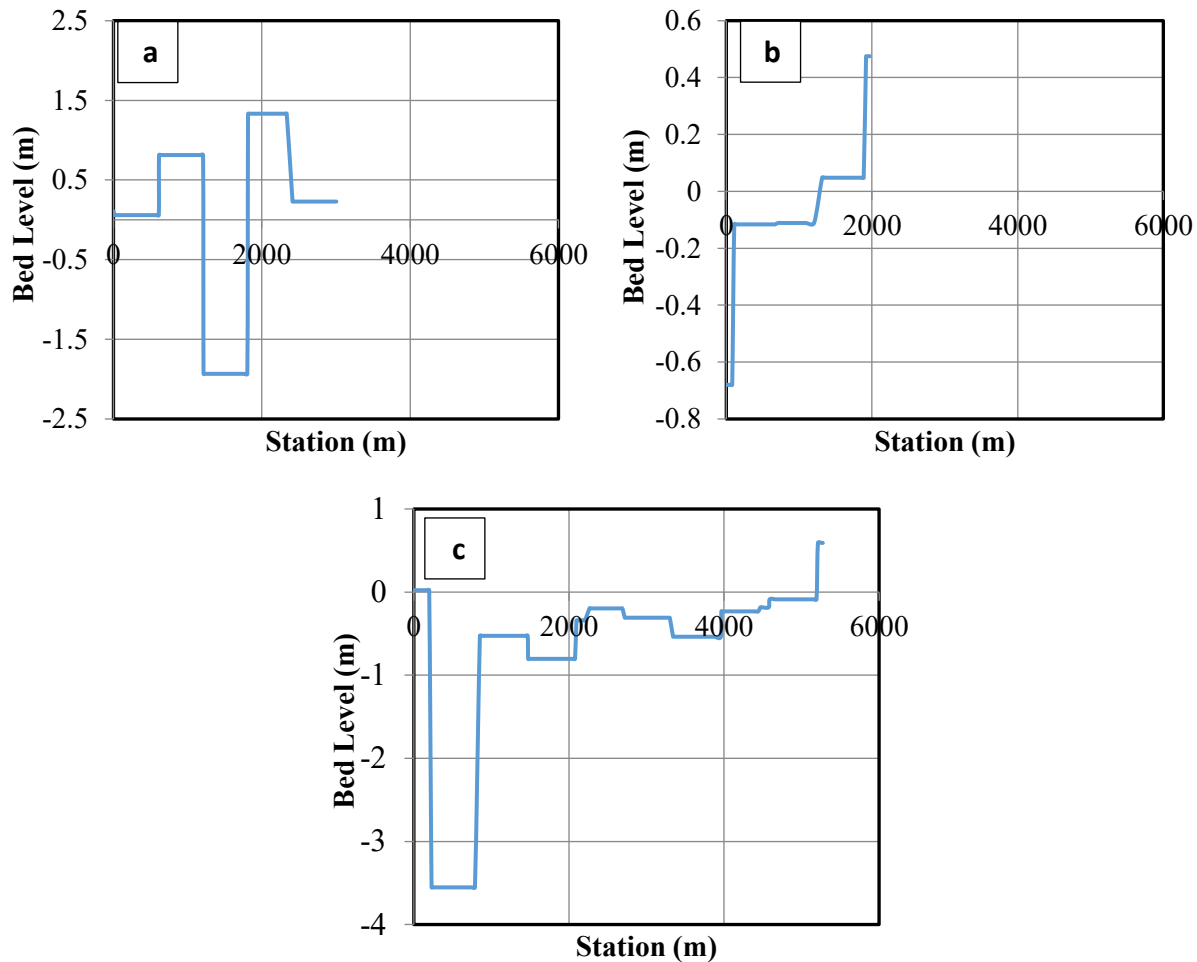


Figure 13. Profile line erosion and deposition at Km 5 (a), Km 255 (b), and Km 422 (c).

Regression analysis is typically used to establish relationships, and power-law-type equations are used to express the curves. To reconstruct long-term sediment transport, the sediment rating curve can be employed. (Majeed et al., 2021) applied the 1D HEC-RAS model to determine the critical sedimentation station when the bed increases. As with other forecasting methods, the rating curve of the sediment is a frequently used predictor for calculating the transportation of the sediment. The peak amount of total load transport rate is $8100 \text{ kg m}^{-1} \text{ s}^{-1}$, which corresponds to the flood flow of $205000 \text{ m}^3/\text{s}$ and then decreases, associated with the shortage in flood discharge. The power formula for the total sediment load concerning the flood discharge, as anticipated by the Laursen (Copeland) equation in the HEC-RAS model, was shown in (Eq. 9) for the study reach.

$$q_{tk}^* = 0.2022Q^{0.8615} \quad (9)$$

Where: q_{tk}^* : discharge of the total sediment ($\text{kg m}^{-1} \text{ s}^{-1}$), and Q : discharge of the flood (m^3/s), with a coefficient of determination factor R^2 equal to 0.816 as represented in Fig. 16.

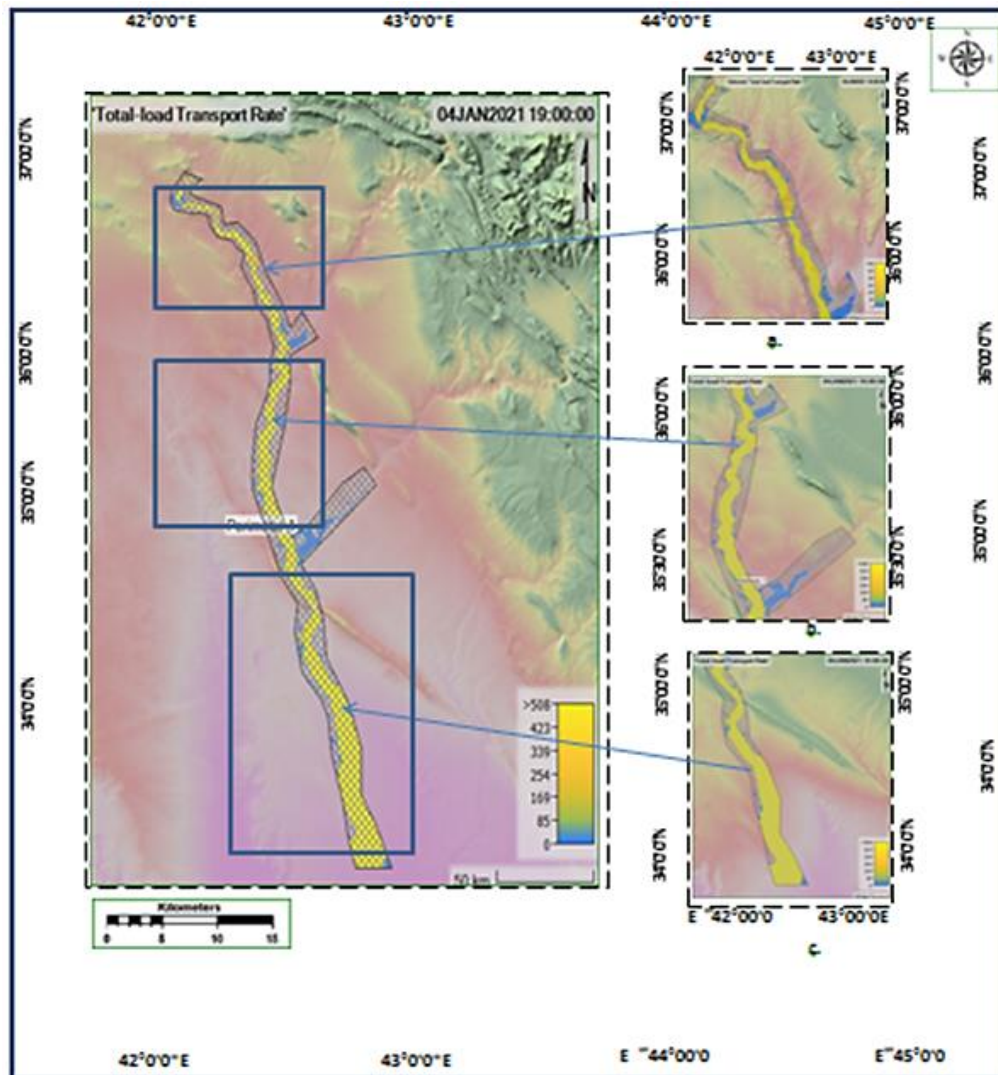


Figure 14. 2D map of total load transport rate visualization.

3.5 Recommendations and Study Limitations

This study on sediment transport resulting from the failure of Mosul Dam was limited by several factors, most notably the uncertainty arising from assumptions about land use and discharge, besides the limited availability of data. Future studies could enhance our understanding of sediment transport patterns by incorporating long-term discharge data or climate variability scenarios. Initially, the lack of high-resolution field data, such as sediment grain distribution and density, limited the accuracy of transport predictions, especially in mixed-load systems. Moreover, the lack of post-failure observations (since the dam did not fail) led to model validation using historical data. Additionally, mathematical requirements limited the model's accuracy. On the other hand, the use of a quasi-coupled sediment transport framework in the HEC-RAS 2D model, which updates bed morphology at a slower rate than flow hydraulics, may lead to inaccuracies under failure conditions. The model did not take into account the karst foundation and internal erosion characteristics of the Mosul Dam, ignoring subsurface processes that influence sediment flow. As a result of data limitations, the current model assumes flood discharge and simplified discharge conditions in the event of dam failure.

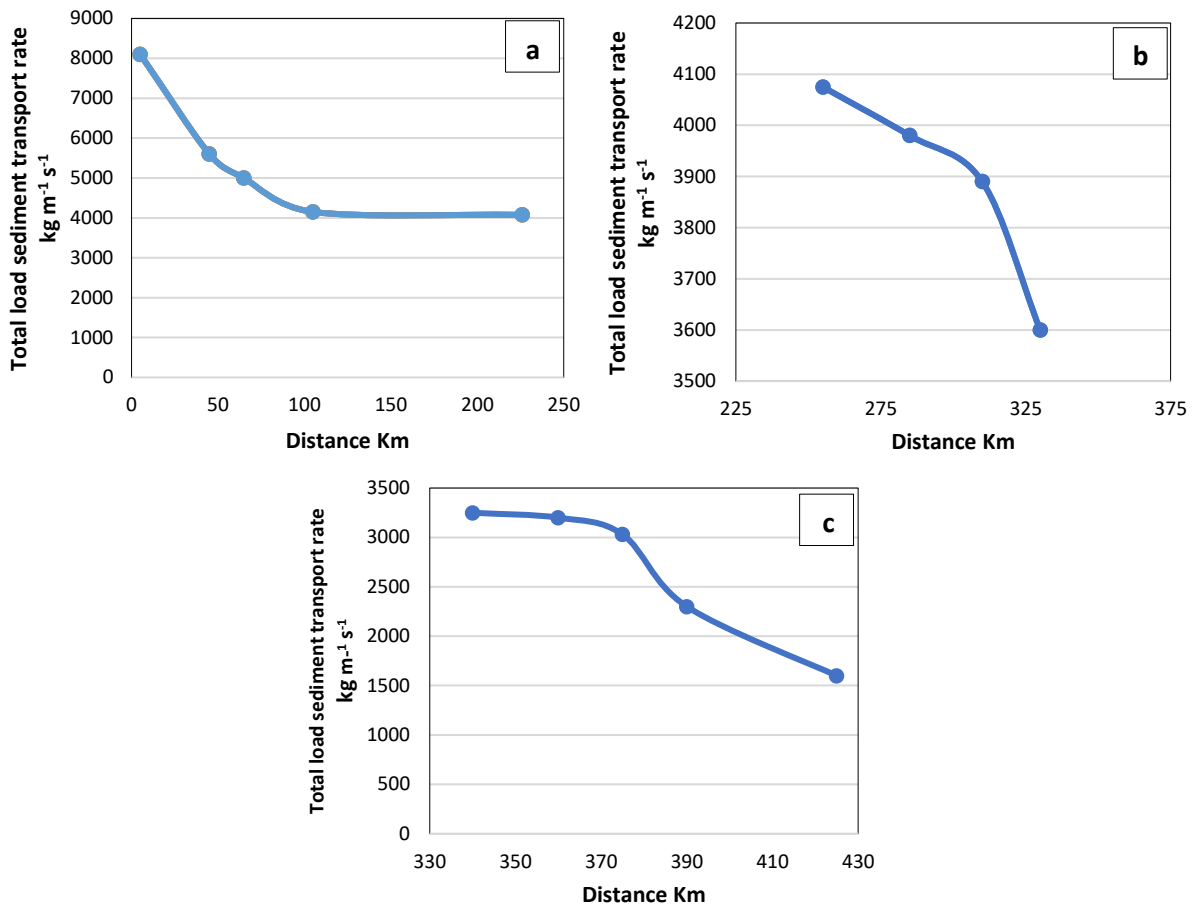


Figure 15. Total load sediment transport rate due to flood waves at Km 5 (a), Km 255 (b), and Km 422 (c)

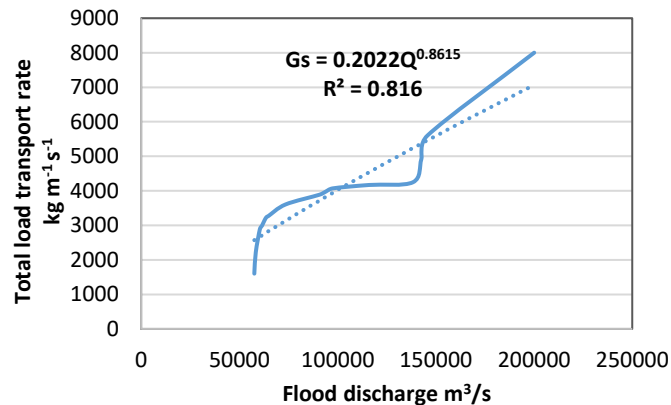


Figure 16. Relationship between the simulated total load transport rate and flood discharge

Incorporating a long-term discharge record could allow the model to account for fluctuations in flow regimes, including low-flow conditions and flood events, which significantly influence sediment transport and deposition dynamics. Long-term discharge data are available, both historical records and future projections from global models. Future research is recommended to incorporate dynamic land use changes by incorporating temporal land cover data and watershed development patterns, implementing more detailed discharge



scenarios that account for seasonal variations and extreme events, developing comprehensive field monitoring programs to validate the model, applying uncertainty quantification methods to assess the impact of model assumptions, incorporating climate change scenarios to assess long-term sedimentation patterns, improving the spatial and temporal resolution of input data, and implementing more advanced sediment transport algorithms. These improvements would significantly enhance model reliability and provide more accurate predictions for sedimentation management in the Tigris River downstream of Mosul Dam. Overall, these limitations highlight the need for integrated approaches that combine field data, dynamic dam failure modelling, and high-resolution simulations to improve prediction reliability in dam failure risk assessments.

4. CONCLUSIONS

According to the results acquired from the hydraulic software, the following points can be briefly obtained:

- 2DHEC-RAS is suitable for producing maps incorporated with terrain images that describe the distribution of the parameters of erosion, deposition, and total load sediment transport rate associated with the flood wave in 2D unsteady non-equilibrium flow conditions.
- Using the finite volume technique, numerical 2D depth-averaged hydrodynamic, transport-dispersion, and morphological models were successfully developed. On the other hand, this technique minimizes, to the greatest extent possible, the numerical error in the solution of the problem resulting from approximating the river geometry.
- The ability of the model to simulate unsteady and non-equilibrium sediment transport is based on the total load transport formula, including the Laursen (Copeland) equation based on advection-diffusion principles and length of adaptation.
- The maximum values of erosion are found downstream of the river, while the maximum deposition is noted upstream of the river reach. Furthermore, the maximum values of the total load transport rate occur upstream of the river.
- According to the outcomes obtained from the 2D HEC-RAS software, the peak value of the total sediment load transport rate is $8100 \text{ kg m}^{-1} \text{ s}^{-1}$, which corresponds to the flood flow of $205000 \text{ m}^3/\text{s}$ and then decreases, associated with the shortage in flood discharge. Furthermore, high variation in bed changes due to flood waves near Mosul Dam (Km 5), while near Sammara Barrage (Km 422) the bed change is highly affected by a flood wave and high difference between the depth of erosion and deposition
- Erosion is influenced by the characteristic flow length. However, the deposition depends on settling velocity. Finally, the erosion and deposition depths varied with the length of adaptation.

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Credit Authorship Contribution Statement

Hussein J. Khadim: Writing–review and editing. Mahmood J. Mohamed: Writing–original draft. Ibtisam R. Karim: Methodology of the work. Mohammed Y. Fattah: Validation. Nadhir Al-Ansari: review and editing the final work



Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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محاكاة نقل الرسوبيات خلال الفيضان باستخدام برنامج HEC-RAS ثنائي البعد في نهر دجلة في العراق

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الخلاصة

تؤثر التغييرات في النظام الهيدرولوجي على جودة المياه بشكل أكبر وكذلك على عملية نقل الرواسب في جميع الأنظمة النهرية. ويمكن قياس نقل الرسوبيات من خلال فهم أعمق لديناميكية الانهار وكذلك توصيف العمليات النهرية المرتبطة بها. تركز الدراسة الحالية على ديناميكية الانهار والمحافظة على البيئة وتقليل تكلفة التدريب ومنشآت التحكم في الفيضانات وتقييم معدل نقل الرسوبيات في حالة الفيضان بحالات ثنائية الأبعاد في نهر دجلة بين سد الموصل وسد سامراء. وتهدف الدراسة إلى تقييم معدل نقل الحمل الكلي للرواسب في ظل ظروف التدفق غير المستقر وغير المتوازن أثناء الفيضان، وذلك باستخدام محاكاة الموجات ثنائية الأبعاد المعتمدة في نموذج 2DHEC-RAS. تم اختيار موقع الدراسة لنهر دجلة للمسافة الممتدة بين سد الموصل وسد سامراء. وبالإضافة إلى ذلك، تم تطبيق معادلات الحمل والانتشار (advection and diffusion) لمحاكاة معدل نقل الرواسب استناداً إلى طول معامل التكيف (adaptation parameter)، كما تمت معايرة معامل خشونة (Manning's roughness coefficient) بما يتوافق مع الغطاء الأرضي. وتمثلت المخرجات في خرائط مدمجة مع نموذج الارتفاع الرقمي (DEM) بأبعاد شبكية تبلغ 100 متر لتوضيح المناطق المعرضة للتعرية والترسيب ثنائي البعد، حيث بلغ متوسط طول التكيف 80.1 متراً. وعلاوة على ذلك، لوحظ تباين كبير في معدل نقل الرواسب نتيجة لموجات الفيضان بالقرب من سد الموصل؛ إذ بلغ المعدل 8100 كغم/متر/ثانية عند الكيلومتر 5 (يقابل تصريف فيضاني قدره 205,000 متر مكعب/ثانية)، ثم انخفض إلى 1600 كغم/متر/ثانية عند الكيلومتر 4.22. وقد أظهر نموذج "لورسن-كوبلاند" (Laursen-Copeland) دقة أكبر في محاكاة نقل الرواسب، وتغيرات منسوب قاع النهر، وأنماط الترسيب. وأخيراً، ساهمت الدراسة في تعزيز خطة التحكم من خلال تقديم تفاصيل حول المخاطر الحرجة في المناطق المعرضة للغمر.

الكلمات المفتاحية: نهر دجلة، الترسبات، نقل الرسوبيات، طول التكيف، 2D HEC-RAS