Journal of Civil Engineering and Architecture 20 (2026) 238-247
doi: 10.17265/1934-7359/2026.06.005

Estimation of the Quantity of Sediment Transport by Al-Gharaf River Southern Iraq Using New Empirical Formula

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Abstract: This study aims to develop a new Empirical Formula to calculate the sediment load in Al-Gharraf River in southern Iraq. The targeted portion of the river stretches for 88 km, starting from the head regulator at the Wassit Governorate and to the cross regulator No. 2 (Wassit and Dhi-Qar governorates boundary). Hydraulic, sediment, and geometric measurements were taken for selected reaches to derive the equation. Thirteen cross-sections along the river were analyzed within the study area. Water samples were collected at different depths, and bed samples were taken for the sections. Sieve analysis, including hydrometry analysis, was conducted on these samples. After statistical data analysis, a new formula was developed to estimate the suspended sediment load in Al-Gharraf River based on data from ten river cross sections manipulated using the SPSS program. The determination coefficient of the new formula was found to be ($R^2 = 0.96$). Statistical indicators were calculated to ensure the accuracy of the excellent formula results. Also, the new formula was applied to the data from Al-Gharraf River collected by other researchers in different years, and the results were also good. Three formulas from previously proposed in literature formulas have been used to estimate the rate of suspension sediment these are; Bagnold (1966), Van Rijn (1984b), and Daham (2021). Bagnold (1966), Van Rijin (1984b) are adopted as a universal to clarify their reliability for use as deterministic equations, specifically for the current study section. While for Daham (20121) formula, its selection as an equation was derived from a previous study on Al-Gharraf River. The results of Van Rijn's (1984b) and Bagnold's (1966) formulas were far off, while the sediment concentrations calculated using Daham's (2021) formula were consistent with the observed sediment concentration with Mean standard Error equal to 9.09%. The obtained results proved that the equation resulting from this study is perfect in sediment calculation investigations along Al-Gharraf River.

Key words: Al-Gharraf River ;Sediment Transport; Determenistic Equation; Suspended Sediment;

1. Introduction

The study of sediment transport mechanisms and transport capacity of stream flows is critical in river hydraulics and geomorphology due to natural rivers being constantly eroded and affected by sediment transport processes. Sedimentation in rivers can lead to severe consequences such as forming sediment bars, reducing flood sediment transport capacity, erosion of hydro-mechanical facilities and damaging water structures, sedimentation at flow channels, and other hydraulic problems. Moreover, it is necessary to study various methods to predict river sediment transport rate to consider the principles of river material extraction and transported sediments by river flow when designing river structures [1].

The study of sediment transport in natural rivers has been the subject of much research in recent decades. Several theoretical and empirical formulas can be used to predict the transport rate for sand bed rivers with reasonable accuracy. For example, sediment transport methods developed by Bagnold [2], Engelund and Hansen [3], Ackers and White [4], Yang [5], and Van Rijn [6] are often applied to compute bed-material load

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in these rivers. However, no universal formula exists that can be suitable to estimate sediment transport for all rivers due to the differences in environmental configuration, morphology of river, hydraulic aspects, and measuring tools. Therefore, a new formula is required for each specific reach. The current study examined the transportation of sediment, its quality, quantity, and rate at a specified distance from Al-Gharraf River. Based on the field measurements of flow, hydraulic, and sediment properties, a predictive formula for sediment transport was extracted in the chosen reaches of the river.

Al-Gharraf River is a branch of the Tigris River, and its primary function is to deliver water to cities in central and southern Iraq. It is 230 km long, and for this study, a selected length of 88 km lying in Wassit governorate was considered. The river has a design discharge of 500 m^3/s, but its operational discharge is about 350 m^3/s. The river's width ranges from 150 m to 80 m, and its bed depth varies from 3m to 8 m. Sediment accumulation in Al-Gharraf River has become a significant problem for the Ministry of Water Resources due to its impact on the river's convenience and benefits.

The related formula was extracted as a predictive formula of sediment transport capacity for the selected river reaches. This study was restricted to a specified distance of Al-Gharraf River between the head regulator in Wassit governorate and cross regulator No. 2, which represents Wassit and Dhi-Qar governorates border (see Fig. 1). The river starts from the upstream of Al-Kut barrage towards Dhi-Qar governorate. Thirteen sections were selected, as shown in Fig. 2 ADCP surveyed the selected sections to collect all necessary hydraulic and geometrical data. Fieldwork for this study was conducted in June 2023.

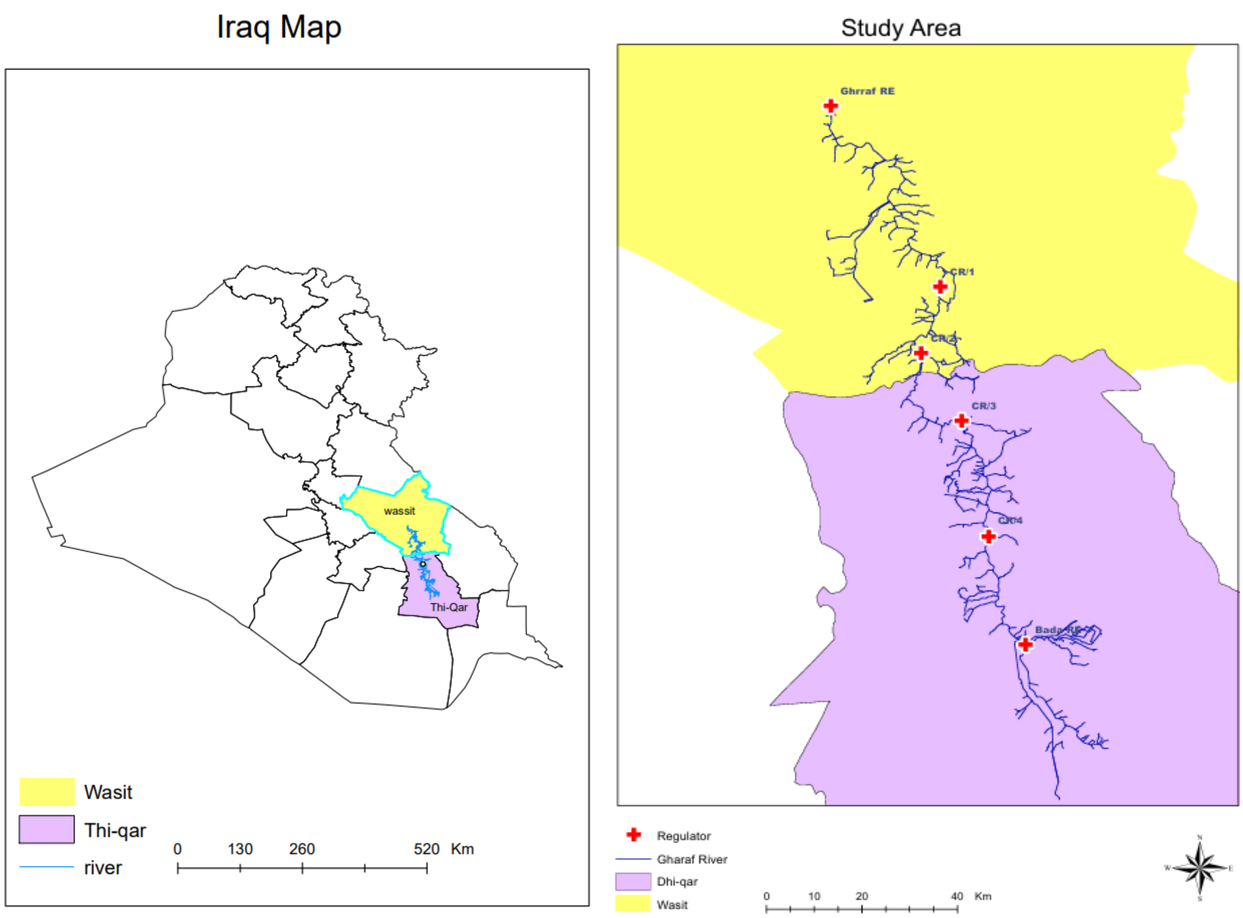

Fig. 1 A map showing the location of the cross regulators on al-Gharraf River, Wasit and Dhi-Qar Governorates, south of Iraq (by Arc. GIS Software).

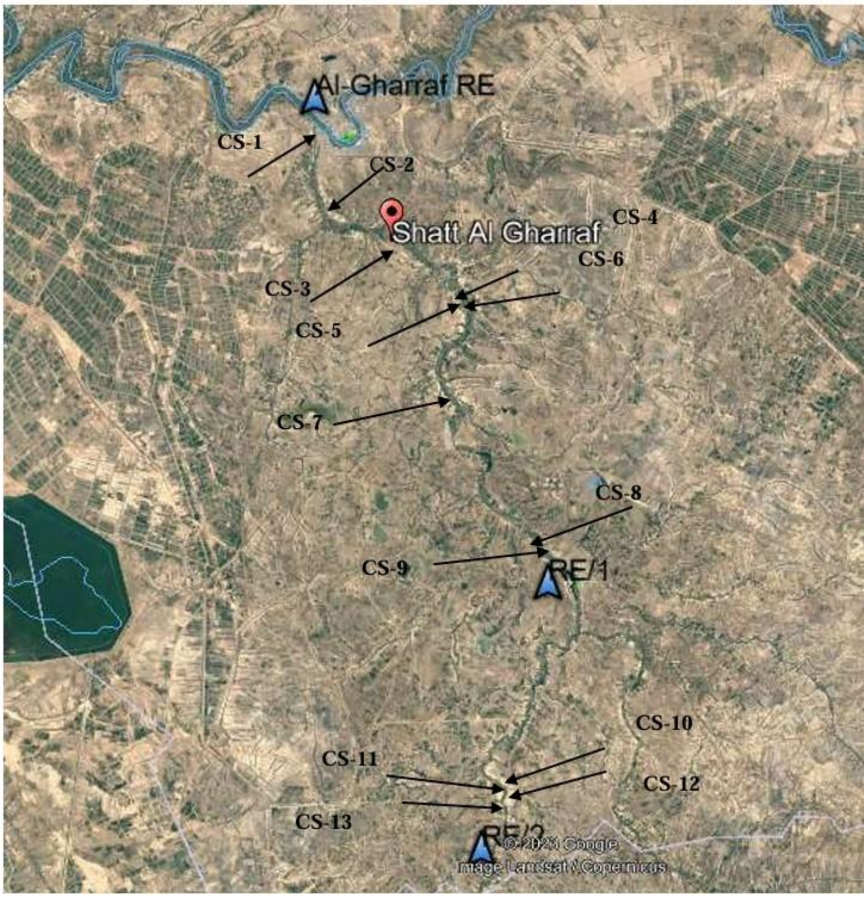

Fig. 2 Plan view of the study reach of Al-Gharaf River with all fourteen sections selected.

3. Field Measurement

In this study, sediment measurement was conducted in thirteen selected sections along Al-Garraf River. These sections were 100-300 meters from each other at varying distances, depending on the nature of the study area and the hydraulic conditions. The total length of the river reach covered by the survey is approximately 88 kilometers, as shown in Fig. 2. The measurements involved discharge, average velocity, width, cross-section area for each cross-section, and sampling of the water-sediment mixture to determine the mean suspended sediment concentration, particle size distribution, and other physical properties of the transported solids. The flow depths ranged from 2.8 to 6 meters, while the flows ranged from 76 to 98 m3/sec. The flow velocities ranged from 0.214 to 0.6 m/s, and the median sediment size of bed material composition was observed to be 0.08 to 0.13 mm. Table 1 provides a summary of the data used in the study.

3.1 Suspended Sediment Sampling

Suspended sediment sampling is conducted to determine the average concentration of suspended sediment in stream cross-sections, weighted by the instantaneous mean discharge. The suspended sediment discharge is then calculated using the measured concentration and flow discharge. A homemade sampler collects suspended samples from selected river reaches and depths. The river width is divided into four quarters. Samples are taken from the depths at (1/4, 1/2, and 3/4) positions of the top width of the stream cross-section, as shown in Fig. 3. In addition, samples are taken from the river bed material to identify the type, size distribution, and gradation as well as calculation of its uniformity. Bed material samples are taken from each subsection of the suspended load and mixed to describe the bed material

Table 1 Measured Data and Parameters.

Sec	Q (m^3/s)	h(m)	V(m/s)	Cg(kg/m^3)	d_{50}(mm)	A (m^2)	b (m)	Slope	Ws (m/s)	ν(m^2 /sec)	S_g
1	98	2.8	0.4	0.0211	0.1	245	139	0.00004	0.0091854	0.00000089	2.5
2	97	2.97	0.355	0.018	0.08	275	118	0.00004	0.0072503	0.00000089	2.85
3	96	3.93	0.346	0.019	0.1	273	97	0.00004	0.0107163	0.00000089	2.75
4	76	6	0.214	0.014	0.12	358.5	64	0.00004	0.013227	0.00000089	2.5
5	91	4.45	0.356	0.0248	0.12	251	70	0.00004	0.0141969	0.00000089	2.61
6	88	2.66	0.439	0.0244	0.1	200	88	0.00004	0.0105326	0.00000089	2.72
7	90	3.5	0.403	0.025	0.1	217	77.2	0.00004	0.0101039	0.00000089	2.65
8	91	4.43	0.46	0.0254	0.13	198	71	0.00004	0.0191454	0.00000089	2.85
9	83	2.89	0.475	0.0285	0.1	174	80.6	0.00005	0.0093079	0.00000089	2.52
11	94.5	3	0.4	0.029	0.09	175.9	91	0.00005	0.0081842	0.00000089	2.65
11	94.4	4.2	0.45	0.053	0.09	188	70.6	0.00005	0.008085	0.00000089	2.63
12	89.9	4	0.489	0.056	0.09	183.7	69.7	0.00005	0.0084322	0.00000089	2.7
13	92.4	5.9	0.503	0.0744	0.11	183.6	60.6	0.00005	0.013189	0.00000089	2.78

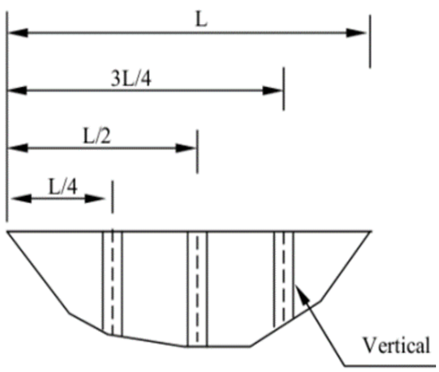

Fig. 3 Selection of sampling verticals [9].

for the entire cross-section. The laboratory work at the Civil Engineering College/Wassit University conducts sieve analysis and hydrometer tests on the bed material samples to measure the suspension sediment concentration at each section.

4. Developing a New Formula

Suspended sediment in the adopted reach of Al-Gharraf River is a consequence of various influencing parameters contributing to sediment transport in this area. These parameters include; water flow properties, sediment material properties, and geometrical variables of the cross section. According to well-known background knowledge related to sediment transport in rivers, these parameters have a direct influence. Table 1 summarizes the site measured data (Q, h. v, b. A, S), results of laboratory (ws, d_{50}, c_g) works and related parameters for the thirteen cross sections undertaken. The volumetric suspended sediment transport rate is basically depended on the aforementioned influencing variables as listed in functional relationship in Eq. (1) below:

$$(h, V, \rho, b, w_s, g, q, \upsilon, \rho_s, d_{50}, c_g) \qquad (1)$$

Where:

h = current average depth (m)

V = current average velocity (m/sec)

ρ = water density (kg/m^3)

b = top width of the channel (m)

w_s = fall particle velocity (m/s)

g = acceleration of gravity (m/sec^2)

q_s = volumetric suspended sediment transport rate (m3/s/m)

υ = water kinematics viscosity (m^2/sec)

ρ_s = sediment density (kg/m^3)

d_{50} = median diameter (m).

c_g = weight concentration (mass of suspension of sediment transported in a unit flow volume, (kg/m^3)

From the functional relationship Eq. (1), it can be adopted some convenient dimensionless parameters related to the case study; these are:

$$ØS = \frac{qs}{\left(\left(\frac{\rho s}{\rho} - 1\right) g\right)^{0.5} d_{50}} \qquad (2)$$

$$D_* = d_{50}\left[\frac{(\frac{\rho s}{\rho}-1)g}{\upsilon^2}\right]^{0.3} \quad (3)$$

$$\Theta_{cr} = \frac{ws^2}{\left(\frac{\rho s}{\rho}-1\right)gd_{50}} \quad (4)$$

$$c_v = \frac{c_g}{\rho s} \quad (5)$$

$$q_s = c_v * q \quad (6)$$

$$\emptyset_s = f\left(D_*, \Theta_{cr}\ , \frac{b}{h}, \frac{v}{w_s}\right) \quad (7)$$

So,

$\emptyset_s$: Transport rate parameter

D_*: Particle mobility parameter

Θ_{cr}: particle mobility parameter for initiation of suspension

The study used the above dimensionless parameters because their form contains most of the influencing of Eq. (1) and simplifies the setup of a deterministic formula. The purpose of an empirical formula is to minimize the need for extensive field measurements. This can be achieved by limiting the measurements for the river (width, flow depth, average current velocity, and the median particle size of the bed material). After performing regression analysis, a determination coefficient was derived with an R^2 value of 0.96.

$$\emptyset_S = 0.99[\frac{V}{w_S}]^{1.9} * \frac{1}{\left[\frac{b}{h}\right]^{1.07}} * \left[{\Theta_{cr}}^{0.678}\right] * \frac{1}{\left[{D_*}^{0.92}\right]} \quad (8)$$

Where:

$$w_S = \left(\frac{(S-1)gd_{50}}{18v}\right) \quad 0.001 < d < 0.1mm \quad (9)$$

$$w_S = \frac{10v}{d_{50}}\left[\left(1+\frac{0.01(s-1)gd_{50}}{v^2}\right)^{0.5} - 1\right] \quad 0.1 < d < 1mm \quad (10)$$

5. Test the Efficiency of the Proposed Formula

Three formulas have been used to estimate the rate of suspension sediment these are; Bagnold [2], Van Rijn [6], and Daham [7]. Bagnold [2], Van Rijn [6] are adopted as a universal to clarify their reliability for use as deterministic equations, specifically for the current study section. While for Daham's [7] formula, its selection as an equation was derived from a previous study on Al-Garraf River. These formulas were tested using measured data to prove the reliability of using as the deterministic equations to calculate the amount of suspended sediment transport in the river undertaken. Thus, the possibility of adopting them as a predictive formula has been focused, by comparing their outputs with the outputs of the new equation proposed for the current study. To determine the efficiency of the selected formulas, their results are compared with the observed (measured) sediment discharge in the reach of the study using statistical methodology.

5.1 Comparison Using Statistical Relations

With measured values, three methods were used in the study to evaluate the performance of each formula by comparing them.

A: Mean Standard Error

Due to the high difference between predicted and measured sediment rates at various intervals, a mean standard error was used to test the accuracy of the new suggested formula [8].

$$MNE = \frac{100}{N}\sum_{i=1}^{n}\left|\frac{So-Sc}{Sc}\right| \quad (11)$$

MNE is the Mean Standard Error, S_o is the observed sediment rate, S_c is the predicted sediment load, and N is the number of expected values. In this method, a lower statistical criterion (close to zero) shows a higher accuracy in model performance.

B: Discrepancy Ratio, which is a ratio used to test the accuracy of the computed and measured values [9].

$$\text{Discrepancy Ratio (DR)} = \frac{\boldsymbol{computedq_s}}{\boldsymbol{measuredq_s}} \quad (12)$$

C: Root Mean Squared Error

The Root Mean Square Error (RMSE) calculation is widely used to analyze errors. It accurately measures the magnitude of the deviation between an estimated (measured or calculated) value and the actual value being sought. The RMSE has the same units as the measured and calculated data; smaller values indicate better agreement between the measured and calculated values [10].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(So - Sc)^2}{N}} \quad (13)$$

In which: S_o observed sediment rate, S_c Is the predicted sediment load, and N is the number of expected values.

6. Results and Discussions

After applying Eq. (8) to determine the transport rate parameter, the volumetric suspended sediment transport rate (q_s) calculated by using Eq. (2). Fig. 4 illustrates the scattering the calculated and observed of suspension sediment. The figure shows that the data is closely distributed around a straight line, indicating high similarity between the calculated and measured data.

To verify the proposed formula, some of the field measurements were previously conducted at some sections of AL-Gharraf River by Daham and Maatooq et al. [7, 9]. These data were used to verify the reliability of Eq. (8) for calculating the suspended sediment transport within the studied reach of the river. To verify the proposed formula, the sediment discharge of AL-Gharraf reaches for the selected three cross section from the present work and from previous aforementioned studies are calculated and scheduled in Table 3.

Table 2 Observed and predicted values of sediment discharge for 13 sections.

Sec.	Observed Qs(kg/s)	Predicted Q_s via New Formula (Eq. 5.12)
2	1.74	1.74
3	1.73	1.78
4	1.06	1.08
5	2.25	3.24
6	2.14	2.35
7	2.43	2.26
8	2.31	2.52
9	2.41	2.02
10	4.79	4.43
13	6.58	5.64

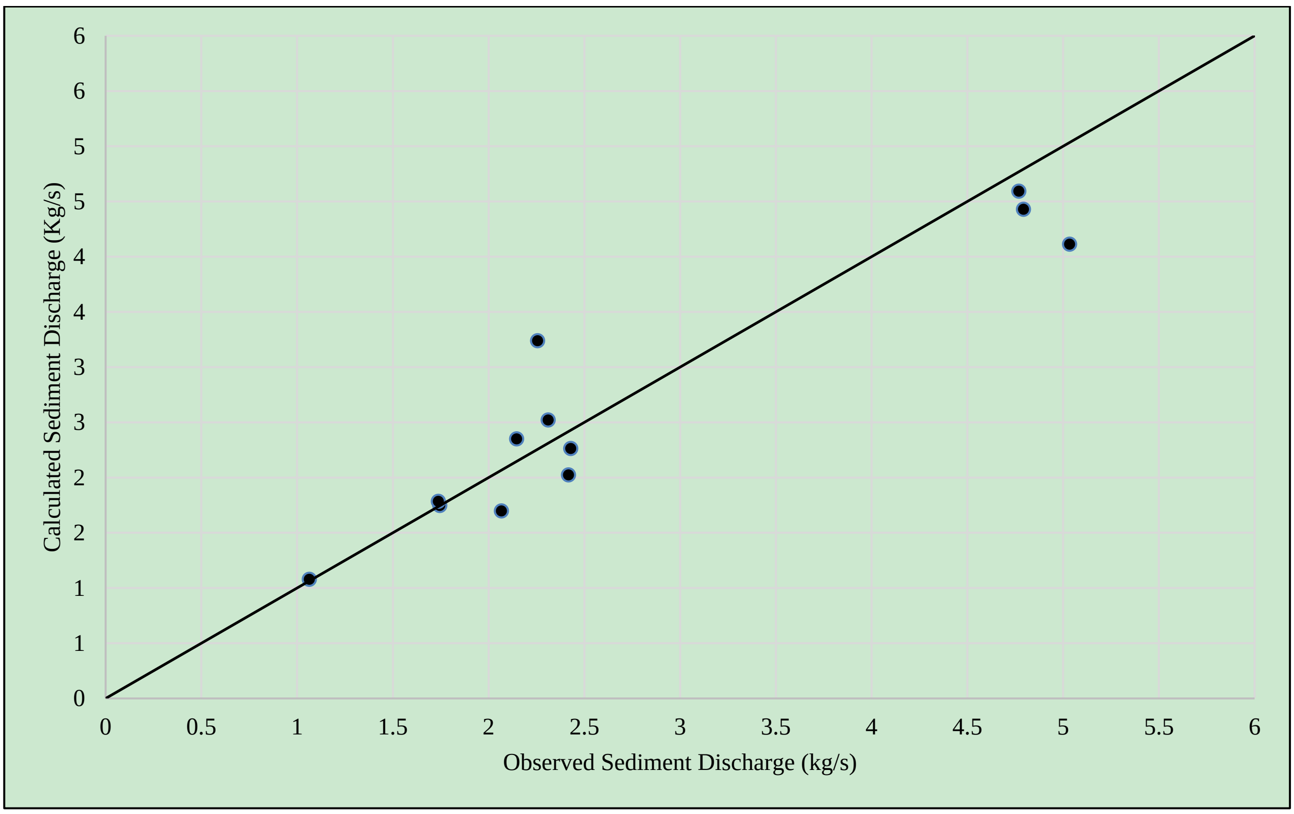

Fig. 4 Comparison between measured and computed sediment load using the new formula.

Table 3 Observed and predicted values of sediment discharge by new formula.

Reaches	Section No,	Observed values Qs (kg/sec)	Computed values Qs (kg/sec)
Three section of al-Gharraf River (2023)	1	2.07	1.69
	11	4.77	4.59
	12	5.03	4.11
Al-Gharaf River [9]	1	18.04	12.55
	2	15.58	16.23
	3	21.49	12.95
	4	15.86	11.91
	5	14.94	12.33
	6	12.83	18.41
	7	13.77	8.41
	8	11.88	10.01
	9	11.98	15.34
	10	8.97	5.87
	11	7.04	7.96
	12	4.31	1.69
	13	5.71	2.20
Al-Gharaf River [7]	1	22.5	14.49
	2	20.5	11.17
	3	17	17.09
	4	19	15.32
	5	11.6	12.50
	6	8.5	10.47
	9	8.5	10.17
	10	8.4	6.43
	11	8.4	8.33
	12	8.4	7.77
	13	10	6.96
Al-Gharaf River (2023)	2	1.75	1.67
	3	1.82	1.71
	4	1.06	1.03
	5	2.26	1.94
	6	2.15	1.52
	7	2.15	2.05
	8	2.31	2.74
	9	2.42	1.94
	10	2.37	2.41
	13	5.03	3.94

Fig. 5 demonstrates that the data of Daham [7] and Al-Gharraf (2023) were distributed closely around the straight line. Based on the figure, it can be observed that the results of the new formula are concentrated around the bottom of the straight line. At the same time, Daham [7] is dispersed at the beginning and middle of the line, while Maatooq & Omran [9] distributed under the line. Maatooq et al. [9] examined the River's sedimentary conditions at a low discharge rate of not more than 45 m^3/s, at shallow depths, at low velocity, and at the other section of the River that the present thesis are studied, therefore, it is noted that the calculated values by new formula don't completely match the observed values of sediment discharge where the mean standard error was 18.1%. However, for sediment transport calculation by the related deterministic equation, this discrepancy is acceptable, as indicated in many previous studies and mentioned by Van Rijn [6]. On the other hand, Maatooq et al. [9] study area was located in Dhi-Qar Governorate, between Al-Nasr City and Al-Bada cross regulator, approximately 150 km away from the head regulator at Wasit Governorate, where the sediment amounts are higher. Daham [7] studied the upper part of the river which is the same area as the current study, in addition, the flow velocity ranged between 0.21 to 0.5 m/s in Daham [7] and 0.21 to 0.6 m/s in Al-Gharraf (2023), so there is well agreement between observed and calculated values of sediment discharge by the new proposed formula, where the Mean Standard Error was 6%. Daham [7] study cured during the winter season with high discharges of up to 250 m^3/s. On the other hand, this study was conducted during the summer season, with a discharge rate not exceeding 100 m^3/s and under steady flow conditions.

Three formulas have been used to estimate the rate of suspension sediment these are: Bagnold [2], Van Rijn [6], and Daham [7]. These formulas were tested using measured data to prove the reliability of using as the deterministic equations to calculate the amount of suspended sediment transport in the river undertaken. The results of the rate of sediment as computed by the previous three formulas are listed in Table 4 to evaluate the performance and reliability of each formula, the following statistical indicators were calculated, Discrepancy Ratio (DR), Mean Standard Error (MSE), and Percentage of Error. The comparison results of Discrepancy Ratio (DR) are shown in Table 5, which represents the discrepancy ratio in the range of 0.75-1.25,

Fig. 4 Comparison results of using the new empirical formula on the sedimentation data of Al-Gharraf River by other researchers.

0.5-1.5, and 0.25-1.75 which was adopted by some researchers (e.g., [8] and [9]). The new suggested formula performed best in the study reach, followed by Daham [7], as the value of the new formula is closer to 1. It is clear from Table 6, that the new formula has (MNE) equal to 5.8%, which is much less than (MNE) of Bagnold and Van Rijn formulas. Then comes Daham [7] formula, which had a Mean Standard Error of 9.09%, because Daham ([7] formula and the new formula were conducted on the same reach of Al-Gharraf river. The Mean Standard Error for Van Rijn [6] formulas was found to be 100%, indicating a complete deviation of the calculated sediment discharge from the observed sediment discharge. In contrast, the Mean Standard Error for Bagnold [2] formula stood at 77%, suggesting that its accuracy is just 33%. On the other hand, the Mean Standard Error for the new predictive formula was recorded at 5.8%, reflecting an accuracy of 94.2%. This indicates that the new predictive formula performs well in predicting the suspended sediment load. The computation of percentage of error results are listed in Table 7 for comparison purposes. It is clear from Table 7 that the proposed equation gives quite a good percentage of Error compared with the others. As noted from the data percentages included in Table 7 that the error rate does not exceed 20% when using the new equation proposed by the current study. In the table, it is noted that 70% of the calculated values fell within an error margin of no more than 10% compared to the measured data, while less than that, about 30% of the calculated values, fell within the 20% margin of error.

Table 4 Predicted values of suspended sediment discharge by the previous formulas compared with the measured at thirteen sections undertaken.

Sec	Observed Qs (kg/sec)	Van Rijn (1984b) (kg/s)	Bagnold (1966) (kg/s)	Daham (2021) (kg/s)
1	2.06	3.13	4.09	1.23
2	1.74	82.27	5.07	1.95
3	1.73	1.32	3.42	2.15
4	1.06	0.38	1.46	2.58
5	2.25	9.53	2.43	2.19
6	2.14	3.75	3.22	1.00
7	2.43	3.14	3.18	1.89
8	2.31	5.60	3.38	2.35
9	2.41	8.41	5.11	1.31
10	4.79	49.25	6.14	1.631
11	4.77	7.67	7.01	3.55
12	5.03	5.02	7.67	3.45
13	6.58	9.34	8.13	5.75

Table 5 Comparison discrepancy ratio between the computed and the measured values.

Formula	Discrepancy Ratio		
	0.75-1.25	0.5-1.5	0.25-1.75
Van Rijn (1984b)	0%	38%	61%
Bagnold (1966)	14%	50%	75%
Daham (2021)	46%	54%	85%
New Formula	100%	100%	100%

Table 6 Mean standard error.

Formula	Mean Normalized Error
Van Rijn (1984b)	80%
Bagnold (1966)	77%
Daham (2021)	10%
New Formula (Eq. 5.12)	9.6%

Table 7 Percentage of error comparison.

Formula	percentage of Error									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Bagnold [2]	0%	7.6%	0%	7.6%	23%	15%	0%	7.6%	7.6%	30%
Van Rijn [6]	7.6%	0%	7.6%	0%	15%	7.6%	15%	7.6%	0%	38%
Daham [7]	15%	54%	47%	22%	7%	0%	0%	0%	0%	0%
New Formula	70%	30%	0%	0%	0%	0%	0%	0%	0%	0%

7. Limitation of the Predicted Formula

The developed transport formula was established using data measured during the period available for field work. The formula was derived using the data of ten cross-sections, and then it was validated using the data of the other three stations. The computed formula is applied to the rivers that have the following criteria:

- The flow rate values ranged between (76 to 98) m^3/s.
- The range of the flow depth and the average bed slope of the river were 2.8-6 m and 4-5 cm/km, respectively.
- The velocity values ranged between 0.21-0.60 m/s.

8. Conclusions and Recommendations

After analyzing data from 13 cross sections of Al-Gharraf River, the following conclusions are derived:

It was concluded that there are significant sediment discharges in various sections along Al-Gharraf River reach within the Wasit Governorate. This conclusion was reached after conducting field integrated sampling for suspended sediment for thirteen sections along with sampling of bed material.

analysis indicated that the riverbed soil primarily comprises sand, silt, and clay. Most of the bed material is sandy, with a median grain size of 0.08-0.13 mm.

A new formula produced a mean standard error of 5.8%, a discrepancy ratio of 100% within the range of 0.25-1.75

According to the study, the estimated annual total sediment transportation was approximately 86246 tons for the selected reach of the above river.

It is recommended to use the new empirical formula to determine sediment concentrations for various sections of the river. This equation has demonstrated its validity when applied to data from other researchers and different sections of the river.

Studying the sediment transport along Al-Gharraf river. More research is needed to present a suitable river training configuration that minimizes sediment transport in the channel. Studying the effect of scouring, deposition, and other morphological parameters through the study reach.

Acknowledgements

The authors are grateful for the scientific support towards this research by the Civil Engineering Department, University of Technology, Baghdad, Iraq.

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