Spatial total load rating curve for a large river: A Case study of the Tigris River at Baghdad

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Spatial total load rating curve for a large River-Reach: A Case study of the Tigris River at Baghdad

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Spatial total load rating curve for a large River Reach: A Case study of the Tigris River at Baghdad

Abstract

The Tigris River in Baghdad is a large broad sand-bed river of which is supply limited of sediment transport due to resulting from the implementation of a water flow regulation scheme comprising a series of reservoirs and barrages. Therefore, the significant tremendous reduction in the flow turns the water discharge has affected the hydraulic performance of the river and turned it into an under-fit river of complicated morphology where—many islands and bank deposits have been showed up across an 18km reach in addition to the essential sinuosity. Measuring sediment load at individual cross section cross-sections in the river gives misleading estimates and the corresponding sediment rating curve has a locally limited using prediction. A spatially sediment rating by investigating sediment loads over the complicated reach is required to overcome the local limitations. Sediment transport rates have been investigated at 16 cross section cross-sections along an 18km study reach of the River Tigris within Baghdad river by collecting suspended load, bed load and bed material samples. The velocity profiles and the water discharges were measured using by means of at the sampling stations using an Acoustic Doppler Current Profiler (ADCP) at the sampling sections. The measurement results indicated that the suspended load is the dominant mode of transport (93.5%). However, bedloads were taken in consideration to determine the total loads. The average annual transport rate during the period 2009-13 was estimated at 3.21 million tons. A spatial total load rating curve in the form of a power function was established and examined against the sediment measurements beside. Twenty-two previously published total load formulae where also applied at the same sections and of these to the same reach. The Colby 1964 formula gave the closest fit results to the actual measured loads. According to the final comparisons results obtained, it Based on
the results from this study are recommended to use the proposed procedure is established for using establishing a spatial total load rating curve to estimate sediment transport rates for similar morphologically complicated rivers. The results suggest that average annual transport rates during the period 2009-13 was estimated at 3.21 million tons. The annual transported quantities of the total load were estimated at 2.47 and 4.23 million tons for 2009 and 2013 respectively. 

Keywords: Sediment sampling; Total sediment load; Sediment rating curve; Spatial variation; Supply-limited; Under-fit river; Tigris River.

1. Introduction

Watershed: The eroded soils erosion from watershed, migrating stream channels and often accelerated by streams and due to human activities interventions, are the main sources of fluvial sediments (Vanoni, 2006). Since these sources of sediment are virtually unlimited, and the capacity of the streams are sufficient to mobilise it, sediment transport will continue (Friend, 1993). Construction of large dams traps the sediment from the watershed causing aggradation upstream of the dam whilst the released water from the dam is almost sediment-free; causing degradation of the river downstream of the dam (Meade and Moody, 2010; Kondolf, et al., 2014; Issa, 2015). Total flow downstream is also often diminished as barrages on the rivers divert part of the river flow away thereby reducing transport capacity causing aggradation downstream. Therefore, permanent regulation schemes on river systems and/or climatic changes, particularly in regions of low precipitation, will disturb the water flow and sediment supply, and this will subsequently lead to changes in the river course, its dimensions and characteristics and will negatively impact the supply of sediment which may lead to under-fit conditions, such as in the case of the Tigris River in Baghdad (Ali, 2016). A supply limited condition of limited supply of fine sediment is often the case in most natural rivers (Hickin, 1995), so, bed-material is being the main source of the
sedi-ment load that affects their morphology, erosion, deposition and migration (Turowski et al., 2010).

Predicting the sediment load is of primary importance for river engineering and geomorphology (Madej, 2001; Parker et al., 2007; Recking, 2009). The sediment rating curves are the commonly used predictor that is used for estimating sediment transport as well as other in addition to various prediction formulae. Sediment rating curves can be used for reconstructing long-term sediment transport records or estimating loads carried during gaps compensating for missing data in existing sediment transport records (Walling, 1977b; Asselman, 2000) as well as being in addition to using them to define as a boundary condition for estimably sediment load estimation in morphological models. Usually, one cross section is considered sufficient for measuring the total load in rivers and the bed load is taken as a fraction of the total load or even ignored (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Whipple and Tucker, 2002; Brocard and van der Beek, 2006). In morphologically complicated rivers, such as in under-fit rivers, considering an individual cross section as a reference point for sediment measurements for the whole reach in order to build the sediment rating curve with the sense of local erosion and sedimentation, can be spatially misleading because of localised erosion and sedimentation.

The bulk of the sediment load is transported will occur in two modes; in suspension for the finer particles in suspension, which are affected by the flow turbulence, and in contact with the bed for the coarser particles in contact with the bed which are sliding, rolling or saltating according to the boundary shear stress conditions (Hickin, 1995; WMO, 2003). Direct measurements of the total sediment load requires measuring the two components of the load simultaneously. The bedload can be measured directly using pressure difference type sensors, basket type samplers, pit type samplers or more
sophisticated techniques (UNESCO and IRTCES, 2011). The Helley-Smith sampler, which is a direct method belongs to the first type, is a manually operated portable sampler (Diplas et al., 2008) that is specifically designed to measure the transport of coarse material in rivers (Helley and Smith, 1971). Different approaches can be used for measuring the suspended sediment concentration within the water column, such as depth-integrated method or point-integrated methods (Edwards and Glysson, 1998). The traditional sampling techniques of the sediment are the bottle and trap technique and pumping techniques.

Acoustic samplers and optical samplers are other kinds of sampling techniques for measuring suspended sediment concentration and load (van Rijn, 1993). Sampling of bed material can be achieved by scooping, dredging, grabbing or core sampling (van Rijn, 1993).

In this research, an attempt to establish a sediment rating curve that can spatially represent the total transported sediment load at a reach of Tigris River in Baghdad was achieved. By considering 16 cross-sections for sediment load measurement along an under-fit river reach of 18 km in length can help in overcoming the spatial variation of local erosion and sedimentation conditions. In each cross-section the sediment bedload and suspended loads were measured spatially at 16 cross sections along a reach of Tigris River in Baghdad of 18 km in length in an attempt laterally using the Helley-Smith sampler and suction pump respectively to compute the total sediment load directly using field measurements.

A comparison of total load and field measurements with twenty two pre-existing sediment load mathematical formulae was held to achieve the best formula can use for the river reach indirectly using mathematical formulae. Flow reduction and the current source of sediment supply were considered as major factors affecting the total sediment load in the reach. Finally, a spatial sediment rating curve was established for the under a condition of...
fully controlled flow, under-fit Tigris river in Baghdad and compared with a number of the prediction formulae.

2. Literatures Review

2.1. Local Studies

Geohydraulique (1977) conducted a training study of the Tigris River (Iraq) to improve the river flow conditions and specify the flood capacity of the river in Baghdad. The study included field measurements of flow and collected suspended load samples and bed material samples spatially at three cross-sections and temporally on six occasions. The analyses of sediment samples showed that the concentration of the suspended sediments were relatively ‘low’ and did not reach as high as 3 g/l throughout the whole period, whilst it was less than 0.2 g/l during low flow periods. They developed a sediment rating curve based on their measurements.

Al-Ansari et al. (1979) applied nine prediction formulae of sediment discharge to the Tigris River (Iraq) at the Sarai Baghdad gauging station. They used the geometry and hydraulic conditions obtained from Geohydraulique (1977) and direct suspended sediment measurements for the period 1969-1975. They proposed using the Yang1973 formula as the closest predictions to the actual measurements where it was estimated that sediment transport rates were ~ 4.6 million ton/year in average.

Al-Ansari and Toma (1984) studied the morphology of the Tigris River (Iraq) between the Al-A’ameh and Al-Sarafiya Bridges (4.7 km reach length). They collected bed material samples along the reach and from the islands. They found that the changes in the geometry had a meandering planform and a meandering sinuosity form. The bed material was a mixture of coarse, medium and fine sand with traces of clay whilst the clay proportions increased on the islands and in the river banks.
Al-Ansari et al. (1986) observed the suspended and solute loads of the Tigris River at Sarai Baghdad continuously for the period 1983-1985 which was considered as a dry period. They concluded that the average daily discharges of suspended and solute loads were 30,000 ton and 40,000 ton respectively.

Khalaf (1988) also studied sediment transport in the Tigris River in Baghdad. He measured suspended load at two gauging stations different sections. He also collected bed material samples from these stations to find out the type of bed sediment. He combined his measurements with the available historical records for suspended load starting from the year 1953 to find out the best of 14 prediction formulas between fourteen sediment estimation formulas. He concluded that the Laursen’s (Year? 1958) and modified Yang’s (1964) formulas with slight adjustments gave the best predictions for the sediment load. He attempted to develop a new prediction formula based on using the dimensional analysis concepts techniques and physical arguments by identifying the major significant parameters those control sediment transport in rivers. His formula is mainly related to the incorporating mobility index and boundary effective shear stress.

Hobi (2010) measured the suspended sediment load in the Euphrates River (Iraq), downstream of the Kuffa Barrage, using a point-integrated sampling method. He compared his measurements with the prediction of sediment transport using of a 3D morphodynamic model for different scenarios of operation. He proposed an operation scenario to reduce the trapped sediment in the barrage.

2.2. International Studies

Walling (1977a) derived several power function rating curves for the Creedy River in England, depending on the season and river discharge stage. He also estimated the errors produced from using them by comparison with a 15 minute record of stream turbidity.
Fenn et al. (1985) conducted an evaluation for using a standard ordinary least square regression technique for deriving rating coefficients from different grouped observations according to seasons and climatic conditions.

Van Rijn and Gaweesh (1992) measured the total load of sediment in different cross-sections of the Nile River (Egypt) downstream from the Aswan Dam using a total sediment load sampler that had been designed to measure the bedload and the suspended load simultaneously. The median particle sizes of the sand bed were in the range of 300-500 µm. The average cross-section velocities were in the range from 0.5 m/s to 1 m/s. They found that the sampling efficiency was slightly larger than unity (1.2-1.4) for low velocities.

Asselman (2000) used different fitting procedures to derive power function sediment rating curves for many locations along the Rhine River and its main tributaries; she related the differences in the rating curves coefficients to watershed characteristics.

Baranya (2009) conducted a hydrodynamic survey of a 6 km long reach of an entirely sand bed reach of the Danube River (Hungary) by means of Acoustic Doppler Current Profiler (ADCP) to estimate the hydro-morphological parameters of the reach and apply the used analysis of ADCP backscatter data for the estimation of suspended solids concentration. He analyzed the uncertainties arising from both the measurement method and the data processing applied.

Latosinski et al. (2014) corrected the ADCP backscattered signals from measurements in four zones in the Parana River (Argentina) and calibrated them with the concentration of the suspended bed-sediment that was measured using a depth-integrated sampler. They found differences of less than 46% in the results assessed using moving-boat ADCP measurements with the total suspended load of bed sediment measured using traditional methods.
2.3. Tigris River

The Tigris River is one of the most important rivers in the Middle East. It rises from the Taurus Mountain range in the south-eastern part of Turkey and flows toward the southeast for 1580 km, passing through the Turkish- and Syrian borders and before entering Iraq. In Iraq, it flows to the south until it combines with the Euphrates River at Qurnah, that eventually forming the Shatt Al-Arab River which discharges its water into the Arabian Gulf (Fig. 1).

Within Baghdad City, the capital of Iraqi capital city, the Tigris River bisects Baghdad into two parts for a distance-length of about 50 km within the urban zone. The northern part of the Tigris River reach extends for 18 km length from Al-Muthana Bridge at-in the north to the Sarai Baghdad gauging station at the center-centre of Baghdad (Fig. 2), which This was selected as the study reach used in this work. This reach has a single thread, compound meanders, and general alluvial plain characteristics. The river banks are protected against erosion by aligned stones and cement mortar between levels 29 and 37 m.a.s.l. at the beginning of the reach and drop gradually to the south. Recently, the dominant water levels in the reach are have always been below the protection level (Ali, 2013).

The study reach has exhibited many growing islands, side and point bars in the river course, mainly developing during the last two decades (Fig. 2). A study by Ali (2016) regarding predictions of the river bed changes showed that the Tigris River has behaved like an under-fit river to adapt with its current hydrological condition. It deposits sediment on the shallow part of the cross-section slowing with low flow velocity, and deepens the incised route, leaving much of the former wide section as a bankfoot floodplain for the newer recessive river (Ali, 2016).

This pattern of erosion and sedimentation has impacted the hydraulic performance of the river, such as by reducing the flooding capacity, flow, causing impeding navigation and...
reducing the efficiency of water intakes of water treatment plants, as well as other environmental and aesthetic impacts (Ali et al., 2014).

The sediment observations in the Baghdad reach are available for the period between 1953 and 1982 (Geohydraulique, 1977; Khalaf, 1988). The measurement of the sediment load was stopped at a time coinciding with the construction of the distant upstream Mosul Dam on the river. Some attempts were made to measure the sediment load for short periods of time in 1983 and 1987, for research purposes (Khalaf, 1988). Thus, there is a lack of continuous data on the sediment load of the river since 1988, which is required, resuming the measurements and evaluating the sediment load essentially after damming the Adhaim Tributary, the closest upstream tributary to Baghdad, in 1999.

All previous measurements of sediment load in the Tigris River included only the suspended load exclusively while there was no attempt to measure the bedload in the past.

2.1.3.1 Flow Regulation and its Effect on Sediment Supply

The flow of the Tigris River is fully controlled in Baghdad by a system of dams and regulators constructed on the main river and the tributaries upstream of Baghdad (Fig. 3). These regulating schemes have decreased the average monthly discharge of the river from 1207 m$^3$/s for the period 1931-1959 to 927 m$^3$/s for the period 1960-1999, the period during which major dams and regulators upstream of Baghdad were constructed, according to the records obtained from the Sarai Baghdad gauging station (Fig. 4). Furthermore, for the period 2000-2013, the average discharge has been lowered further to 522 m$^3$/s.

The flow hydrograph at Sarai Baghdad (Fig. 5) shows that the maximum flow takes place during April and May in the past. Most of the sediment was transported in that period (Al-
Ansari et al., 1979). In addition, these flow peaks were washing out the accumulated sediment in the river reach in Baghdad. After implementing the regulation scheme in Iraq and Turkey in addition to the effect of the dry climate period (Al-Ansari, 2013 and 2016; Al-Ansari et al., 2015), these seasonal peaks have been diminished gradually in the Tigris River since 1990. As a result of flow attenuation, there are no more peaks that no systematic disturbance to the recent trend of sedimentation is likely to occur in the river segment.

At a glance on There has been a significant effect of the implemented regulation scheme on the delivery of sediment from the headwater catchments, as the trapping efficiency for sediment particles by dams has reached up to 95.33% at the Mosul Dam reservoir on the main river (Issa, 2015), where the total delivered sediment inflow into the reservoir was 1.19 km³ between 1986 and 2011. Accordingly, the rate of sedimentation in Mosul Dam reservoir is 4 ton/s assuming a sediment density of 2650 kg/m³.

The remaining uncontrolled source of sediment that can be delivered to Baghdad is the restricted area from the lower sub-basin of the Adhaim tributary and the catchment between the Samarra Barrage and Baghdad (the area bounded by the dashed green polygon in Fig. 3), as well as the erosion of river bed and banks. Most of the year, the flow of the Adhaim Tributary is extremely low (about 5 m³/s), while during the rainy season, which is usually between January and April, the discharge might reach 200 m³/s. The upper part of the catchment area of the tributary is composed of sandstone and limestone, while in the lower parts of the catchment, the river flows in alluvium (silt and clay) areas (Malaz et al., 1982). These areas do make available sediment that can be delivered to Baghdad during high flow events.

The delivery of sediment from the Adhaim Tributary has not been measured, but looking at a glance on the possible extra flow contribution (rather than the flow that released from
the Adhaim Dam) can give an indication of the amount of delivered sediment delivered from this tributary. The extra contributions of flow from the Adhaim Tributary sub-basin and the back feed from the Tharthar Lake toward the Tigris River were determined using the mass balance concept. That contribution did not exceed 260 m³/s during 2004-2005, which was a moderate flow year compared with recent drought years. As an average, the extra contribution was 8% of the average monthly discharge at the Sarai Baghdad gauging station for the same year. So, with all this evidence, the river was considered as being a limited source of sediment supply before entering Baghdad, and the bed sediment has to be considered as the main source of transported sediment.

2.2.3.2 River geometry and bed composition

The study reach consisted of a series of 7 meanders (see figure Fig. (2)) with radii of curvature ranging from 475m to 1245m (University of Technology-Iraq, 1992). Along the 2nd and 3rd meanders, there are two islands have grown and there are several areas of bank deposition. The morphology and bed sediment of the river inside Baghdad were investigated several times by Geohydraulique (1977), Al-Ansari and Toma (1984), Khalaf (1988), University of Technology-Iraq (1992) and recently 46 bed samples were collected along the northern reach in Baghdad using a van Veen grab (Al-Ansari et al., 2015). The grain size of the sediment was analysed using sieves and the hydrometers test. It was noticed that fine sand dominated the bed with an average median size of 0.178 mm. The size of the bed sediment relatively has decreased compared to less than in earlier investigations (see Al-Ansari and Toma, 1984). In addition, the sediments were moderately well sorted, finely skewed and leptokurtic (Al-Ansari et al., 2015).

Geohydraulique (1977) concluded that the Tigris River sediment is “bed-load” (bed-material load), since the suspended load concentrations never reached 3 g/l in high...
and never exceeded 0.2 g/l in low water periods.

3.4 Methodology

3.4.1 Sediment Sampling

Measuring the total load of sediment requires measuring the two components of sediment. The bedload, the part that moving in contact with the bed, can be measured using manually operated portable samplers such as Helley-Smith sampler (Diplas et. al., 2008), while different techniques can be used for measuring the suspended sediment along the water column, such as depth-integrating sampling or point-integrating sampling (Edwards and Glysson, 1998). Sampling of bed material can be done by scooping.

The suspended load and the bed load were measured spatially at 48 sampling points distributed over the quartiles (the right, the center and the left of the cross-section) at 16 cross-sections along the study reach of 18 km in length (Fig. 65). These cross-sections were chosen to reflect different morphological conditions in the river (six sections in a straight portion, four of them in depositional sites or sand bars, and ten sections in meanders with, two of them at islands sites). All sediment samples were collected at the same time day for each cross-section.

The limitation of sampling points to three at each cross section was due to the limited period of the security permission that the authors got to navigate the river for conducting bathymetric survey and collecting sediment samples. The difficulties that the author has faced in the field work were mainly related to safety and security issues.

Ten days were required to complete the sampling procedure for the entire study reach in ten days. The water discharges were measured by ADCP and they ranged between 445 and 650 m³/s and the corresponding average velocities were between 0.51 to 0.76 m/s during the sampling period. This range of discharges is...
considered as an acceptable representative of the current hydrological conditions according to the flow hydrograph of the river (Fig. 5).

A Helley-Smith bedload sampler was used to measure the bedload. At each sampling point, five repetitions of sampling integrated over 60 seconds were conducted at the same sampling time to overcome temporal variations in bedload transport with the presence of ripples and sand dunes. For one sample (referred to as a Zero-time sample), the sampling time was zero and the sampler was lifted to the surface immediately after it had contacted the bed. This was undertaken at all were collected at sampling points to overcome the initial and possible 'scooping' effect of the sampler and the scooping effect of the sampler on the bed.

For the suspended load, a point-integrated sampler using a suction pump and a flexible hose was used to collect 212 water samples of 500 ml volume at several depths in the water column. The number of samples taken at each sampling point was chosen depending on the depth of the water; the higher the deeper the water column, the higher the number of samples as indicated in Table (1).

The sampler was designed to be isokinetic by selecting the intake nozzle diameter (8mm) and the pumping rate of discharge (130 litre/hr) to produce a suction velocity of (0.718 m/s) close to the ambient velocity of the stream. As well as, the suction velocity was higher than the settling velocity of all particle sizes of the bed material. The intake nozzle of the sampler was oriented with the flow direction in a way similar to that as used in the Delft-Nile sampler of Van Rijn and Gaweesh (1992). The sampler was cleaned out from any remaining of the previous samples before between every new sampling by discharging the retained water in the pump and the hose.

Velocity profiles at sampling points were determined from the readings of ADCP according to the location of the sampling point in the cross-section. Repetitions
of ADCP readings were used to smooth the velocity profile when the Doppler reading was sharp and diverged from the logarithmic profile.

3.2.4.2. Calculations of Sediment Load

Water samples were filtered in the laboratory using slow filter paper of 2–4 μm retention. The moisture content of filter papers was determined in advance to neutralize it. After pouring the water sample gradually on the filter paper in the funnel, a vacuum was applied to accelerate the filtration. Then, the filter papers were then oven-dried in the oven at 70°C for 24 hr. The weights of retention weights of fine particles entrapped were determined and converted to sediment concentrations in (g/l) units. The grain size distribution of the suspended sediment samples couldn’t be determined for suspended sediment samples due to the low concentration of suspended sediment in the samples where the average concentration was 0.19 g/l and the maximum one was only 1.1 g/l.

The velocity measurements using ADCP gives the opportunity to measure the near-bed velocity and even bed-moving velocity (Atsuhiro et al., 2009). Even so, the uppermost 11 cm part of the velocity profile (between the water surface and the ADCP transducer) is the unmeasured part that was about 11 cm depth. On the other hand, the second unmeasured zone of suspended sediment was the zone near the bed where the sampler could not collect a sample. To compensate the both two unmeasured zones, the extrapolation techniques proposed by van Rijn (1993) were applied. According to van Rijn (1993), the velocity at the water surface was assumed equal to the closest measured velocity in to the surface of the water column, while the lower part of concentration profile was extrapolated by three methods (for details see van Rijn (1993)). The first method considered the sediment concentration on at the bed assumed to be was equal to that at the closest sampling point. The second method extrapolates the sediment concentration on the bed by a power formula. While The third method last one computes the sediment concentration on the bed from another...
The average of the three extrapolations has to be considered (see Fig. 76). These three extrapolations are described as follow:

- The sediment concentration on the bed assumed to be equal to the closest sampling point.
- The sediment concentration on the bed was calculated from the power formula $c = AY^B$

where:

\[ Y = (h - z)/z \quad \text{dimensionless vertical coordinate,} \]

\[ z \quad \text{vertical coordinate above bed,} \]

\[ h \quad \text{water depth,} \]

\[ A, B \quad \text{are coefficients determined by applying a regression method on the measured concentrations of the first three sampling points above the bed.} \]

- Selecting $B = 0.1$ to 5 varied by step 0.1

- Computing

\[ A = \frac{\sum (Y^B c) / \sum (Y^B Y^B)}{\sum (A Y^B - c)} \] ... (1)

\[ T = \sum (A Y^B - c) \] ... (2)

- Repeating the procedure for all the range of $B$. The $A$ and $B$ coefficients corresponding to a minimum $T$-value are selected as the "best" coefficients.

- The sediment concentration on the bed was computed from the exponential formula $c = e^{\sum E z + F}$

where:

\[ z \quad \text{height above bed} \]

\[ E, F \quad \text{are coefficients determined by applying a linear regression method on the measured concentrations of the first three sampling points above the bed.} \]

\[ E = \frac{\sum (z_k \ln c_k) - \sum (z_k) \sum (\ln c_k)}{\sum (z_k^2) - \left( \sum z_k \right)^2} \] ... (3)
The depth-integrated suspended sediment load \( g_s \) per unit width was computed as:

\[
g_s = \sum_{i=1}^{N} (v_i c_i + v_{i-1} c_{i-1})(z_i - z_{i-1}) / 2 \tag{5}
\]

where:

- \( v_i \): flow velocity at height \( z_i \) above the bed,
- \( c_i \): sediment concentration at height \( z_i \) above the bed,
- \( N \): total number of points along the water column including extrapolated and interpolated values.

Figure (87) shows the extrapolated velocity and concentration profiles at some selected cross sections. At each sampling point along the water column, the point velocity that obtained from the velocity profile was multiplied by the measured sediment concentration. Then the unit suspended load (per unit width) was calculated by applying the trapezoidal integration rule on the products of point velocity and point concentration throughout the water column. The total suspended load for the cross section \( G_s \) was determined by multiplying the unit suspended load by the corresponding width of the section portion. The results of these suspended load calculations were tabulated in Table (2).

From 240 bedload samples collected along the northern reach of the Tigris River, the masses of the replicated samples at each sampling point were averaged, and the masses of zero-time samples were subtracted from the averages for each according to its sampling point. The net average masses were reduced by 50% as due calibration studies by Emmett (1980) showed the trapping efficiency of the Helley-Smith sampler was, where the calibration studies have suggested about the sampler mentioned that its trapping efficiency is...
...about 175% for particles ranging between 0.25 and 0.5 mm (Emmett, 1980) and it is about it is estimated to be 200% for particles ranging between 0.125 and 0.25 mm (Emmett and Hubbell, 1977). The bedload masses were converted to bedload sediment discharges \( Q_bG_b \) and the results are also tabulated in Table (2).

The suspended sediment discharges \( G_s \) were combined with the bedload discharges \( G_b \) by direct summing of both sediment discharges at each cross-section to determine the total sediment loads \( G_t \) at 16 cross-sections along the northern reach as shown in Table (2).

### 3.3.4.3. Sediment Rating Curve

Prediction of sediment load is of prime importance for river engineering and geomorphology (Recking, 2009). It affects the driving fluvial processes (Cook et al., 2013). The sediment rating curve is the most common predictor used for estimating sediment transport as well as with other prediction formulas. The sediment rating curve can be used for reconstructing long-term sediment transport records or compensating for that which is missing data in existing sediment transport records (Walling, 1977b; Asselman, 2000). It is often used to provide as well as for using as a boundary condition in morphodynamic models.

The usual procedure to establish a sediment rating curve is by collecting sediment samples over a wide range of discharges at a certain-given cross-section of the river reach, and then using one of the regression techniques to determine the best coefficients of the rating equation which is usually takes the form of a power function form (Walling, 1977a; Fenn et al., 1985). Such a rating curve may be a good representative of sediment transport at the sampling location, but there is no guarantee that it will be as good as it is, where it is to be used if applied for other locations of different morphology.
Looking for a sediment rating curve that can be spatially reliable for a river reach of complicated morphology is preferable for river engineering and modelling especially when there is evidence of sedimentation processes occurring along that river reach. Such a spatial sediment rating curve can be used as a sediment inflow or outflow boundary condition in morphodynamic models at any cross-section along the reach. Instead of repeating sediment measurements at one location for a period of time, sediment samples will be collected from several locations along the river’s study reach, and this will represent the spatial variance in the topography, such as meandering, a riffle-pool, or an island, for that river reach on the condition that there is no tributary, distributary or regulator along that river reach. In addition, the sampling period has to include an acceptable range of water discharges from a hydrological perspective.

The sediment rating curves were established previously for the Tigris River inside Baghdad (Geohydraulique, 1977; Al-Ansari et al., 1979) using the suspended load measurements at three gauging stations (Sarai Baghdad, north of Baghdad and south of Baghdad) when none of the dams had been constructed yet on the main river in Iraq. After the start of the Mosul Dam operation on the Tigris River in 1986, a modification was applied to the sediment rating curve (Khalaf, 1988) depending on more measurements in the north of Baghdad gauging station. It should be mentioned, however, that historical records were still used. All these in each of these studies, used historical records in which the rating curves took the form of a power functions.

4.5 Results and Discussion

4.5.1 Total Sediment Load

The ratios of bedload to suspended load given in Table (2) show that the maximum percentage ratio was 6.5% and the minimum percentage ratio was 0.63%. These ratios indicate that suspended load is the dominant mode of sediment...
transport along-across the study reach and it is the possible that exchange between the bedload and the suspended load occurs depending on the hydro-morphological conditions at each cross-section. According to table (2), the sediment concentration drops sharply due towards the left bank sedimentation between CS2 and CS3, CD4-2 and CS5, CS11 and CS13. The dredging activities between CS2 and CS3 converted the segment to a sediment trap. The left side of CS3 was hidden by a huge bank deposition and the flow velocity was very low that was insufficient to hold the delivered sediment from CS2 (see Fig. 8). The effect of sharp meandering, an armoured deep bed and a spiral flow, was quite clear on the drop of the delivered sediments to CS5 that was a pool type section. Similar condition was in CS13. Generally, the cross-sections having a relatively high bedload ratio, in other words they have low sediment concentration, are either when water flow from a narrow river section to an expanded a wide section coming downstream onto a narrow river section, a broader and shallower section and the flow velocity tends to be slower that reduces the competence of the section contraction; such as between CS5 and CS6-1, or due to dredging operations for deepening the sections which are losing some of their competence; such as a CS3, or a section of pool morphology where high deposits of finer sediment occurred on the inner bank due to the spiral flow; such as at CS13. The coarser sediments usually tend to transport as a bedload over such cross-sections. River geometry is an influencing factor affecting the spatial distribution of the total load, as well as, the spatial distribution of flow velocities which were correspondingly affected by the river geometry. Flow competence is an interesting manner to determine in future work over the study reach to understand the possible exchanges between the suspended loads and the bedloads.

The maximum total load was 192.9 kg/s at CS2 corresponding to a water discharge of 459 m³/s while the minimum total load was 30.441 kg/s at CS3 corresponding to a water discharge of 464.4 m³/s. Comparing with previous measurements of suspended sediment
load (Geohydraulique, 1977, Al-Ansari et al., 1979, Khalaf, 1988) for the same range of low water discharges, the current suspended load has been reduced by around two-thirds of the previous suspended load before structures controlling the flow in the main river were introduced which probably returns to the limitations of sediment supply from the head catchments.

4.2.5.2. Sediment Rating Curve

After adding the current measurements of the total load to the previous measurements, a new sediment rating curve (Eq. 61) was established with the determination coefficient of determination (R²) of 0.7934 as shown in Figure (989).

\[ G_{t(all)} = 0.0002Q_w^{2.1351} \]  

where

- \( G_t \): total sediment discharge (kg/s)
- \( Q_w \): water discharge (m³/s)

In spite of the differences between Equation (61) and the previous rating curve produced by Geohydraulique (1977) (see Fig. 89), some of the current measurement locations values are still close to the old ones used by Geohydraulique which are showing distinct separation from Eq. (1). This closeness could return to the possible similarity between the current measurements and the Geohydraulique ones since both were conducted in at least two sections those almost spatially identical. As well as, the hydro-morphological conditions of the sampling cross-sections could also be similar since all of the measurements were conducted during low discharges.

Considering the changes in the hydrological scheme of the Tigris River, especially the effect of the Mosul Dam on the flow hydrograph in Baghdad, another rating curve needs to be established depending on the basis of sediment measurements beyond after the Mosul dam became operational. The available measurements conducted since...
that time are those conducted by Khalaf (1988) in 1987 as well as the current measurements. These measurements of 1987 were included were conducted during high water discharges only around 2000 m$^3$/s. Inclusion two of these sets with the current of measurements provides the ability an opportunity to establish a sediment rating curve (Eq. 2) that extends over a range of water flows from between 400 m$^3$/s and 2000 m$^3$/s as shown in Equation (7) and Figure (9). This rating curve is referred to as the named “after Mosul Dam rating curve” to distinguish it from the rating curve of overall available data (Eq. 62) as shown in Figure (89).

$$G_{(afterMosulDam)} = 0.0428Q_{w}^{1.235}$$

The trend of the second rating curve (Eq. 2) was higher steeper than the first rating curve (Eq. 1) due to effect of the applied regulation scheme on the river and the tributaries that limited the sediment supply toward the study reach. In addition to the implanting activities these applied widely on extended areas between the Tigris River and the Euphrates River by three irrigation projects that cover 2,500 km$^2$ of agricultural areas those irrigated from the Mosul Dam Reservoir and drained to the Tharthar Lake (Issa, 2015). Similar irrigation projects for smaller scales were established to the east of the Tigris River on the Lesser Zab Tributary downstream of the Dokan Dam.

The percentage of the corresponding errors, according to Equation (3) (Walling, 1977a), produced from applying the sediment rating curve at the same sampling locations, according to Equation (8) (Walling, 1977a), are shown in Figure (10). The predicted sediment load at 7 cross sections (43.75% of the whole sections) have corresponding error of range A 26.66% of the estimated load have errors ranging between +10% and -10%, and an accumulated 46.66% of the estimations have errors ranging of between -25% and +25%, while the corresponding error of predicting sediment load through the whole reach (16 cross sections) is within the range -60% and +200%.
and an accumulated 66.66% of the estimations have errors ranging between -50% and +50%, and an accumulated 80% of the estimations have errors ranging between -100% and +100%, then a 20% of the estimated load have errors greater than +100%.

\[
\text{Error(\%)} = \left(\frac{\text{RatingCurveEstimation}}{\text{MeasuredBedload}} - 1\right) \times 100
\] .................................(83)

According to the results in table (3), the estimation errors using the sediment rating curve (Eq. 2) were less than the errors of using other applied prediction formulae in the next paragraph. However the promises results of using the spatial sediment rating curve, further investigations on sediment loads during high flows are required to improve the second rating curve (Eq. 2) that increases the reliability of the rating curve over a wider range of water discharges for future uses.

4.3.5.3. Total Load Prediction Formulas

Twenty two total load prediction formulae were applied to on the study reach, as listed shown in Appendix A, to evaluate the most suitable formula that can be used to predict the total sediment load along the river reach. The results of applying the prediction formulae along sixteen cross-sections are were compared with the measured total load in the same cross-sections displayed as shown in Figure (110) showing a comparison with the measured total load discharges in the same cross sections. Three zones of different discrepancy ratios (r), the ratio of the predicted value to the corresponding measured one, were added to the figure to explain the distribution of the compared results around the perfect agreement line.

Many formulae predicted considerably higher or lower sediment discharges, while the results of three formulae were closer to the measurements. These formulae were from the Colby1964, the Brownlie1981, and the Guo-Julien2004 formula.
formula with average discrepancy ratios of 1.17, 0.74 and 1.42 (errors of 17%, -26% and 42%) respectively. The predictions of the Colby formula were distributed on both sides of the perfect agreement line where 64.7% of the predictions are within the first discrepancy zone $0.5 < r < 2$ (-50% < error < +100%) and the accumulated percentage 94.1% of prediction are within the second discrepancy zone of $0.25 < r < 4$ (-75% < error < +300%) is 94.1%. In addition, the same similar distribution for the predictions of the Brownlie and Guo-Julien formulae with lower (r) values recognized were identified.

Table (3) shows the percentages of the predicted sediment discharges for all prediction formulae according to each range of the discrepancy ratio (or error percentage). Some of the other predictors have limited results within the discrepancy zone $0.5 \sim 2$ (error $-50\% \sim +100\%$), such as Garde-Dattatri, Graf-Acaroglu, Einstein, Toffaleti and Chang et al., but however, the accumulated percentage of their results didn’t reach the limit 50% within the zone as shown in Table (3).

To explain the scattering behaviour of the total load formulas at different cross sections along the study reach, they were applied at these cross sections for a range of discharges between 400 and 700 m$^3$/s. Figure (12) shows the results of the predictions at eight cross sections (CS1, CS3, CS6-1, CS6-4, CS7, CS9, CS11 and CS14) and it seems from the figure that the behaviour of most of the total load formulas is consistent, with the exception of the Guo-Julien formula at CS1 and CS6-4, where it has two distinct slopes, a steep slope for low flow until 500 m$^3$/s then a gentle slope for higher flow. The variation of the hydraulic radius with water discharge is not consistent at all cross sections nor is the flow-mean velocity which leads to such results for the more sensitive formulas. According to the results in Figure (12), it is hard to state that there is a unique prediction formula that can predict the total sediment discharge along the whole study reach with a stable range of errors. It is
Even when using those formulae where their results are compatible with field measurements in regular cross-sections, there is still no guarantee of getting the same compatibility at irregular cross-sections (meanders, sand bars, etc.), since the pattern of erosion and sedimentation is varying spatially along the reach of the Tigris River in Baghdad.

The average annual total load quantity was estimated using the total load rating curve for the period 2009-13 was 3.21 million tons. The load was at its minimum value (2.47 million tons) in 2009 and at its maximum value (4.23 million tons) in 2013.

5.6. Conclusions

The implemented regulation scheme on the Tigris River has limited the sources of sediment supplying the downstream river; it has also decreased the average water flow by 44% compared to the previous period. This reduction in water discharges is accompanied by a reduction in the concentration of the suspended load by one-third for the same range of water discharges.

Limited local sources can supply fine sediment to the river reach during rainy seasons or during high flows, while the main source of transported sediment in the Tigris River in Baghdad is the erodible material from the bed and the banks of the river.

The ratios of the measured bedload to suspended load indicated that the suspended load is the dominant mode in the total sediment transport with a minimum percentage contribution of 93.5%. The total load ranged from 29.1 to 190.3 kg/s.

The total load prediction formula closest to the field measurements was the Colby formula (1964). The scattering in the results of total load predictors can be attributed to the spatial variance in topography while it has less effect on the sediment rating curve.

A new spatial total load rating curve has been established to estimate the sediment load along a river of complicated morphology with much evidence of
evidences of active erosion and sedimentation processes operating through the reach are going on in progress of an advantage of reliable use along the river of complicated morphology with many evidences of sedimentation processes are going on. The associated errors from using the total load rating curve are within reasonable levels and less than the errors produced from most of the other twenty two total load predictors. Further measurements of sediment loads during higher water flows are definitely required to improve the accuracy of the spatial sediment rating curve over a wider range of water flows.

The estimated annual transported quantities of total loads were 2.47 (minimum) and 4.23 (maximum) million tons for 2009 and 2013 respectively. The average annual transport rate for the period 2009-13 was 3.21 million tons.

In general, due to the complicated pattern of erosion and sedimentation in the large regulated underfit rivers with the state of underfitness, such as the Tigris River in Baghdad, using the spatial total load rating curve is preferable for morphologically complicated rivers to overcome the misleading of the empirical prediction formulae when they are used at individual optimal cross section with certain control parameters those are widely varying across such underfit rivers.

6.7 References


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Appendix A: Total Load Prediction Formulas

A wide spectrum of total load or bed sediment load prediction formulas have been proposed and developed by many researchers based on different approaches. For each approach, a specified concept was considered as motivation for deriving the approach’s formula and a certain number of parameters were controlled in the laboratory measurements to estimate the constants of each formula. Brief descriptions for the following approaches are given below:

7.4.8.1 Unit stream power concept
The rate of work being done by a unit weight of water in transporting sediment must be
directly related to the rate of work available to a unit weight of water (Yang, 1996). Yang
emphasized the power available per unit weight of fluid to transport sediments.

a. Yang1973 formula (Yang, 1996)
b. Maddock1973 formula (Maddock, 1976)
c. Maddock1976 formula (Maddock, 1976)
d. Yang1979 formula (Yang, 1996)

7.2.8.2 Shear stress approach

The movement of bed material particles will start when the criteria of incipient motion is
exceeded. So, shear stress near the bed will entrain the sediment particles and set them into
motion as long as the shear stress is greater than the critical shear stress of the particles. The
following formula which belong to this approach were used in this work:

a. Laursen1958 formula (Vanoni, 2006)
b. Chang-Simons-Richardson1965 formula (Yang, 1996)
c. Brownlie1981 formula (Julien, 2010)

7.3.8.3 Probabilistic approach

Probability concepts were introduced in bed sediment load prediction by the pioneering
work of Einstein in 1942. The turbulent flow fluctuations are the driver for sediment
entrainment rather than the flow forces exerted on the particle. Both the entrainment and the
deposition were expressed in probability terms (Yang, 1996).

a. Einstein1950 bedload function (Graf, 1971)
b. Garde-Dattatri1963 formula (Garde, 2006)
c. Colby1964 formula (Yang, 1996)
d. Graf-Acaroglu1968 formula (Graf, 1971)
e. Toffaleti1969 formula (Yang, 1996)
7.4.8.4 Regression approach

Data driven models (regression, Artificial Neural Network) were used to explain the bedload transport process due to the limitations of defining this complex process into a precise formula (Talukdar et al., 2012). The following formulae were used within this approach:

- c. Van Rijn1984 formula (Van Rijn, 1993)

7.5.8.5 Power Concept

This approach has developed from the concept that there is a relation between the available energy into the river with the rate of work done by the river to transport sediment (Yang, 1996). The following formulae was used within this approach:

- c. Ackers-White1973 formula (Yang, 1996)
- d. Ackers-White1990 formula (Van Rijn, 1993)

7.6.8.6 Regime approach

This approach was developed based on the regime theory where the data used for establishing its relationships was taken from large stable irrigation canals (Vanoni, 2006). The following formula is used:

- a. Inglis-Lacey1968 formula
These twenty two total load formulaes were applied on the study reach to predict the total sediment load discharge and find out the more suitable formulaes.

Two kinds of data sets were required for applying the total load formulaes, physical properties of river bed sediment and hydraulic-geometric parameters of the study reach. These data sets were determined by direct measurements and analysis of sampled sediment. The results published by Al-Ansari et al. (2015) contained most of the datasets, while other datasets were tabulated in table (4).
Figure 1. Map of Iraq with major rivers and streams (Tigris River Basin is the green shaded area) (ESCWA, 2013)
Figure 2. Tigris River course inside Baghdad.
Figure 3. Schematic Diagram of Tigris River Hydrological Scheme (MWR, 2005).