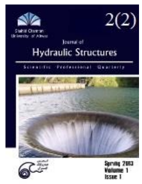
Journal of Hydraulic Structures
***J. Hydraul. Struct.*, 2016; 2(2):74-84**
DOI: 10.22055/jhs.2016.12874



Estimation of Sediment Transport Rate of Karun River (Iran)

Navideh Najafpour [1]
Samad Emamgholizadeh [2]
Hasan Torabi poudeh[3]
Amir Hamzeh Haghiabi[4]

Abstract

Several types of sediment transport equations have been developed for estimation of the river sediment materials during the past decades. The estimated sediment from these equations is very different, especially when they applied for a specific river. Therefore, choice of an equation for estimation of the river sediment load is not an easy task. In this study 10 important sediment transport equations namely; Meyer-Peter and Muller (1948), Einstein (1950), Bagnold (1966), Engelund and Hansen (1972), Toffaleti (1969), Yang (1996), Van Rijn (2004), Wiuff (1985), Samaga et al. (1986) and Beg (1995) are used to estimate sediment load of the Karun River in Iran. The estimated sediment load compared with the measured field data by using statistical criteria such as root mean square error (*RMSE*), mean absolute error (*MAE*) and correlation coefficient (R^2). Results showed that Engelund and Hansen formula can provide reliable estimates of sediment load of the Karun River which have high suspended sediment load concentration with *RMSE* of 3725 ton/day, *MAE* of 1058.82 ton/day and R^2 of 0.41. Bagnold and Wiuff formulas estimated the total sediment load 280 % and 700% more than the measured values and the Van Rijn, Tofaleti and Bagnold formulas estimated the sediment load 99 %, 71% and 93 % lower than the measured values, respectively. The comparison indicated that Samaga, Einstein, Tofaleti and Yang equations with low accuracy are not suitable for estimation of sediment load of the Karun River. The main reason for this difference is related to fact that the Karun River carries fine sediment (wash load) which these equations not considered it.

Keywords: Sediment, Suspended load, bed load, transport formula, Karun River

Received: 09 July 2016; Accepted: 25 November 2016

---

[1] Ph.D. Student in Water Engineering, Lorestan University, Iran, navideh_najafpour@yahoo.com
[2] Associate Professor, Department of Water and Soil Engineering, Shahrood University of Technology, Iran. S_gholizadeh517@shahroodut.ac.ir (**Corresponding author**)
[3] Assistant Professor, Department of Water Engineering, Lorestan University, KhoramAbad, Iran. Torabi1976@gmail.com
[4] Professor, Department of Water Engineering, Lorestan University, KhoramAbad, Iran. haghiabi@yahoo.com

1. Introduction

Since natural rivers are subject to constant erosion and sediment transport processes, the study of sediment transport mechanisms and sediment transport capacity of stream flows is considerably important in hydraulics and morphology behaviors of a river (Sheppard, 1963; Roushangar et al., 2014). Sediment transport and sedimentation in rivers have serious outcomes that lead to formation of sediment bars and therefore reduction of flood capacity (Cazanacli et al., 2002), reduction the reservoir capacity and its lifetime (Hassanzadeh et al., 2011) and severe erosion of hydro mechanical facilities (Ghomeishi and Hemadi, 2007). Also erosion and deposition along the river change the morphology of river and as result the cross section, stability and the capacity of rivers will change (Habibi, 1994; Kiat et al., 2008). Various equations such as mathematical modeling, physical modeling or both are used by investigators to study of sediment transport, river hydraulics, and river channel changes (Kiatet al., 2008). Sediment transport in natural rivers has been widely studied in the past few decades and there are many theoretical or empirical formulas that can be used with reasonable accuracy to predict the sediment transport rate for sand bed river. For example, the sediment transport equations developed by Bagnold (1966), Engelund and Hansen (1972), Yang (1996) and Van Rijn (2004) are often applied to compute bed- material load in rivers.

The significant difference between results obtained by different formulas emphasizes the necessity of assessing predicted values by different formulas in varying river conditions (Yang, 1996). As the existing formulas predict the maximum sediment transport capacity of a river, so the measured sediment load may be less than the calculated sediment loads by these formulas. A large number of comparison studies have been done to test the predictability of various sediment transport equations covering a wide range of flow conditions and sediment types, but the accuracy of computational sediment transport models has remained a “challenging question” yet (ASCE, 2004). For selecting the most proper equations for estimation of sediment discharge for a river, it is necessary to evaluate them. The literature review show that different studies were performed to predict the suspended sediment load (Wu et al., 2008; Zhang et al., 2012; Heidarnejad, and Gholami, 2012), bed load(Yang and Wan, 1991; Sirdari et al., 2001; Haddadchi et al., 2013) and total load (Wu et al., 2008; Roushangar et al., 2014) of rivers.

For example Cea et al. (2014) used different sediment transport formulations (Meyer-Peter and Muller (1948), Wong–Parker (2003), Einstein-Brown (1950), van Rijn (1984), Engelund and Hansen (1967), Ackers-White (1973), Yang (1973), and a Meyer-Peter and Muller), which commonly used in morphological studies in rivers. Also they analyzed the relevance of corrections on the sediment flux direction and magnitude due to the bed slope and the non-equilibrium hypothesis. Haddadchi et al. (2013) evaluated the ability of twelve bed load sediment transport equations with two types of grain size namely bed load and bed material. For this purpose they used field data which collected by handheld bed load sampler in Narmab River, northeastern Iran. They showed that the best results when achieved the bed load grain size were used to the equations of Shocklitsch, Meyer-Peter and Mueller, while the equations of Engelund and Hansen, Van Rijn and Einstein perform well with bed material grain size.

The Karun River is the main important river in Iran. The present paper aims is to evaluate the ability and performance of the ten commonly used sediment transport formulas to prediction the sediment transport capacity of this river.

2. Data, Methods and Models

2.1. Study sites and data

The study area is located in the Karun River Basin, Iran (Fig. 1). The Karun River is the largest river in Iran which several large dams (The Karun 1, 2 3 and 4) constructed on this river. Its average discharge is 575 m^3/s. The basin area is about 62,570 km^2, with altitudes between 25 and 4397.6 m MSL. The total length of the river is 950 km. It collects the runoff of extensive areas and conveys to the Persian Gulf. This river supplies water demands of 16 cities, several villages, thousands hectares of agricultural lands, and also with having four large dams has an important role in power generation. The Karun joined with many permanent tributaries such as Dez and Kuhrang before passing through Ahwaz city in the Khuzestan Province.

This study uses hydraulic and physical properties of sediment data collected in Ahvaz hydrometric station on the Karun River to estimate sediment transport rate of this river. The hydrometric station located in the city of Ahwaz (35°34´ N to 35° 34.9´ N and 53°28´ E to 53° 28.9´ E) and it is one of the first order hydrometric station providing long and relatively reliable data. More than 103 series data of this station, from the period of 2002 to 2012, used as input data for calculations of sediment transport rate of this river. Table 1 shows the statistical indices of the measured variables i.e., suspended sediment discharge (Q_s), flow discharge (Q), velocity (V), depth (y), mean diameter of bed materials sediment (D_{50}), water surface slope (S), water temperature (T) and cross-section width of station (W).

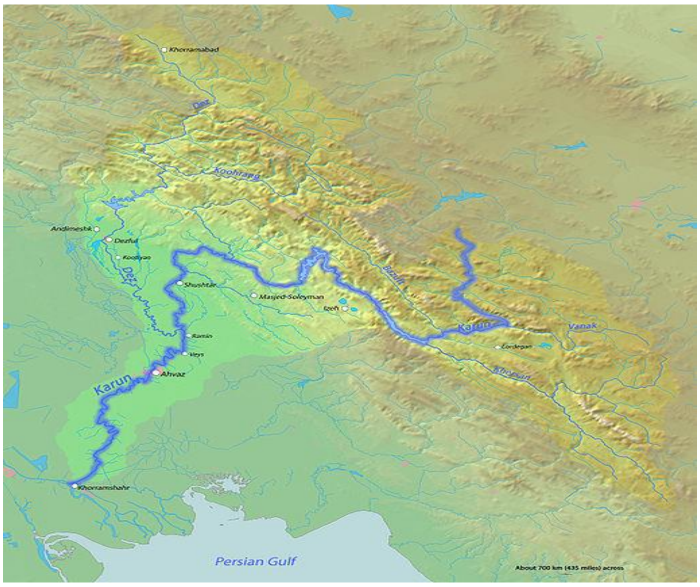


Fig.1. The Karun River basin in Iran

Table1. Summary of applied data in calculations of total and suspended sediment load in Karun River

	Minimum	Average	Maximum
Sediment discharge (ton/day)	689.47	122085.9	1904336
Flow discharge (m^3/s)	188	865.9	3546
Velocity(m/s)	0.26	0.57	1.39
Depth (m)	3.24	1.81	6.69
D_{50} (mm)	0.119	0.1	0.7
Slope(%)	0.000219	0.0004	0.0007
Temperature(°C)	8	20.82	32
Section width (m)	273	338	399.13

Prediction of bed load flux remains a significant problem in understanding river morphodyanmics for geomorphic and engineering applications. In most watershed and river engineering projects, 20 to 30% of suspended load is generally considered as bed load. This assumption may not be correct in some cases (Torabi-Pode, 1999). In this study, the bed load of the Karun River was not measured systematically at Ahvaz hydrometric station. Therefore, bed load of the Karun River has considered 5 to 10% of suspended load that reported by Torabi-Pode (1999).

The performance of sediment transport equations was evaluated based on three statistical metrics, namely mean absolute error (MAE), root mean square error (RMSE), and correlation coefficient (R^2). These metrics can be shown by

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(P_i - \overline{P})^2}} \quad (3)$$

Where, n is the number of data, O_i is the observed values, P_i is the predicted values and the bar de notes the mean of the variable.

2.2. Sediment Transport Formulas

Deterministic sediment transport formulas can be expressed by one of the following forms:

$$q_s = A_1(Q - Q_c)^{B_1} \quad (4)$$

$$q_s = A_2(V - V_c)^{B_2} \quad (5)$$

$$q_s = A_3(S - S_c)^{B_3} \quad (6)$$

$$q_s = A_4(\tau - \tau_c)^{B_4} \quad (7)$$

$$q_s = A_5(\tau V - \tau_c V_c)^{B_5} \quad (8)$$

$$q_s = A_6(SV - S_c V_c)^{B_6} \quad (9)$$

Where, q_s= sediment discharge per unit width of channel, Q = water discharge, V = average flow velocity, S = energy or water surface slope, τ= shear stress, τV= stream power per unit bed area, V_S= unit stream power, A_1, A_2, A_3, A_4, A_s, A_6, B_1, B_2, B_3, B_4, B_s, B_b= parameters related to flow and sediment conditions, and c = subscript denoting the critical condition at incipient motion. Also the modified version of Yang (1996) equitation was used because this version was specially modified for rivers with high concentrations of fine suspended materials. For Van Rijn’s equation, the 2004 version was selected because the new formulas were improved greatly especially for fine sediment. Table 2 shows the used equations:

Table 2. Equations which used for calculation of sediment load in Karun River

Researcher	*Equation*
Bagnold (1966)	$\frac{\gamma}{\gamma_S-\gamma} q_b \tan\alpha = \tau V\ e_b$
Engelund and Hansen (1972)	$q_t = 0.05V^2\gamma_s(\frac{d_{50}}{g(G_s-1)})^{1/2}(\frac{\tau_0}{(\gamma_s-\gamma)d_{50}})^{3/2}$
Yang (1996)	$LogC_t = 5.165 - 0.153Log\frac{\omega_m d_{50}}{\nu} - 0.297Log\frac{V_*}{\omega_m} + (1.78 - 0.36\ Log\frac{\omega_m d_{50}}{\nu} - 0.48\ Log\frac{V_*}{\omega_m})Log\left[\frac{VS}{\omega_m}\frac{\gamma_m}{(\gamma_s-\gamma_m)}\right]$
Van Rijn (2004)	$q_b = \gamma\ \rho_s\ f_{silt}\ d_{50}\ d_*^{-0.3}\left(\frac{\tau'_{b,cw}}{\rho}\right)^{0.5}\left[\frac{\tau'_{b,cw}-\tau_{b,cr}}{\tau_{b,cr}}\right]^{\eta}$
Meyer-Peter Muller and derivatives (1948)	$\gamma\frac{Q_s}{Q}\left(\frac{K_s}{K_r}\right)^{3/2} d\ S = 0.047(\gamma_s-\gamma)D_m + 0.25\left(\frac{\gamma}{g}\right)^{1/3}\left(\frac{\gamma_s-\gamma}{\gamma}\right)^{2/3} q_b^{2/3}$ $D_m = \sum_{i=1}^{n} D_{si}\, i$

where γ and γ_s are specific weights of water and sediment, respectively, q_b is bed load transport rate per unit width, tan α is the ratio of tangential to normal shear force, τ is shear stress along the bed, e_b is the efficiency coefficient, V is the average flow velocity; q_t is total sediment discharge by weight per unit width, d_{50} is the mean diameter of the bed materials; g is the gravitational acceleration; G_s is the specific gravity given by $\frac{\gamma}{\gamma_s}$; f_{silt} is a silt factor; τ_{bcr} is the instantaneous grain related bed-shear stress due to both currents and waves; ρ_b is the critical bed-shear stress according to shields; ρ is the density of water; η is the dimensionless particle size; C_t tis the weight concentration of sediment in ppm; ω_m is particle fall velocity; Q_S id the part of the water discharge apportioned to the bed; Q is the total water discharge; K_S = Strickler's coefficient of bed roughness; K_r = the coefficient of particle roughness; d is the mean depth; S is the energy gradient; D_m is the effective diameter of bed-material mixture; n is the number of size fractions in the bed material, D_{si} = the mean grain diameter of the sediment in size fraction i, and ih.

3. Results and Discussion

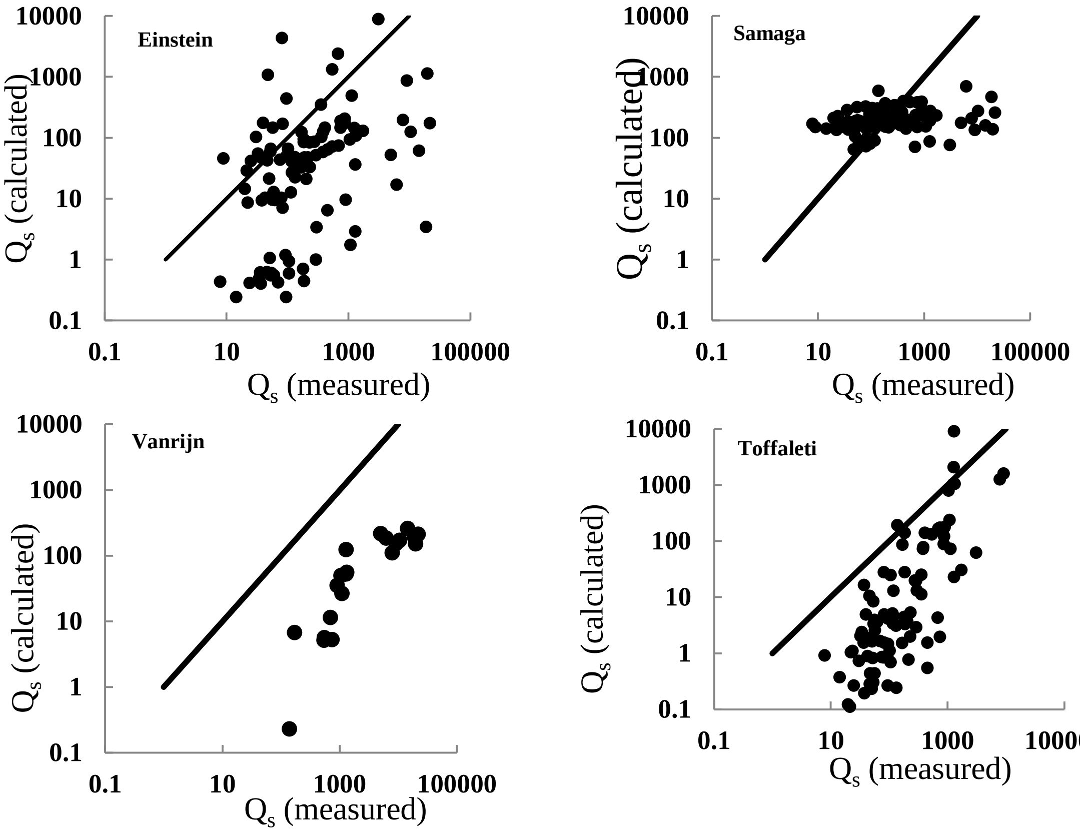
The total sediment load of Karun River was calculated by the selected formulas namely Meyer-Peter and Muller, Engelund and Hansen, Yang and Beg while suspended load were calculated by Bagnold, Van Rijn, Toffaleti, Einstein, Samaga et al and Wiuff equations.

Since at Ahvaz hydrometric station only the suspended load is measured, therefore for calculating total load, 5 - 10 % of suspended load considered as bed load. For comparing the measured and calculated sediment loads, in addition to RMASE, MAE and R^2, the ratio of R (R=calculated load/ measured load) are used. The results are shown in Table 3. Also the calculated sediment load compared with field measurement data in Fig. 2.

Table 3. Comparison between computed and measured sediment load of the Karun River

No.	Method	R^*(Average)	RMSE (ton/day)	MAE (ton/day)	R^2	$0.5<R^*<2$
1	Einstein(Suspended load)	1.34	4262	1520	0.0032	13
2	Bagnold(Suspended load)	0.064	4167	1393	0.61	0
3	Samaga(Suspended load)	2.33	4115	1334	0.027	33
4	Toffaleti(Suspended load)	0.301	2504	893	0.68	10
5	Van Rijn(Suspended load)	0.0055	4145	1392	0.74	0
6	Wiuff(Suspended load)	22.6	54435	15187	0.35	2
7	M-P-M(Total load)	0.019	4186	1406	0.68	25
8	Engelund and Hansen(Total load)	1.41	3725	1058	0.41	63
9	Yang(Total load)	2.05	8493	2344	0.16	31
10	Beg(Total load)	0.73	10601	3405	0.52	22

*R= Calculated load/Measured load



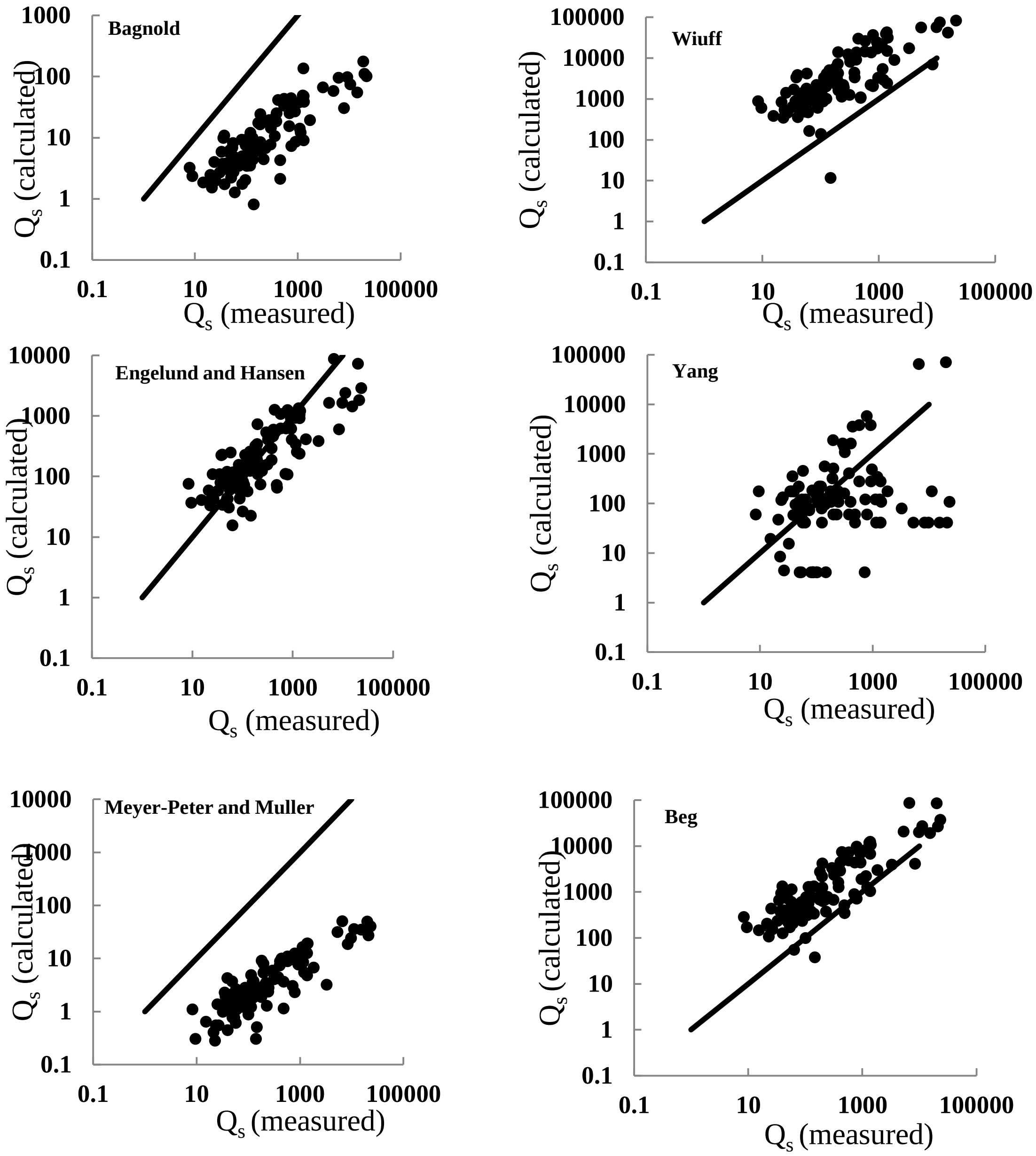


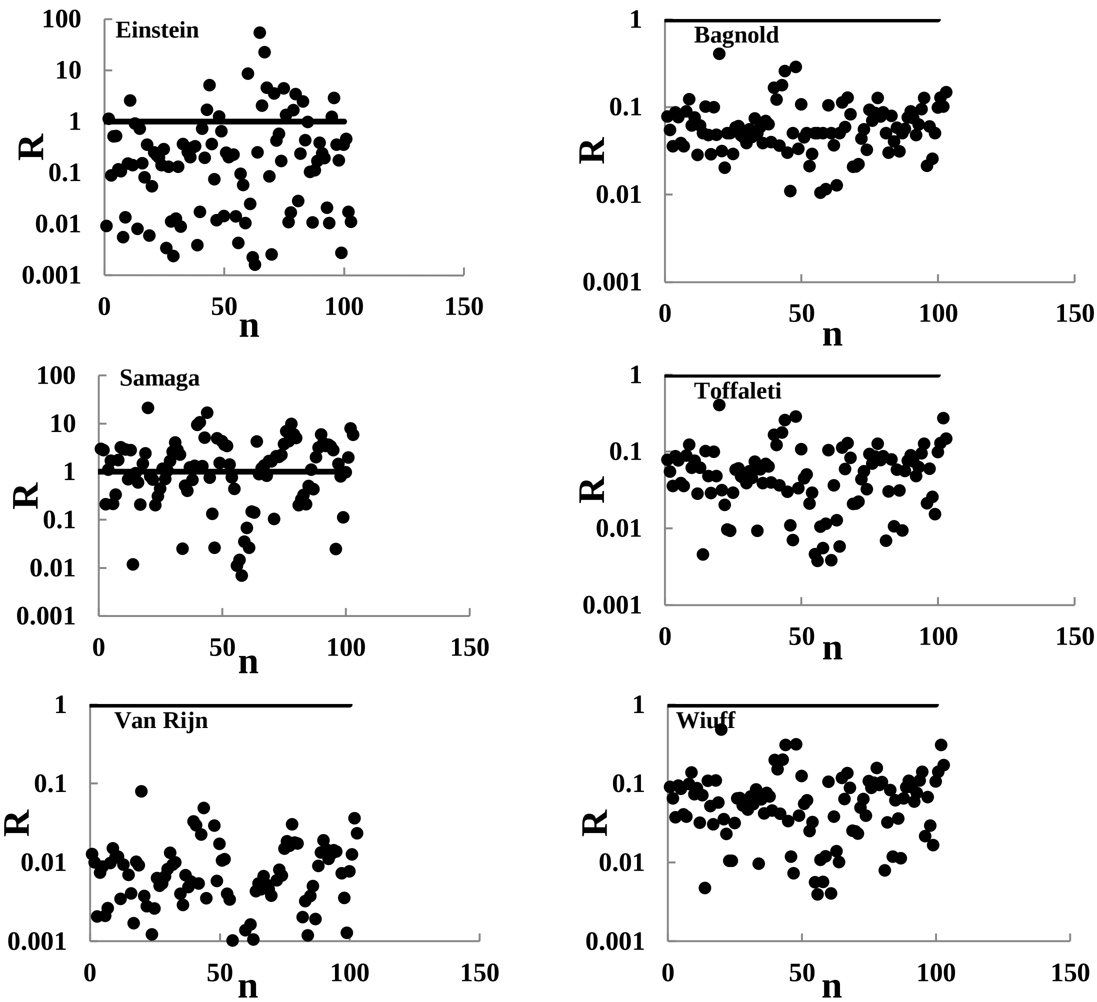
Fig. 2. Comparison between measured and calculated sediment load concentration of The Karun River

From the results of Table 3 and also Fig. 2 it can be concluded that Wiuff equation predicts the suspended sediment load of the Karun River higher than the measured values with RMSE of 54435 ton/day and R^2 of 0.35. While Bagnold and Toffaleti equations predict suspended sediment load less than measured values with RMSE of 4167 and 2504 ton/day and R^2 of 0.61 and 0.68 respectively. The predicted values of sediment load by Einstein, Samaga and Van Rijn equations are unclear and imprecise (Fig. 2 a, c, e, i).

Beg equation predicts suspended sediment load of the Karun River higher than measured values with RMSE of 10601 ton/day and R^2 of 0.52. Meyer-Peter and Muller equation estimates total sediment load of the Karun River less than measured values with RMSE of 4186 and R^2 of

0.68. The prediction of Yang equation is unclear, while Engelund and Hansen equation is less imprecise (Fig. 2 h) and seems to produce the best prediction of total sediment load among the selected equations with RMSE of 3725 and R^2 of 0.41.

Overall, no accurate equation exists to determine the best sediment prediction formula since the use of various statistical methods produce different results. Fig.3 shows the sediment load ratios (R= calculated load / measured load) with different equations. The depicted points in this figure closer to R = 1 indicate that the selected equation performs more accurately to estimate the sediment transport load. Also if the depicted points be scattered in direction of R = 1, the selected method should be modified by applying a corrective coefficient. Results of Fig. 3 show that for estimation of suspended and total sediment load of the Karun River, Bagnold equation and also Beg and Engelund and Hansen equations produced a relatively accurate prediction, so applying corrective coefficient increased the accuracy of these equations (see Table 4).



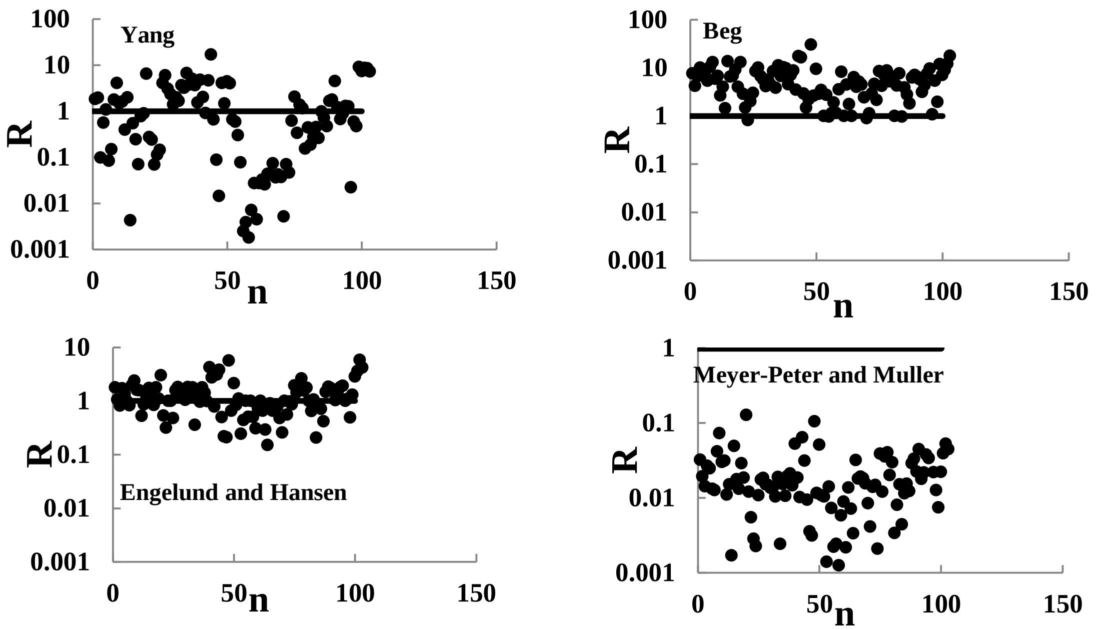


Fig.3. The proportion of computed and measured sediment load concentration for the Karun River with different equations

Table4. Summary of applying corrective coefficient to produce better results

Method	Corrective coefficient	0.5<R<2	RMSE (ton/day)	R^2
Bagnold(suspended load)	10	58	4212	0.61
Engelund& Hansen(total load)	1	63	3725	0.41
Beg(total load)	0.1	57	3573	0.52

Samaga (suspended sediment load) and Yang (total sediment load) equations underestimated sediment load of the Karun River and sometimes overestimated sediment rate mainly due to flow high-velocity. Large scatter of calculated results by Van Rijn, Einstein and Toffaleti (suspended sediment load) and Meyer-Peter and Muller (total sediment load) equations show that these equations are not appropriate to determine sediment load of the Karun River which contains abundant fine and suspended materials; however, they perform more successfully in laboratory flumes. Weak performance of these six equations can be attributed to delay of sediment deposition velocity which is not normally considered in such equations.

The main reason for low accuracy of the sediment transport equations goes back to the fact that these equations are developed base on laboratory data so that they cannot accurately predict sediment load under field conditions (Shafai-Bajestan, 2008). The accuracy of these equations can be increased by application of corrective coefficients. In all the selected equations, the bed particle size was used due to the lack of data regarding suspended particle size and also average flow velocity was used instead of direct measurement of flow velocity from different river profiles, hence scatter of depicted points was larger in Van Rijn (suspended sediment load), which are more sensitive to flow velocity and sediment particle size (Torabi-Pode, 1999). The calculated sediment load by experimental formulas is total bed material which excludes wash load. On the other hand, with the existence of fine, erosion sensitive formations around the study area, a large wash load is expected to occur in the Karun River. Thus, the large portion of difference between measured and calculated sediment load by the selected equations is related to the washed load of the river. Also, since sediment load is calculated by experimental formulas for averaged river depth and width while morphological features of a river are different in time, thus a difference is always expected between the calculated and observed sediment load.

4. Conclusion

Various formulas including Einstein, Bagnold, Samaga, Toffaleti, Van Rijn and Wiuff equations are used to determine suspended sediment load and also Yang, Beg, Englund and Hansen, Meyer-Peter and Muller equations applied to determine total sediment load of the Karun River. The 103 series of field data at Ahvaz hydrometric station used and the results were compared by the measured suspended load. The following conclusions can be drawn:

The best estimation of the Karun River suspended sediment load was produced by Bagnold method as less erroneous predictions was obtained. In Bagnold equation due to less scattered points around R = 1(calculated/measured load), a corrective coefficient of 10 can be used to obtain better result.

Also, for estimation of total sediment load of the Karun River the best prediction were obtained by Englund and Hansen and Beg equations. In the Beg equation due to less scattered points around R = 1(calculated/measured load), a corrective coefficient of 0.1 can be used to obtain better result. Extreme scatter of results by Einstein, Yang and Samaga equations in the study area shows that such equations were not proper to predict sediment load material of the Karun River and the coefficient applied in these formulas, which were obtained on lab flumes, are not good to be used for natural rivers.

The results produced by different formulas were considerably different than the observed values which can be related to the wash load which none of experimental formulas considered it.

References

1. ASCE Task Committee of Computational Modeling of Sediment transport Processes. “Computational modeling of sediment transport processes. *J. of Hydraul. Eng.*, 130(7): 597-598 (2004.).
2. Bagnold, R.A. “An approach to the sediment transport problem from general physics. U.S. Geol, Survey prof, Paper 4221, Washington, USA (1996).
3.Cea, L. Bladé, L. Corestein, G. Fraga, I. Espinal, M. and Puertas, J. “Comparative analysis of several sediment transport formulations applied to dam-break flows over erodible beds”, *J. of Hydraul. Res.*, **50**(4), pp. 364-375 (2014).
4. Engelund, F. and E. Hansen. “A Monograph on sediment transport in Alluvial Streams”, Teknish Forlag, Copenhagen (1972).
5. Ghomeishi, M. and Hemadi, K. “Determination of gradation suspended sediment and relation between suspended material and flow hydraulic parameters in province Khuzestan Rivers. Design researches of water and electricity organ of Khuzestan”, In Persian, pp: 178 (2007).
6. Habibi, M. “Sediment transport estimation methods in river systems”, Doctor of Philosophy thesis, Department of Civil and Mining Engineering, University of Wollongong (1994).
7. Haddadchi, A. Omid, M.H. Dehghani, A.A. “Bed load equation analysis using bed load-material grain size”, *J. Hydrol. Hydromech*. **61**(3): pp. 241–249 (2013).
8. Hassanzadeh, H. Faiznia, S. Shafai Bajestan, M. and Motamed, A. “Estimate of Sediment

Transport Rate at Karkheh River in Iran Using Selected Transport Formulas", *World Appl. Sci. J.* 13 (2): pp. 376-384 (2011).

9. Heidarnejad, M. and Gholami, A. "Modeling Suspended Sediments in Dez Basin (Case Study: The Tale Zang Hydrometric Station) ", *Int. Res. J. of Appl.and Basic Sci.,* **3** (2), pp. 402-407 (2012).
10. Kiat, C.C. Ghani, A.A. Abdullah, R. Zakaria, N.A. "Sediment transport modeling for Kulim River . A case study", *J. of Hydro-envi. Res.* **2** , 47-59 (2005).
11. Roushangar, K. Vojoudi Mehrabani, F. Shiri, J. "Modeling river total bed material load discharge using artificial intelligence approaches (based on conceptual inputs) ", *J. of Hydrol.,* 514, pp. 114-122 (2014).
12. Martin, Y. "Evaluation of bed load transport formulae using field evidence from the Vedder River, British Columbia", *Geomorphology,* 53, pp. 75–95 (2003).
13. Shafai-Bajestan, M. "Hydraulics of sediment transport (second edition) ", Shahid Chamran University Press, Ahwaz, Iran, In Persian, pp: 549 (2008).
14. Sedaei, N. and Honarbakhsh, A. "Suspended sediment estimation formulae analyzing with Analytical Hierarchy Processing", *Int. J. of Agri. and Crop Sci.*, IJACS, **16**(5): pp. 1765-1774 (2013).
15. Sheppard, J.R. "Methods and their suitability for determining total sediment quantities", Proceedings of the Federal Inter Agency Sedimentation Conference (PFISC), Miscellaneous publication no. 970. Agricultural Research service, USDA Washington, D.C. **32**: pp. 272-287(1963).
16. Sirdari, Z.Z. Ghani, A. and Sirdari, N.Z. "Bed load transport predictions based on field measurement data by combination of artificial neural network and genetic", *Pollution*,**1**(1): pp. 85-94 (2014).
17. Torabi-Pode, H. "Rate equations for estimating sediment of the rivers of Khuzestan", Master's thesis, University of Chamran, Ahvaz (1999).
18. Van Rijn, L.C. "A unified view of sediment transport by currents and waves, part I: initiation of motion, bed roughness and bed load transport", *J. Hydrau. Eng., ASCE,* **33**(6): pp. 649-667(2007a).
19. Van Rijn, L.C. "A unified view of sediment transport by currents and waves, part II:Suspended transport", *J. Hydraul. Eng., ASCE,* 33(6): pp. 668- 689 (2007b).
20. Yang, C.T. and Wan, S. "Comparisons of selected bed-material load formulas", *J. of Hydraul. Eng.,* 117, 8, 973-989 (1991).
21. Yang, C.T. "Sediment Transport: Theory and Practice", McGraw- Hill Companies, Inc. New York, USA, (1996).