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Suspended Sediment Formulae Evaluation, Using Field Evidence from Soolegan River

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Abstract: Predictions of suspended sediment load for Soolegan River in Iran using selected empirical equations were made based on 355 sets of data. Data covers flow discharges from 3.11 m^3/s to 43.81 m^3/s, flow velocities from 0.22 m/s to 1.03 m/s, flow depths from 0.5 to 1.03 m. the equations used in the evaluation are Einstein, Bagnold, Toffaleti, Brooks, Chang-Simons-Richardson and Lane-Kalinske. The selection was based on the purpose of this paper, illustrating the performance of six suspended sediment formulas in Soolegan River and in addition the integrated formulae were also evaluated. Graphical comparisons of the calculated and measured transport rates are shown. The accuracy and reliability of these formulas are verified. The results of the evaluations showed that Brooks had the best estimations while the same results for integrated formulae showed that Lane–Kalinske and Bagnold estimated the suspended sediment discharges better than integrated and non-integrated ones.

Key word: Evaluation · Soolegan River · Integration · Suspended sediment formulae

INTRODUCTION

Improving knowledge on suspended sediment yields, dynamics and water quality is one of today's major environmental challenges addressed to scientists and hydropower managers [1]. These advances will continue in the future as the acquisition of reliable and long-term suspended sediment concentration (SCC) time series are generalized to many hydrometric stations. In mountainous catchments, major fractions of the annual suspended sediment yields (SSY) are transported over a very short time period generally corresponding to several floods [2, 3]. Therefore high-frequency SSC monitoring is required for reliable SSC and SSY estimates. Nevertheless, a reliable and easy method to obtain a direct, continuous SSC measurement is not currently available. Although a great progress is expected with, for instance, the backscatter acoustic method [4, 5]. Their application is still limited to large rivers and canals. Work on quantification of fine-grained sediment movement based on the time-dependent, advection-dispersion equation was presented by Scarlatos and Li [6]. Erosion and sediment transportation determination are the important matters in watershed management. Management of watershed can be easier if the amounts of sediment discharges in rivers are measured very accurately [7]. On the other hand suspended sediment estimation is the most important problem, because there are so many groups that need this kind of data [8]. The development of hydraulic sediment occurs in response to needs of the active programs of water resources projects. Most of the information concerning the feedback effect of sediment transport on flow characteristics relates to the case of suspended sediment [9]. A number of sediment transport models and formulas can be found in the literature that is used to study sediment transport in alluvial channels. Most of the transport models are based on simplified assumptions that are valid in ideal laboratory conditions only and may not be true for much complicated natural river systems. Models based on more sophisticated theoretical solutions require a large number of parameters that are impossible or difficult to gather for a natural river

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system [10]. Xia *et al*. [11] compared four different methods of determining bank full discharge in the lower Yellow River and found that a method using a stage–discharge relation from one-dimensional hydrodynamic - model is of higher prediction accuracy than the other three methods. Eder and *et al*. [12] compared five different methods and also integrated models of calculating SSC in a classic non-linear optimization setting, which allows gauging their relative merits and showed that for the calculation of the total of suspended sediment, application of a single event rating approach was already sufficient to obtain reliable event loads with respect to the observed benchmark turbidity data. Tena *et al*. [13] found that calculations of sediment load are based on continuous discharge and turbidity records, the latest calibrated with direct suspended sediment sampling that covered the whole range of observed hydraulic conditions. Gao [14] found that in practice, the empirical equation can be used to estimate the maximum possible bed-load transport rates during high flow events, which is useful for various sediment-related river managements. Kisi [15] compared three methods of neural network with each other, a comparison of results indicated that the NDE models give better estimates for suspended sediment in river than NF, NN and RC techniques. In this paper, predictions of suspended sediment for Soolegan River were made and analyzed using the selected equations and also these equations were integrated by applying SPSS-17 software.

MATERIAL AND METHODS

Study Area: Application of six suspended sediment estimation formulae is tested in Soolegan River in Iran. Sediment discharge and sediment concentration and also water discharges series for the stations are used to develop and verify models performances. Soolegan Station is located in Soolegan River at 51° 14´ latitude ?38 ?31 longitude. The drainage area of this river is about 1992 km^2 and the station that these data are used from, is located in 2086 meters higher than see level. This river is located in North karoon basin. The basin is one part of Zagros mountainous lands and is covered by limy and marly soils. The mean rainfall depth of the basin is about 500 mm, which in contrast with other areas in Iran is considerable. This basin also is filled with semi-dense forests. The main source for this river is Vanak River and its length is recorded to about 164 km and the drainage area of this river includes 22 percent of North Karoon basin (Figure 1).

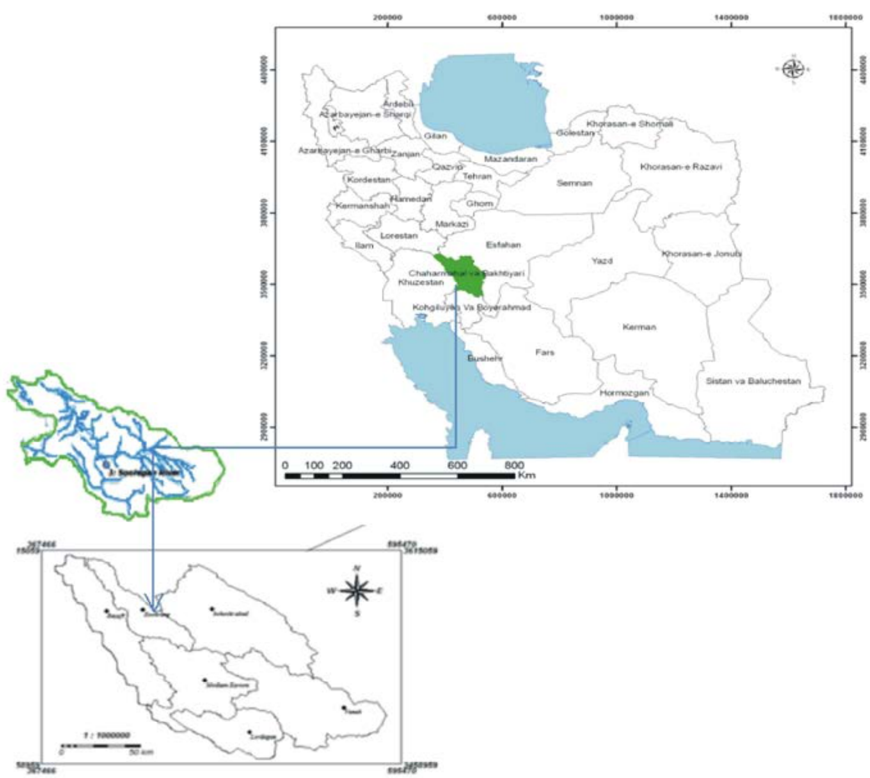


Fig. 1: Soolegan River

Table 1: Range of data used in the development of equations

Data source	Flow depth (m)	Mean velocity of water(m/s)	Mean water discharge (m^3/s)	Mean of suspended sediment discharge (ton/d)	Maximum water discharge (m^3/s)	Minimum water discharge (m^3/s)	Maximum suspended sediment discharge (ton/d)	Minimum suspended sediment discharge(ton/d)
Laboratory-field-formula	Up to 1.03	0.625	23.46	18.90	43.81	3.11	120.219	0.2

Data Sources: The range of all data used in this study lie within the range of data used in the development of the selected equations. This is illustrated in Table 1. The numbers of the years that data was collected from is about 30 years. Abnormal distribution of data have such effects that may lead to high fluctuations in figures and reduces the reliability of analytical results, thus normalization of data is necessary. At first imperfect data were eliminated and then the absent data were estimated by using interpolation method (Table 1).

Data used in this study are collected from one of the smallest rivers in Iran. The river data include the data from Soolegan. The river under study is categorized as a small river with aspect ratio smaller than 5. Data covers flow discharges from 3.11 m^3/s to 43.81 m^3/s, flow velocities from 0.22 m/s to 1.03 m/s, flow depths from 0.5 to 1.03 m. Data from 1986 to 2007 were collected for validation and also calibration of the methods.

Methodology

Suspension: The finer particles of the sediment load of streams move predominantly as suspended load.

Suspension as a mode of transport is opposite to what Chang-Simons-Richardson called "surface creep" and to what he defines as the heavy concentration of motion immediately at the bed. In popular parlance this has been called bed load, although as defined in this publication bed load includes only those grain sizes of the surface creep which occur in significant amounts in the bed.

Formulae: Chang-Simons-Richardson [16] derived a sediment transport model in which, he assumes the below formula valuable

$$\varepsilon_s = KU_* \frac{y}{D}(D - y) \tag{3}$$

And also defining the amount of ε_s equal $\beta KD\xi U_*(1 - \xi)^{1/2}$ And introducing the abbreviation

$$\xi = y/D$$

The shear stress may be determined

$$U_0 = (gds)^{1/2} \tag{4}$$

And also considering the term C_a as the suspended sediment concentration in water depth a and C_y the concentration in water depths y, is estimated in the form of

$$\frac{c_y}{c_a} = \left(\frac{d-y}{y}\frac{a}{d-a}\right)^z \tag{5}$$

In which the concentration of these particles at y is c_y and the concentration c_a of the same particles at distance a. y is the variable of integration, the dimensionless distance of any point in the vertical from the bed, measured in water depths d. with

$$z = \frac{v_s}{0.40u_*} \tag{6}$$

y measured with d as unit

$$A = a/d$$
$$u_* = \sqrt{\tau_0 / s_f} = \sqrt{S_e R g}$$

By replacing equation (3) in equation (5)

$$\frac{C}{C_a} = A_1\left[\frac{\xi^{1/2}{}_a}{1-\left(1-\xi_a\right)^{1/2}}\right]^{z_2} \tag{7}$$

The suspended sediment discharge would be estimated in this form

$$q_{sw} = \gamma D C_a\left(VI_1 - \frac{2U_*}{K}I_2\right) \tag{8}$$

In this equation there are two factors $I_1$and I_2 that can be obtained either from the graphs I_1-ξ (Fig. 3) and also I_2-ξ (Fig.4).

Table 2 shows that Chang-Simons-Richardson with five input parameters cannot estimate the suspended load accurately.

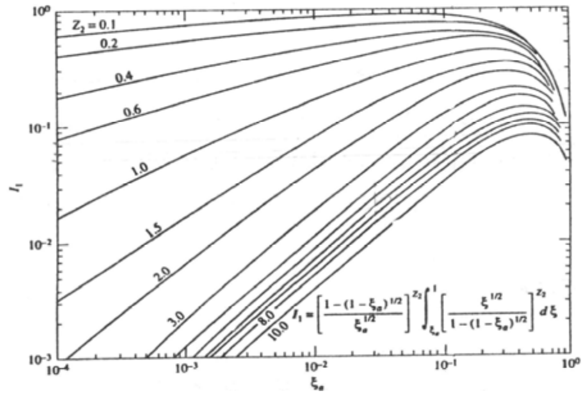


Fig. 3: I_1-ξ_a (ξ in water depths a), graph for determining the mount of I_1 for individual depths (Yang, 1940)

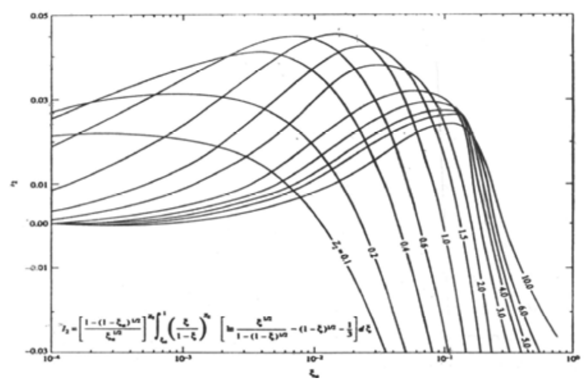


Fig. 4: I_2-ξ_a (ξ in water depths a), graph for determining the mount of I_2 for individual depths (Yang, 1940)

Bagnold [17] derived a stream-based sediment transport model. In that model, Bagnold assumes the sediment is transported in two modes, i.e., the bed load transport and the suspended transport. The bed load sediment is transported by the flow via grain to grain interactions; the suspended sediment transport is supported by fluid flow through turbulent diffusion. The suspended sediment rate can be calculated using the below formula [1].

$$g(S_g - 1)q_{sm} = 0.01\tau(\overline{u}^2 / \omega_s) \tag{9}$$

Where ω_s, is the fall velocity of sediment, S_g is assumed as the ratio of water density by sediment density. ū is the mean velocity, τ is the shear stress and at last q_{sm} is the sediment discharge. Table 2 shows that Bagnold with five input parameters cannot estimate the suspended load accurately.

Table 2: Methods performance in Soolegan River

formulae	R^2	NS	D_v
Einstein	51/0	49/0	28/0-
Lane-Kalinske	42/0	39/0	03/1-
Bagnold	46/0	75/0	2/0
Brooks	83/0	65/0	14/0
Toufalleti	21/0	68/0	03/4-
Chang-Simons-Richardson	70/0	71/0	67/1-

Brooks [18] derived a sediment transport model in which he takes the half-logarithmic velocity distribution in to account and also determined that suspended sediment discharge depends on suspended sediment concentration. The suspended sediment rate can be calculated using the below formula [18];

$$\frac{q_{sw}}{C_{md}q} = T_B(k\frac{V}{U_*}, Z_1, E) \tag{10}$$

Where Z_1, is a function of $Zi = \frac{\omega_i V}{C_Z RS}$

In which ω_i is the fall velocity, V is the water velocity, R is the hydraulic radius, S is the bed slope and C_z is the factor which depends on temperature. $E=e^{-(kv/U^*)-1}$ and C_{md} is the suspended sediment concentration in y=D/2 numbers, q is assumed as the water discharge. K is the Van-Karman coefficient equal with 0.4 mean velocities and at last q_{sm} is the sediment discharge.

The hydraulics of uniform flow includes basically the description of the velocity distributions and of the frictional loss for turbulent flow. Einstein has found that in describing sediment transport the velocity distribution in open-channel flow over a sediment bed is best described by the logarithmic formulas based on v. The vertical velocity distribution is as equation 11:

$$\frac{u_y}{u_*} = 5.50 + 5.751\log_{10}\frac{(yu)}{v} = 5.751\log_{10}\left(9.05\frac{yu_*}{v}\right) \tag{11}$$

For smooth boundaries and:

$$\frac{\overline{u}_y}{u_*} = 8.50 + 5.75\log_{10}(y/k_s) = 5.75\log_{10}(30.2y/k_s) \tag{12}$$

For hydraulically rough boundaries. The transition between the two, including the rough and smooth conditions, may all be combined in the form:

$$\frac{\bar{u}_y}{u_*} = 5.75\log_{10}\left(30.2\frac{yx}{k}\right) = 5.75\log_{10}\left(30.2\frac{y}{\Delta}\right) \quad (13)$$

Whereby x is given in figure 1 as a function of k_s/δ. herein are:

$\bar{u}_y$ = The average point velocity at distance y from the bed
$u_* = \sqrt{\frac{\tau_o}{S_f}}$ = the sheer velocity
s_f The density of the water
S_e The slope of the energy grade line
R The hydraulic radius
g The acceleration due to gravity
y The distance from the bed
v The kinematic viscosity of the water
k_s The roughness of the bed
x A corrective parameter
Δ = K_s/X the apparent roughness of the surface
δ The thickness of the laminar sub layer of a smooth wall

Beside the above parameters and equations there is a function as sediment concentration in water depths y. it must be mentioned that this factor is estimated as a function of concentration in water depths a.

$$\frac{Cy}{C_a} = \left(\frac{d-y}{y}\frac{a}{d-a}\right)^z \quad (14)$$

In which the concentration of these particles at y is c_y and the concentration c_a of the same particles at distance a. y is the variable of integration, the dimensionless distance of any point in the vertical from the bed, measured in water depths d. with

$$z = \frac{v_s}{0.40u_*} \quad (15)$$

y measured with d as unit

$$A = a/d$$
$$u_* = \sqrt{\tau_o/S_f} = \sqrt{S_e R_g}$$

The integral of suspended load moving through the unit width of a cross section may be obtained by combining equations (13) and (14).

$$\int_y^d c_y \bar{u}_y dy = \int_y^d c_a \left(\frac{d-y}{y}\frac{a}{d-a}\right)^z 5.75u_* \log_{10}(30.2y/\Delta)dy \quad (16)$$

C_a the reference concentration ration at the level y=a. (C_a is measured in weight per unit volume of mixture).

Z defined in equation 14 as the settling velocity v_s of the particles divided by the Karman constant 0.40 and the shear velocity u_*.

The performance of Einstein to estimate the suspended sediment is evaluated using RMSE and R^2. Table 2 shows that Einstein with five input parameters cannot estimate the suspended load accurately.

Lane-Kalinske [19] derived a suspended sediment transport model in which their approach was based on $\varepsilon_s=\varepsilon_m$, they assumed that β=1 and introduced this equation

$$\varepsilon_s = kU_*\frac{y}{D}(D-y) \quad (17)$$

The average of this parameter is obtained

$$\bar{\varepsilon}_s = \frac{\int_0^D \varepsilon_s dy}{D} = \frac{kU_*}{D^2}\int_0^D (yD-y^2)dy \quad (18)$$

Herein are:
$u_* = \sqrt{\frac{\tau_o}{S_f}}$ = the sheer velocity
g the acceleration due to gravity
y the distance from the bed
k Van-Karman coefficient equal to 0.4

Beside the above parameters and equations there is a function as sediment concentration in water depths y. It must be mentioned that this factor is estimated as a function of concentration in water depths a.

$$\frac{c_y}{c_a} = \left(\frac{d-y}{y}\frac{a}{d-a}\right)^z \quad (19)$$

In which the concentration of these particles at y is c_y and the concentration c_a of the same particles at distance a. y is the variable of integration, the dimensionless distance of any point in the vertical from the bed, measured in water depths d. with

$$z = \frac{v_s}{0.40u_*} \quad (20)$$

y measured with d as unit
Introducing the abbreviation

$$P_L = \frac{\overline{C}}{C_a} \quad (21)$$

Defining the above equations suspended sediment discharge is estimated in this form

$$q_{sw} = qC_aP_L \exp\left(\frac{15\omega a}{U_*D}\right) \quad (22)$$

ω: Is the fall velocity, q is the water discharge and at last q_{sw} is the suspended sediment discharge.

The performance of Lane-Kalinske to estimate the suspended sediment is evaluated using RMSE and R^2. Table 2 shows that Lane-Kalinske with input parameters cannot estimate the suspended load accurately.

Toffaleti [20] derived a suspended sediment transport from Einstein and Chain formulae and also used deep integration of concentration profile multiplied by velocity profile. The total velocity profile is obtained from

$$U = (1+\eta_v)V(Y/R)^{\eta_v} \quad (23)$$

In which U is the velocity in water depths of Y in relation to bed, V is the average velocity in river and η_v is an explanatory parameter

$$\eta_v=0.1198\times0.00048T_F \quad (24)$$

T_F is the temperature in Fahrenheit.

Toffaleti divided the vertical depth in to four parts and estimated the suspended sediment concentration for each part separately. Introducing the abbreviation.

$$Zi = \frac{\omega_i V}{C_Z RS} \quad (25)$$

ω_i Is the fall velocity, V is the water velocity, S is the bed slope, R is the hydraulic radius, with

$$C_Z = 260.67\text{-}0.667T_F \quad (26)$$

If the amount of Z_i assumed be more than η_v, so it can be supposed that it is equal to 1/5 η_v and the suspended sediment discharge for upper zone in the vertical profile would be defined

$$q_{SUi} = Mi\frac{(R/11.24)^{0.244Zi}(R/2.5)^{0.5Zi}\left[R^{\eta_1} - (R/2.5)^{\eta_1}\right]}{\eta_1} \quad (27)$$

For the median one

$$q_{Smi} = Mi\frac{(R/11.24)^{0.244Zi}\left[(R/2.5)^{\eta_2} - (R/11.24)^{\eta_2}\right]}{\eta_2} \quad (28)$$

For the below zone

$$q_{SLi} = Mi\frac{(R/11.24)^{\eta_3} - (2di)^{\eta_3}}{\eta_3} \quad (29)$$

With

$$Mi = \frac{43.2Pi(1+\eta_v)VC_{Li}}{R^{\eta_v - 0.756Zi}} \quad (30)$$

And

$$\eta_1 = 1+\eta_v - 1.5Zi \quad (31)$$

$$\eta_2 = 1+\eta_v - Zi \quad (32)$$

$$\eta_3 = 1+\eta_v - 1.756Zi \quad (33)$$

In equation P_i is the percentage of sediments with d_i diameter, C_{Li} must be calculated for each diameter in water depths Y.

Definition the parameters and the equations for each part in the vertical profile the total suspended sediment discharge passing through the unit width of the river would be obtained adding three amounts of suspended sediments that are calculated.

Model performances were tested using (D_v), ‘‘coefficient of correlation” (CORR) and Nash–Sutcliffe model ‘‘efficiency coefficient” (CE). D_v represents well the predicted values match with the observed series and coefficient of correlation describes how simulated and observed data set move. Nash–Sutcliffe model ‘‘efficiency coefficient” (CE) is an important statistic describing model fitness. A value of CE = 1 indicates perfect model fit while, CE = 0 represents that the model is as good as the mean model [10]. Nash–Sutcliffe coefficient is estimated using below formula.

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2} \quad (34)$$

In which Qm_i is the observed data, Qs_i is the estimated data and $\bar{Q}m$ is the mean of the observed data. Also there is another formula that estimates (D_v), the difference percent coefficient. The formula is;

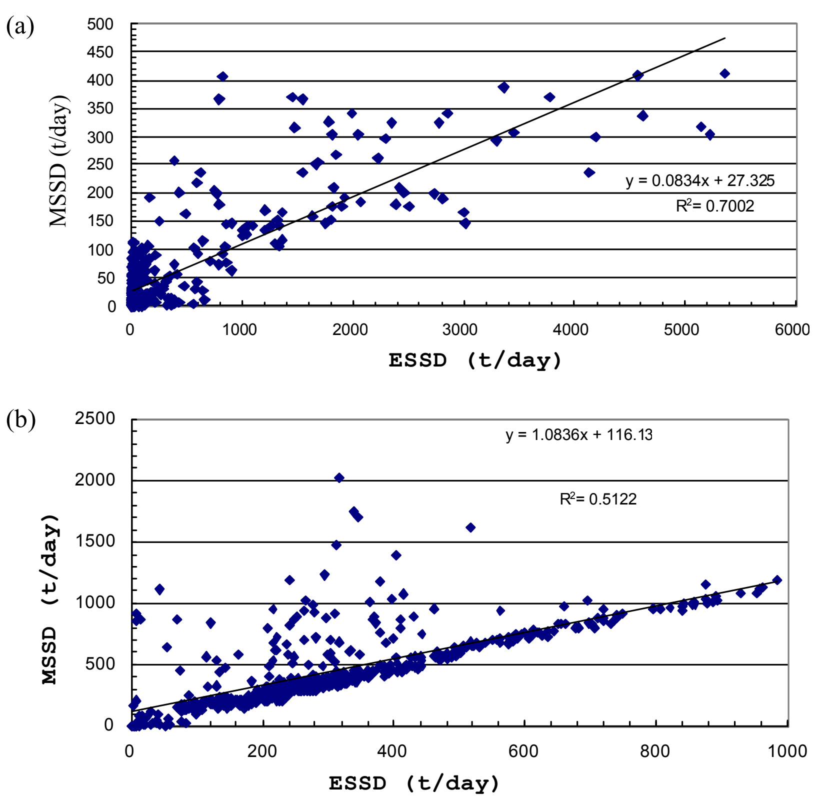
$$D_V = \frac{V - V'}{V} \times 100 \quad (35)$$

In which V′ is the estimated data and V is the observed data.

Formulae Calibration: To calibrate the models there are two conditions; if the formulae are considered in the first class of the first separation, the calibration would be done rewriting the method in the "C" programming language. But if the formulae are supposed to be put in the second class in the first division, the situation would be different because in this condition the formulae are classified in to two parts. The formulae that have linear relationship can be calibrated by using SPSS 17, but another group cannot be calibrated the same because SPSS 17 cannot analyze the nonlinearity relationships between parameters. So the nonlinearity formulae in this article were not calibrated.

RESULTS

Evaluation: Evaluation of suspended sediment discharge estimation shows that all the formulae except one are vary in the same direction. The evaluation of these six formulae is shown in table 2. Among all the six equations Brooks has the best estimation for suspended sediment discharge. All the figures (Figure 2) evaluate the performance of the formulae considering each estimated suspended sediment discharge by the equations in function of observed suspended sediment discharge. It can be recognized that Chang-Simons-Richardson in contrast with other equations estimates the suspended sediment discharge more accurately but not as well as Brooks, also it is obvious that Lane-Kalinske and Bagnold formulae estimate the suspended sediment discharge with the same accuracy. Einstein can be considered as the same accuracy but not exactly. In addition it must be noted that Toffaleti is the formula that cannot be introduced for any estimation through the suspended sediment discharges in rivers at all. The forth figure shows that Brooks estimated the suspended sediment discharge with the highest accuracy and also it can be said that this formula in comparison with others has the least error in calculation. On the other hand it must be told that this formula is more adaptable with the situation in the river. In these graphs the coefficient that shows the evaluation of the formulae is determination coefficient. Brooks has the most determination coefficient among other formulae.



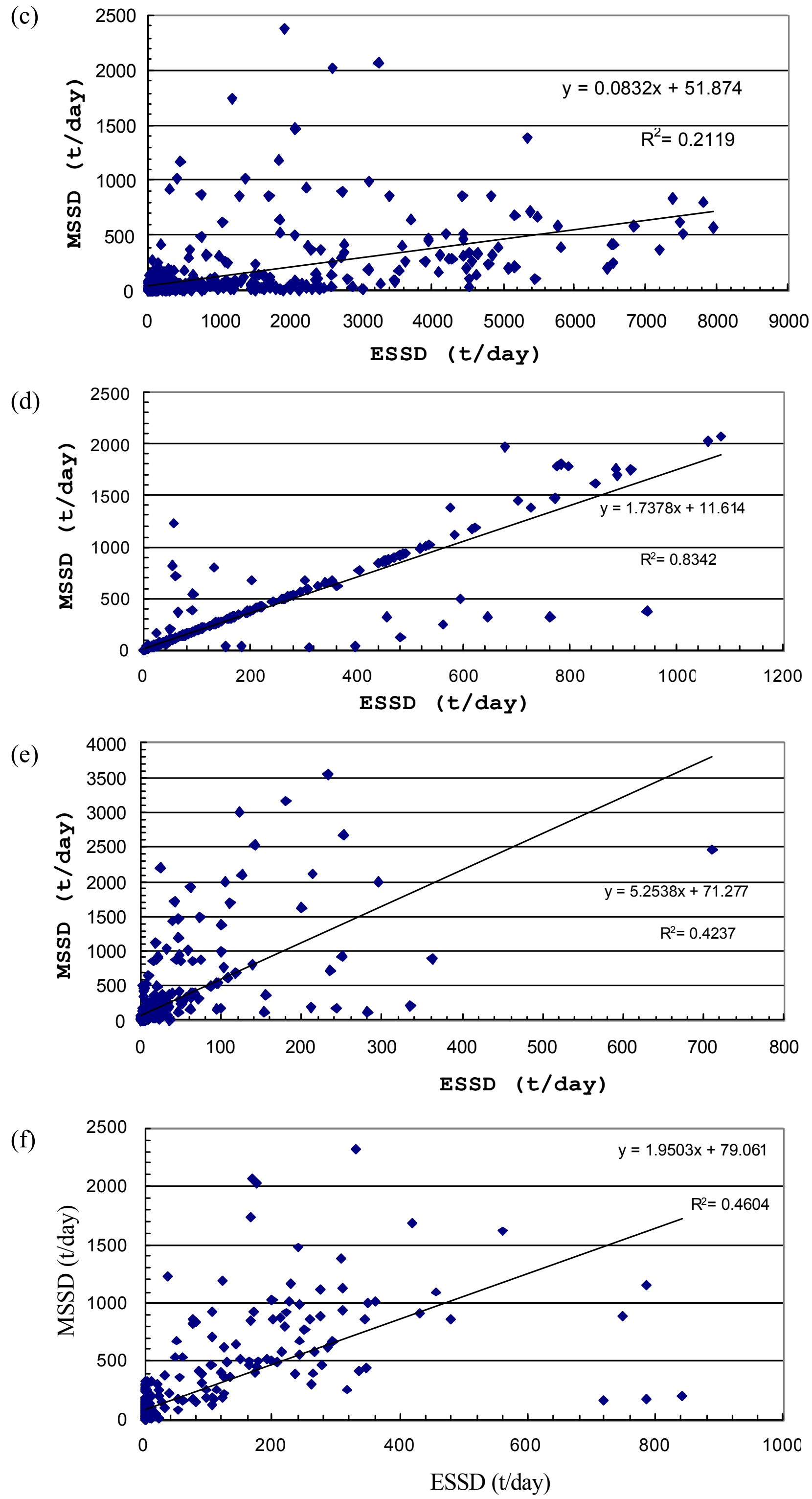


Fig. 2: Observed and estimated suspended sediment discharges values by; a)Chang-Simons-Richardson, b)Einstein, c) Toufalleti, d)Brooks, e) Lane-Kalinske, f)Bagnold in Soolegan
MSSD: is the measured suspended sediment discharge
ESSD: is the estimated suspended sediment discharge

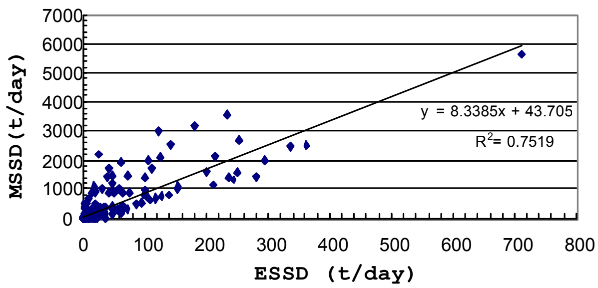


Fig. 3: Observed and estimated suspended sediment discharges by integrated Lane-Kalinske values in Soolegan

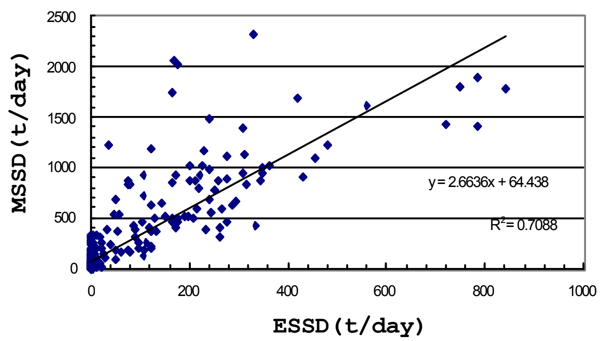


Fig. 4: Observed and estimated suspended sediment discharges by integrated Bagnold values in Soolegan

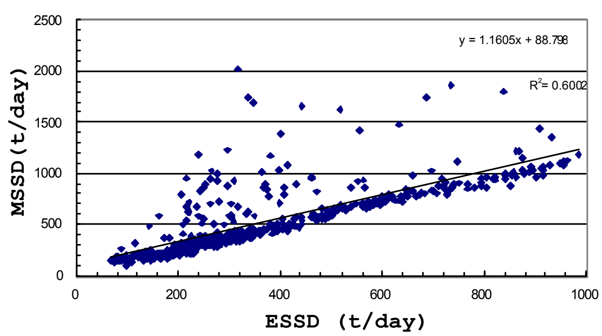


Fig. 5: Observed and estimated suspended sediment discharges by integrated Einstein values in Soolegan

Calibration Methods Application: In order to apply the suspended sediment and water discharge and also suspended sediment concentration in Soolegan River, the three formulae were calibrated using SPSS 17. One of these three formulae is Einstein that is calibrated by being rewritten in "C" programming language. The performance of these three formulae is evaluated in Table 3.

Three upper figures (Figure 5) show whether the integration of the formulae is effective in improving their performance or not. As it is shown the accuracy of all of the formula is raised after integration. The determination coefficient again is used to show the evaluation of the formula. In all three formulae it is increased. But this increasing in the accuracy of Lane -Kalinske in comparison with other two formulae was the most. On the other hand integration had not a lot of influence on the accuracy of Einstein formula.

Table 3: Performance of three integrated formulae

Formulae	R^2	CE	D_v
Lane-Kalinske	75/0	79/0	46/3-
Bagnold	70/0	81/0	08/0
Einstein	60/0	55/0	56/0-

CONCLUSION

Study on the suspended sediment discharge on river with aspect ratio smaller than 5 were conducted. From the evaluations on the selected transport equations, the three equations namely, Brooks, Chang-Simons-Richardson, Einstein gave good performance when tested against field data in comparison with others. On the other hand another three formulae gave poor performance. The result of this paper is consistent with what was found by Ghomshi and Torabipoodeh, Hassanzadeh, Martin [21-23] and also the high changing in the accuracy of Bagnold by integration is consistent with the results of Zhao *et al*. [24]. Although the result was consistent with these findings but it is not consistent with the results of Girma and Horlacher [25]. They have shown that this formula (Bagnold) can estimate the suspended sediment discharge with the high accuracy. Three of the formulae were calibrated among all the six ones, Einstein, Lane-kalinske and Bagnold. Evaluation of the performances of these integrated formulae showed that integrated Lane-kalinske and also Bagnold had better estimation for suspended sediment discharge but Einstein performance did not change anymore. All the three equations that gave the best results are still not significant enough to be used on rivers in other countries despite a good data source used in the development of the equation. Further analysis is necessary to be done in the future. Although some of these formulae perform good and some of them not, but it cannot be told that these formulas perform the same for other rivers. So further research about the performances of these formulae is suggested for other rivers. By determination of the best suspended sediment transport formula for a special river, there is not any need to measure the suspended sediment discharge in the field. In addition, if the best formula for the river is selected, for future projects such as dams construction and other great and expensive projects, the amount of suspended sediment and the total load in the river will be estimated and predicted easily, without spending so much money for going to field and measuring this value. Of course in this way by knowing the trend of river changing and using the selected formula, the best location and capacity for watershed and river management, would be predicted.

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