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Estimations of bedload transport using different shear stress and threshold sediment motion equations by using STE software

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Abstract

One of the most important problem that has become prominent in river engineering and water resources is to predict sediment load in alluvial channels. Sediments are the production of erosion that are being transported using water, wind, ice, and gravity. Accurate estimating the volume of sediments that a particular stream can transport, is one of the main subjects in river morphology. Sediment transport estimation is widely studied and many experimental and semi-experimental equations have been developed but depending on the hydraulic conditions and sediment characteristics in each river, some of these equations may yield better results than the others. In this study, sediment transport estimator (STE) software was used for estimating bedload transport in the Qaresoo river located in Iran, Golestan province, in which bedload is measured. In this software, the abilities of 55 bedload estimator equations were evaluated by using various equations for calculating shear stress and threshold sediment motion and the best combination of them for estimating bed load with the highest accuracy was found using the Genetic Algorithm. The results showed that the best results were achieved by combination shear velocity and threshold shear velocity from Van Rijn (1984) and Hjulstrom (1935), respectively. Using this combination, the best bedload transport formula in the river studied is Chang et al. (1965) with a 62.5% of discrepancy ratio between 0.5 to 2 and 0.91 as the average.

Keywords: Shear Stress, Threshold sediment motion, Sediment Transport Software, STE, Empirical sediment transport formulae, Assessment of bedload estimators.

Introduction

Hydraulic engineers have studied the sediment movements in rivers over the past two centuries because the behaviour of sedimentary materials is important in river hydraulics and its morphology. Sediment load estimation and creating an equation that can calculate the most accurate value has always been one of the most important issues in water engineering and hydraulic structures for better management of water resources. There has been a lot of researches in this field, but despite years of research, there is still no equation that can be used in various rivers and hydraulic conditions. In principle, creating such an equation is impossible because the hydraulic and laboratory conditions in which each equation is developed cannot be responsive to all real conditions. To obtain an equation that provides a better estimate, the conditions of the study area must be compared with the conditions and assumptions in which equations are formed. Accurate estimation of flow and sediment transport rates, as basic information, is important for many river engineering projects. Sediment transport estimation is widely studied and many experimental and semi-experimental equations have been developed but depending on the hydraulic conditions and sediment characteristics in each river, some of these equations may yield better results than the others. On the other hand, for estimating sediment transport rate using empirical equations there are plenty of parameters such as shear stress, threshold sediment motion, fall velocity, etc, that can affect the accuracy of estimations. For calculating such parameters various equations have been introduced by researchers but which equations will provide the most suitable values for shear stress, threshold sediment motion, and fall velocity is a challengeable question for different rivers and situations.

In 1879, the young French engineer (Paul Francois Dominique Du Boys, 1879) proposed his model of sediment transport as a theoretical principle. (1888-1969) Armin Schoklitsch can be named as the first researcher who seriously studied Du Boys bedload transport formula and proposed values for constant coefficients in the equation of Du Boys according to his experiments.

(Haddadchi et al, 2011), by measuring the sediment load in an alpine gravel-bed river named Chehelchay, studied 13 known bedload transport formulas. The results of this study showed that Van Rijn, Meyer-Peter and Müller and Ackers and White estimate bedload transport more accurately.

(Teimourey & Dehghani, 2019-2020), by developing an applied software named STE that has capabilities such as using the quasi-two-dimensional model of Shiono & Knight and intelligent algorithms to increase the accuracy of sediment load estimations, proceeded to examine the accuracy of 34 bedload transport formulas in estimating bedload in rivers of Golestan province and Babolrood river in Mazandaran province. The results of this study showed that by using developed software and quasi-two-dimensional model of Shiono & Knight, the best bedload transport formulas are Toffaleti and Yang for Babolrood and Chehelchay respectively. Also using this software showed that intelligent algorithms and quasi-two-dimensional models are able to increase the accuracy in estimating bedload transport.

(Teimourey & Dehghani, 2020), studied the impact of different threshold sediment motion calculator models on different bedload transport formulas using measured bedload in the Zaramrood river located in Mazandaran province. The results of this study showed that the parameter threshold sediment motion alone is effective in the accuracy of different bedload transport formulas and the best bedload transport formula for the river studied would be Samaga et al if threshold sediment motion is calculated using Goncharof (1964).

Therefore, due to the abundant of equations and models in calculating different parameters and sediment transport rates, the difference of conditions and assumptions in which equations are formed, the impact of using different equations in the accuracy of estimations and lack of existing a suitable software for evaluating different methods and finding the best combination for rivers in order to make calculations easier and increase the speed and accuracy, as well as comparing the results, the need for a fast, applied and accurate software feels in this field.

Material and Methods

STE Software

For estimating rating curve and sediment load in alluvial channels, sediment transport estimator software (STE) was developed by the authors (Teimourey & Dehghani, 2019). In this software, up-to-date equations and algorithms with a user-friendly environment were developed to increase the accuracy of sediment load estimations. In this software, the users can easily choose different sediment load, shear velocity and threshold shear velocity equations to see which equation gives more accurate results. There is also an ability to combine different sediment load estimator formulas to study the efficiency of new formulas with the aim of optimization techniques such as the Genetic Algorithm.

The Sediment Transport Estimator (STE) software was programmed by VB.NET language in Microsoft Visual Studio, provides the following abilities and features for its users (http://www.ste.hwstr.ir/):

- Save, load, edit, and store inputted data and calculated data in Microsoft Access files by type (.accdb)
- Ability to Estimate sediment transport rates in both hydrological and hydraulic methods

- Ability to define different rivers with pictures and descriptions.
- Ability to insert size fractions for each series of sediments in the project and calculate particle diameters automatically by applying polynomial and linear regressions.
- Ability to calculate energy slope using various models.
- Ability to calculate discharge at different depths of flow and present stage-discharge curves for each defined river section using various one-dimensional models and a quasi-two-dimensional Shiono and Knight (1991) model.
- Optimization of Manning roughness coefficients, Eddy viscosity, and secondary flow in the main canal, left and right flood plains using Shiono and Knight (1991) model and the Genetic Algorithm.
- Training ANNs and fitting regression lines to estimate river flow discharges more accurately.
- 56 methods of calculating bed load have been programmed in this software.
- 15 methods of calculating suspended load have been programmed in this software.
- 22 methods of calculating total load have been programmed in this software.
- 17 equations of calculating shear stress have been programmed in this software.
- 39 equations of calculating uniform threshold sediment motion and 6 equations of calculating non-uniform threshold sediment motion have been programmed in this software.
- 22 equations of calculating fall velocity have been programmed in this software.
- Ability to find best combinations of equations and methods to improve the accuracy of estimations
- Ability to calculate and modelling the lateral distribution of sediment transport rates in a defined cross-section
- Ability to receive the observed sediment transport rate and calculate the discrepancy ratio, report details of calculations for each method and equation and eventually introduce the best methods and equations for the river studied.

- Various abilities to improve the accuracy of estimations such as:
  1- Calculating Calibration coefficient
  2- Creating new equations by combining different equations
  3- Training one and two-dimensional artificial neural networks

Shear stress equations

Shear stress is the force applied by flowing water to its boundary. Shear stress is also occasionally referred to as the “tractive force.” But simply, shear stress describes the force of water that is trying to move sediment to downstream. Shear stress is calculated based on the principle of conservation of momentum. For non-uniform flow conditions, the shear stress equation is complex to account for the changes in the depth over a given length; however, for the uniform flow conditions, the complex equation can be simplified to equation 1.

$$\tau = \gamma R S_f \tag{1}$$

There are other equations and methods to calculate shear stress which are obtained using different assumptions and concepts or empirically using field data or by using and combining different equations. Table 1 shows the equations studied in this study.

Table 1. Shear stress equations

Shear Stress Due to Bed Resistance	Shear Stress Due to Grain Resistance	Shear Stress Due to Bed and Grain Resistance
Chezy Equation	Manning-Strickler [D50]	Chezy (c/c')
Manning Equation	Manning-Strickler [D65]	Manning (n'/n)
Darcy-Weisbach Equation	Manning-Strickler [D90]	Van Rijn Equation
Van Rijn Equation	Laursen Equation	
Keulegan Logarithmic Equation	Van Rijn Equation	
Vanoni Logarithmic Equation	Van Rijn Logarithmic Equation	
Einstein Logarithmic Equation		
Van Rijn Logarithmic Equation		

Threshold sediment motion equations

The moment where the directive forces (shear forces) overcome restrictive forces (inertia, friction) is known as the moment of incipient motion and is the threshold of particle entrainment. The shear stress at this threshold is also known as the critical shear stress. In other words, the moment that sediment particles are about to move in the flow direction is the threshold of sediment motion. Various equations and diagrams have been introduced by researchers for calculating this parameter. The most prominent one is known by the shield’s diagram. Table 2 shows the equations studied in this study.

Table 2. Threshold sediment motion equations

Threshold Shields Parameter Calculator Models (Ɵcr)		Threshold Bed Shear Stress Calculator Models (Taucr)	Threshold Velocity Calculator Models	
			Threshold Average Velocity (Ucr)	Threshold Nearbed Velocity (ucr)
Shields (1936)	Van Rijn (1984)	Schoklitsch (1914)	Hjulström (1935)	Mavis and Laushey (1966)
White (1940)	Wiberg and Smith (1987)	Schoklitsch and Krey (1925)	Goncharov (1964)	Carstens (1966)
Kurihara (1948)	Ling (1995)	Kramer (1935)	Lavy (1956)	Garde (1970)
Iwagaki (1956)	Soulsby and Whitehouse (1997)	USWES (1936)	Neill (1968)	
Bonneville (1963)	Wu and Wang (1999)	Leliavsky (1966)	Garde (1970)	
Egiazaroff (1965)	Dey (1999)		Yang (1973)	
Upper Curve of Mantz (1977)	Paphitis (2001)		Zanke (1977)	
Mean Curve of Mantz (1977)	Hager and Oliveto (2002)			
Lower Curve of Mantz (1977)	Zanke (2003)			
Yalin and Karahan (1979)	Wu and Chou (2003)			
Brownlie (1981)	Sheppard and Renna (2005)			
Chien and Wan (1983)	Cao et al (2006)			

Evaluation criteria

For assessing the results different evaluation criteria were used in STE software:

- Discrepancy Ratio (DR):
  The discrepancy ratio is computed by dividing the calculated sediment transport rate into observed sediment transport rate:

$$DR = \frac{q_{calculated}}{q_{observed}} \tag{2}$$

- Score:
  The number of data that are calculated with a discrepancy ratio between 0.5 to 2.
- Error Parameter:
  This parameter represents the calculation error and shows the difference between the calculated and observed values. In this research, the Mean Error Ratio has been selected as equation 3.

$$MER = \frac{\sum_{i=1}^{n}\left|1-\frac{C_i}{O_i}\right|}{n} \tag{3}$$

- Point:
  This parameter is defined to indicate the best methods and solutions for the problem being studied and will be calculated using equation 4.

$$Point = Score + \frac{1}{|Error\ Parameter|+1} \tag{4}$$

Optimization technique

A genetic algorithm is a search heuristic that is inspired by Charles Darwin's theory of natural evolution. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation.

Among all intelligent optimizers, the Genetic algorithm is one of the optimizers that has great flexibility to find the best solution for problems based on selecting features. As mentioned earlier in STE software various equations are programmed to estimate bed, suspended, and total load, and also various equations are programmed to calculate shear stress, threshold sediment motion, fall velocity. A Genetic Algorithm is used to find the best equations that are able to make the final estimations of sediment transport rates more accurately. Different equations of calculating parameters such as shear stress and threshold sediment motion are ranked from 0 to their counts and these values are placed as genes in genetic chromosomes which are the individuals of the genetic population. Indexes in genes will be read in fitness functions and the values will be calculated using the corresponding equations. Calculated sediment transport rates will be compared to observed sediment transport rates and for each individual, the Point parameter will be calculated and the best solution will be the one that has obtained the highest score.

Data collection

The present study data used Haddadchi et al. (2011) dataset in which there are 16 series of sampling for the Qaresoo River located in Iran, Golestan province.

Results and discussion

At the beginning, for initial assessment of bedload transport formulas, common equations for calculating shear stress and threshold sediment motion were selected, the Chezy equation (Eq. 1) as shear stress calculator model and the Shields diagram as threshold sediment motion calculator model. Fig. 2 shows the score percentage variation for different bedload transport formulas. Table 3 presents the top 5 methods based on evaluation criteria.

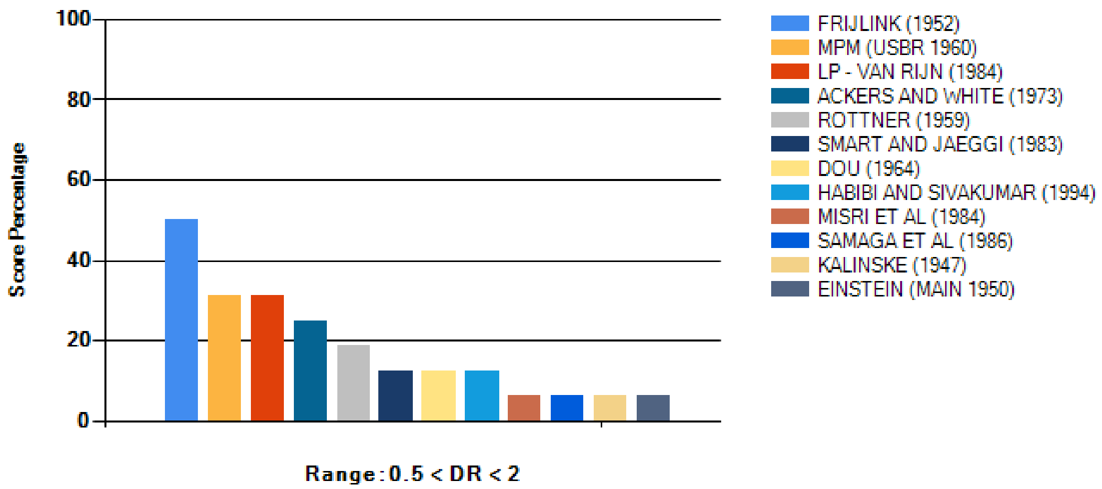

Fig. 2. Score percentage variation for different methods combined with common equations

Table 3. The top 5 bedload sediment formulas combined with common equations

Row	Method Name	Point	0.5 < DR < 2	Mean DR
1	Frijlink (1952)	8.888957	50%	8.63
2	MPM (USBR 1960)	5.851552	31.25%	11.71
3	Layer Properties - Van Rijn (1984)	5.811813	31.25%	15.37
4	Ackers & White (1973)	4.711286	25%	26.31
5	Rottner (1959)	3.817606	18.75%	14.93

According to Table 3 and Fig. 2 the best bedload transport formula is Frijlink (1952) that is able to calculate 50% of data in the discrepancy ratio range of 0.5 to 2 with 8.63 as the average. The alternative bedload transport formula is MPM (USBR 1960) that is able to calculate 31.25% of data in the discrepancy ratio range of 0.5 to 2 with 11.71 as the average.

In the following, it was proceeded to find the best equations for calculating shear stress and threshold sediment motion using the genetic algorithm and STE Software capability. Table 4 shows the best combination of these equations.

Table 4. The Best Equations Found by Genetic Algorithm

Item	The best Value
Shear Stress	Shear Stress Due to Bed and Grain Resistance - Van Rijn Equation
Threshold sediment motion	Threshold Velocity Calculator Models - Threshold Average Velocity (Ucr) - Hjulström (1935)
Bedload Transport Formula	Chang et al (1965)
Point	10.99

Bedload transport formulas were reassessed after combining with the shear stress and threshold sediment motion equations given in Table 4. Fig. 3 shows the score percentage variation for different bedload transport formulas. Table 5 presents the top 5 methods based on evaluation criteria.

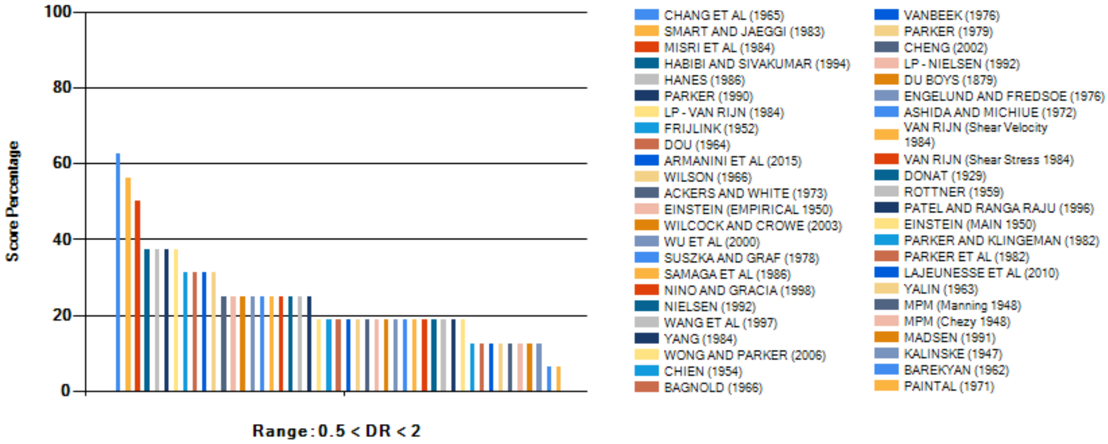

Fig. 3. Score percentage variation for different methods combined with GA found equations

Table 5. The top 5 bedload sediment formulas combined with GA found equations

Row	Method Name	Point	0.5 < DR < 2	Mean DR
1	Chang et al (1965)	10.98836	62.50%	0.91
2	Smart & Jaeggi (1983)	9.986763	56.25%	1.1
3	Misri et al (1984)	8.944554	50%	4.36
4	Habibi & Sivakumar (1994)	6.984217	37.50%	1.04
5	Hanes (1986)	6.983664	37.50%	1.22

According to Table 5 and Fig. 3 the best bedload transport formula for the Qaresoo river is Chang et al (1965) that is able to calculate 62.5% of data in the discrepancy ratio range of 0.5 to 2 with 0.91 as the average. The alternative bedload transport formula is Smart & Jaeggi (1983) that is able to calculate 56.25% of data in the discrepancy ratio range of 0.5 to 2 with 1.1 as the average. This should be noted that this result yields only if shear stress and threshold sediment motion have been calculated using equations given in Table 4.

Comparing Fig. 2 and Fig.3 clearly shows that finding and using proper shear stress and threshold sediment motion calculator models will help most of the bedload transport formulas to estimate bedload transport more accurately.

Conclusions

In this study the abilities of 55 available equations for estimating bed transport rates in the Qaresoo river located in Iran, Golestan province has been evaluated using developed software (STE). The results of this research clearly showed that the parameters shear stress and threshold sediment motion have a considerable effect in estimating bedload rates using bedload transport formula. The best bedload transport formula by using the Chezy equation (Eq. 1) as shear stress calculator model and the Shields diagram as threshold sediment motion calculator model, is Frijlink (1952) which is able to calculate 50% of data in discrepancy ratio of 0.5 to 2 with 8.63 as the average. This is while by using equations found by the genetic algorithm (Table 4), the best bedload transport formula would be Chang et al (1965) that is able to calculate 62.5% of data in the discrepancy ratio range of 0.5 to 2 with 0.91 as the average. So, it is completely obvious that for maximizing the accuracy in estimating sediment transport rates, equations for calculating shear stress, threshold sediment motion, fall velocity and so forth, ought to be selected carefully and optimized for better estimations in the future.

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