INVESTIGATION OF PERFORMANCE OF SEDIMENT TRANSPORT FORMULAS IN NATURAL RIVERS BASED ON MEASURED DATA IN KULFO RIVER, SOUTHERN ETHIOPIA

Nigussie Teklie Girma[1] and Hans-B. Horlacher[2]

[1] Arba Minch University, Institute of Water Technology, Arba Minch, Ethiopia. nigussie_tg@yahoo.com
[2] Institute of Hydraulic Engineering and Applied Hydromechanics, Dresden, University of Technology, Dresden, Germany

Abstract

Reliable prediction of sediment discharge is one of the important elements in the evaluation of riverbed degradation, local scour or deposition around hydraulic structures, reservoir sedimentation, etc.
Most of the existing sediment discharge formulas are either developed and tested in flumes or tested with limited field data. Hence, little is known on their performance in reference with measured flow and sediment data in natural rivers.
This paper presents the evaluation of seventeen existing sediment transport formulas against the field data obtained at a station in Kulfo River, Southern Ethiopia, whose bed material size is varying from very fine sand to small cobbles. Although significant deviations are found between predictions and measured values in these evaluations, a limited number of formulas gave a reasonably good agreement.

Key Words: Southern Ethiopia, Sediment Transport, Kulfo River, bed material, riverbed degradation

1 Introduction

There are wide range of objectives for sediment discharge predictions in natural alluvial rivers. They are depending on what physical phenomena one is dealing with such as reservoir sedimentation, river bed degradation, local scour or deposition around hydraulic structures, effects of sand and gravel mining on river bed equilibrium, etc. Each of the aforementioned situations is unique in its combination of the physical phenomena, while there are a large number of sediment transport formulas, which makes it extremely difficult to choose the appropriate one for a given river and situation. Besides a large number of sediment transport formulas that are presently available, little is known on performance of the existing predictors in reference with measured flow and sediment data in natural rivers. Hence, the use of field data is very important in making more realistic evaluation and selection of sediment transport formulas for a specific site condition.
In this paper, bed load, suspended sediment, and total sediment discharge formulas are investigated based on field data collected from Kulfo River, Southern Ethiopia (see Figure 1) and those with best performance are selected to be used for future sediment studies at the site.

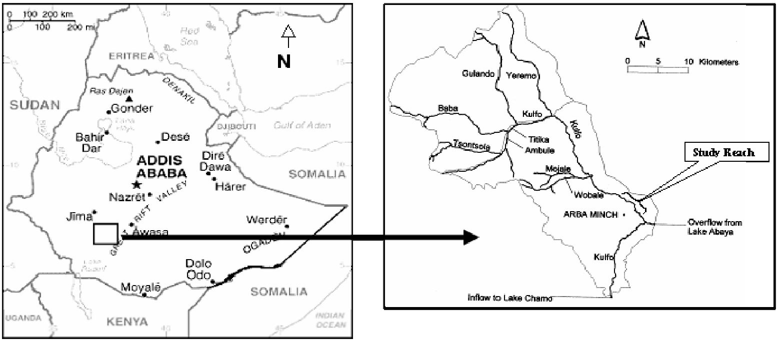

Figure 1 Location of the study site

2 Description of the Study Reach

Field survey is a critical element of any analysis of stream channel conditions as it provides quantitative data on stream conditions. Hence, channel survey of the study reach, which is 4570 m and located in the middle course of Kulfo River, was conducted at different times during the study period.

From this survey the slope was found to vary between 0.7 and 1.4% with an average value of about 1% for the reach. This bed slope, according to Bathurst, et al (1987), is classified as steep. Figure 2 shows the overall longitudinal profile of the study reach where the important locations and sampling stations are indicated.

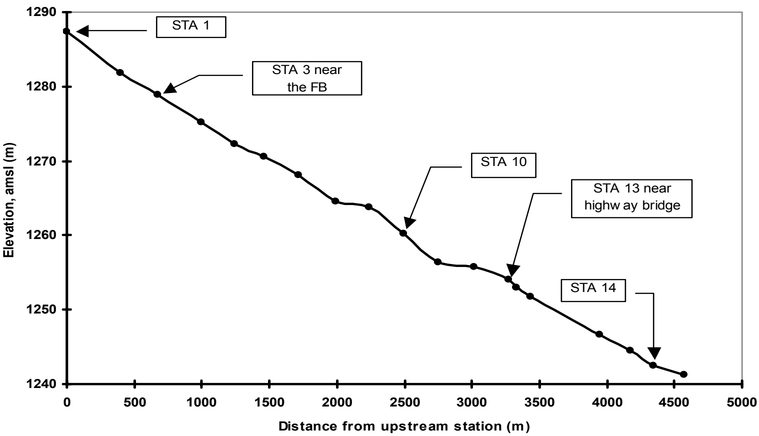

Figure 2 Longitudinal profile of the study reach showing bed material and sediment sampling stations (note: FB – footbridge)

The longitudinal profile of the reach is determined by measuring the distances from a reference station and the corresponding elevations along the thalweg. Cross sections are also located at some specified distances along the channel, based on requirements for water and sediment sampling.

3 Bed Material, Flow and Sediment Transport Data

Extensive flow and sediment data were collected on Kulfo River at a number of stations in the study reach over the period 2002 and 2003. As size distribution is one of the most important parameter in sediment transport studies, detailed sampling and size analysis of both surface and subsurface bed material is performed. This analysis showed the surface material size to vary from medium gravel to small cobbles while the associated subsurface material ranged from very fine sand to small cobbles with median size of 1.6 mm to 17 mm over the reach (Table 1 & Figure 3). The grain size analysis of the subsurface material further showed that it is very poorly sorted with large geometric standard deviation as shown in Table 1.

Table 1 Subsurface bed material characteristics over the reach, Kulfo River

Station	d_{10} (mm)	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	d_{90} (mm)	Geom. Standard deviation	Remark
1	**0.7**	**1.1**	**17.0**	**60.0**	**73.0**	**5.98**	**Most upstream station**
3	**0.4**	**0.7**	**14.0**	**59.0**	**72.0**	**7.07**	
10	**0.4**	**0.7**	**11.0**	**42.2**	**52.4**	**6.82**	
13	**0.3**	**0.6**	**7.6**	**41.1**	**51.7**	**8.22**	
14	**0.1**	**0.3**	**1.6**	**26.4**	**39.8**	**11.82**	**Most downstream station**

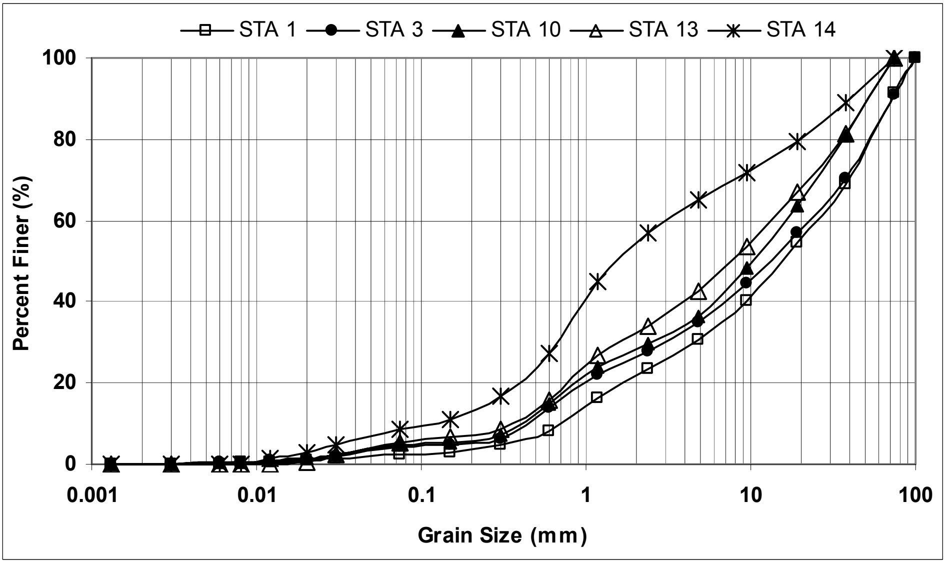

Figure 3 Subsurface grain size distribution of the study reach (stations 1, 3, 10, 13 & 14)

In addition to bed material sampling, hydraulic and sediment data were also obtained. These included flow widths and depths, water discharges, bed load rates, suspended sediment concentrations, and grain size distributions of both suspended sediment and bed load. At one of the sampling stations (i.e., station 3) 310 flow, 257 bed load, and 310 suspended sediment concentration data were obtained at low to high flow events during the study period. The flow varied from 0.48 to 107.5 m³/s, bed load rate from 0.003 to 3.94 kg/s, and suspended sediment concentration from 19.0 to 59741.2 mg/l. These data together with the channel geometric parameters are employed for computation of sediment discharges and for comparison with predictions of various formulas.

4 Methods of Evaluation and Selection of Sediment Transport Formulas

The various existing functions were developed from different sets of field and laboratory data and their predictions may be good in some applications and not in others. As a result, different functions may give widely differing results for a given river. A formula that predicts sediment discharge adequately for one river does poorly for the other river. Therefore, testing of the predictive capability of sediment transport formulas against measured data in the study river is very important for the purpose of selecting and adopting for future sediment studies.

Kulfo is a gravel-bed river; so the selection of formulas was based on their applicability to such conditions. Hence, all transport formulas are not tested; instead those formulas developed for this purpose are selected from literature. The methods used for evaluating the formulas are: (1) comparison of sediment rating curves of calculated sediment discharge versus water discharge with measured values, and (2) calculation of the deviation of predicted sediment discharges from measured values or by means of a discrepancy ratio, r, which is the ratio between predicted and measured sediment discharge.

In the first method comparison is made either with the observed pattern of the sediment discharge or with curves generated through the application of other formulas. Here attention is paid toward the overall performance of the formula in question, while in the second method emphasis is placed on the ability of the formula to duplicate individual data.

Computation of sediment discharge was made either manually or using the SEDDISCH computer program developed by Stevens and Yang (1989). The SEDDISCH program incorporates seven bed material and six bed load discharge formulas within it, out of which those relevant to gravel-bed rivers are selected for computation of sediment discharge using the program.

In this investigation, a total of seventeen sediment discharge formulas were tested using field data from Kulfo River. Table 2 shows summary of comparisons between the formulas based on the data falling in the specified discrepancy ranges; and details about each formula can be found in the references cited.

Table 2 Summary of predictions of the different formulas, Kulfo River

Formula	No. of data	Percentage of data in the range (%)			Type of sediment discharge	Reference
		¼<r<4	1/3<r<3	½<r<2		
Ackers and White	108	19	11	7	TL	Ackers and White (1973)
Bagnold	186	87	80	56	TL (BL, SS)	Yang (1996)
Chang, et al	48	41	30	20	SS	Yang (1996)
Einstein	116	16	11	5	TL (BL, SS)	Simons & Senturk (1992)
Engelund & Hansen	173	87	79	61	TL	Yang (1987)
Graf	186	6	5	4	TL	Graf (1984)
Lane & Kalinske	48	31	31	29	SS	Yang (1996)
Laursen	173	20	10	8	TL	Graf (1984)
Meyer-Peter & Mueller	173	69	65	46	BL	Simons & Senturk (1992)
Parker, et al	52	0	0	0	BL	Parker, et al (1982)
Schoklitsch	185	44	31	12	BL	Graf (1984)
Smart	50	0	0	0	BL	Smart (1984)
Toffaleti	47	79	64	45	TL	Simons & Senturk (1992)
Van Rijn	18	67	50	33	SS	Rijn (1993)
Yang	173	46	31	16	TL	Yang (1996)

Note: BL – Bed Load; SS – Suspended Sediment; TL – Total Load

Figures 2a – 2c are the plots of the predicted against measured sediment discharges for the formulas evaluated. As can be seen from Table 2, the maximum frequency of 61% was attained for the range of $0.5 < r < 2$ for the formula of Engelund and Hansen followed by Bagnold (56%) and Meyer-Peter & Mueller (46%).

Further observation of Figures 2a – 2c show that most of the formulas either under- or overpredicted the measured values. Generally, none of the formulas achieved an r value very close to unity; therefore, the performance of the formulas shall be evaluated after observing their overall trend with respect to the measured values.

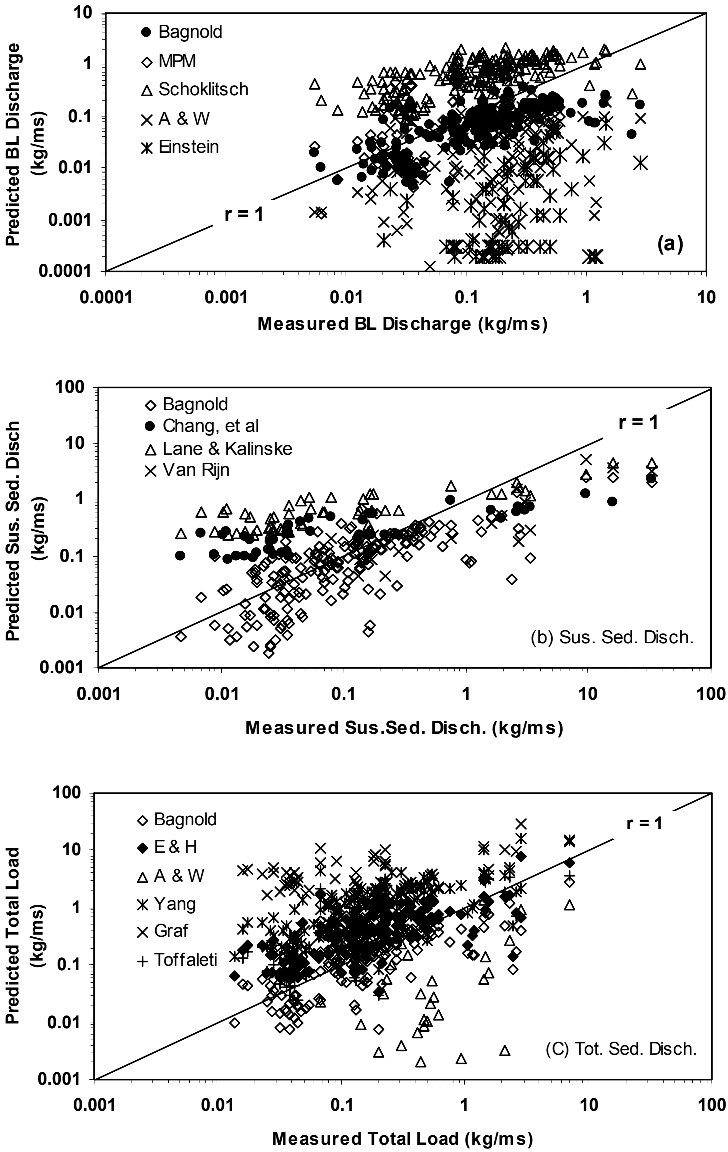

Figure 2 Comparison of measured and predicted (a) bed load, (b) suspended sediment, and (c) total sediment discharges for Kulfo River (r = 1 indicates perfect agreement between measured and predicted values)

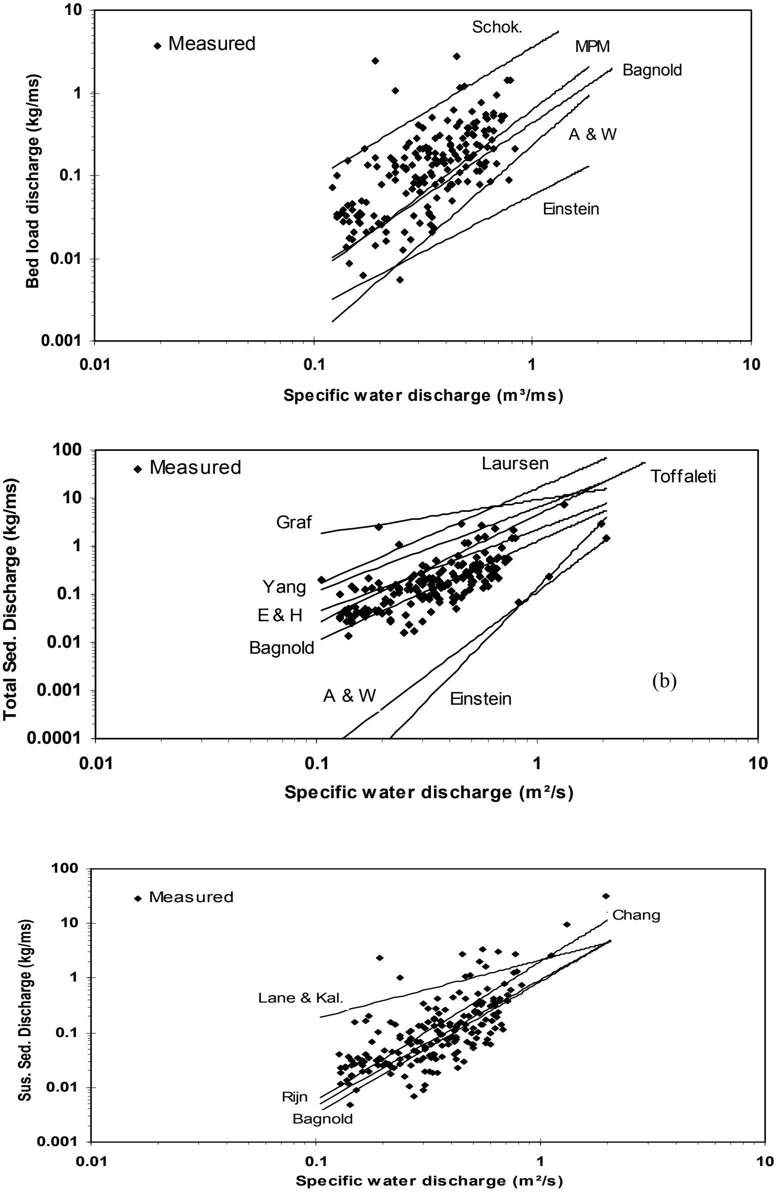

Figure 3 Predicted and measured sediment discharges plotted against water discharge: (a) bed load, (b) suspended sediment, and (c) total load.

Figure 3a – 3c are sediment rating curves of predicted sediment discharge versus specific water discharge with measured values. These curves are based on the second method of evaluation, which show the trend of each formula whether it closely follows the measured sediment discharge or not.

Observation of the slopes of the curves in Figure 3a show that Meyer-Peter and Mueller and that of Bagnold curves follow the trend of the measured bed load discharge data considerably better than the other formulas. In Figure 3b, although the curves of all the equations, except Lane and Kalinske, seem to follow the measured data, based on the consideration of mean discrepancy ratio, only Bagnold´s method is found to be with a better potential as a suspended sediment discharge predictor for the site. In a similar manner, observation of Figure 3c shows, among the total load formulas Bagnold´s curve is very well fitting to the measured data. The slopes of the curves of Engelund and Hansen, Yang, and Toffaleti formulas are also following the trend of measured total load discharge. However, in addition to the two methods of evaluation given above, considering other factors such as simplicity of the formula for application, data requirements, etc., formulas of Bagnold, Engelund and Hansen, and Yang are selected.

Based on this evaluation, out of the seventeen formulas the predictions of two bed load discharge formulas (i.e., Bagnold and Meyer-Peter and Mueller), one suspended sediment discharge formula (i.e., Bagnold), and three total sediment discharge formulas (i.e., Bagnold, Engelund and Hansen, and Yang) gave a reasonably good agreement with measured sediment discharges; and therefore selected.

5 Summary and Conclusion

Out of a large number of formulas evaluated only few of them were found with reasonable agreement with the field data. Therefore, the investigation of the prediction of sediment transport formulas undertaken herein shows the necessity of testing a number of formulas with field data before making final choice of predictors for a given site condition. Finally, although the formulas selected herein are tested for only one river, the results are indicative of those for natural rivers in similar geographic, hydraulic, and sediment conditions.

6 References

Ackers, P. and White, W.R. (1973). Sediment Transport: New Approach and Analysis. Jour. of Hyd. Division, ASCE, Vol. 99, No. HY11, pp. 2041-2060.

Bathurst, J.C., Graf, W.H. and Cao, H.H. (1987). Bed Load Discharge Equations for Steep Mountain Rivers. In: Thorne, C.R., Bathurst, J.C. and Hey, R.D. (eds), Sediment Transport in Gravel-bed Rivers, pp. 453 – 491, John Wiley & Sons Ltd.

Graf, W. H. (1984). Hydraulics of Sediment Transport. WR Publications.

Parker, G., Klingeman, P.C. and McLean, D.G. (1982). Bed Load and Size Distribution in Paved Gravel-bed Streams, Journal of Hydraulic Engineering, ASCE, Vol. 108, No. HY4, pp. 544-571.

Rijn, L. C. van (1993). Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas, AQUA Publications.

Simons, D.B. and Senturk, F. (1992). Sediment Transport Technology: Water and Sediment Dynamics, Water Resources Publications, Littleton, Colorado, USA.

Smart, G.M. (1984). Sediment Transport Formula for Steep Channels, Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 3, pp. 267-276.

Stevens, H.H. and Yang, C.T. (1989). Summary and Use of Selected Fluvial Sediment Discharge Formulas: USGS WR Investigations Report 89 – 4026.

Yang, C.T. (1987). Energy Dissipation Rate Approach in River Mechanics. In: Thorne, C.R., Bathurst, J.C. and Hey, R.D. (eds), Sediment Transport in Gravel-bed Rivers, John Wiley & Sons Ltd.

Yang, C.T. (1996). Sediment transport: Theory and Practice, McGraw-Hill Companies, Inc., New York.