Evaluation and calibration of bedload equation for the mountain ephemeral stream of Gujarat, India

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Bedload is rarely measured in Indian rivers. It is recommended that 5% of suspended load can be taken as bedload in the absence of measured bedload. The present study validates this by direct physical measurement of bedload using the Helley–Smith sampler in an ephemeral mountain stream of Gujarat, India. It was observed that, on an average, the bedload formed 3.97% of the suspended load. The measured bedload flux was 1.02 tonnes/day. To overcome the need and dependability on actual physical bedload measurement, a bedload rating curve against specific discharge was developed to predict the bedload rate in the study reach. Few prominent existing bedload equations selected from the literature were tested against the measured bedload, which over-predicted the bedload transport rate with a discrepancy ratio greater than 2 and RMSE 2.4–48. A calibration coefficient $\xi = 0.00167$ was introduced in the widely used Recking (2013) equation for the study reach resulting in an improvement of the coefficient of variation as 1.92 and RMSE as 1.35.

Keywords: Bedload, hydraulic parameters, mountain stream, sediment transport, suspended load.

PREDICTION of bedload is essential for designing, planning, managing and operating hydraulic projects such as dams, hydropower plants and canals. Sediment movement is affected by various factors, including the construction of reservoirs, changes is in land use and land cover, other types of land disturbances which include mining activities, land and water management, climate change and sediment control programmes[1]. Transporting sediments to water bodies decreases the water quantity and quality, thereby increasing water purification costs and decreasing the availability of ready water for many other uses[2]. Numerous bedload transport equations were developed for the estimation of bedload transport rate. Most of these equations were derived using experimental flume data. The reliable applicability of these equations under different field conditions still needs to be established. Consequently, it is necessary to quantify the sediment transport rate using a direct sampling technique in the field. Incorporating the field-observed data with these equations will help develop the sediment transport model, demonstrating the actual field conditions and providing results with low discrepancy. The collection of bedload from a river is time-consuming and expensive[3]. In India, bedloads are rarely measured as a regular practice. The bedload transport rate depends on various parameters such as average flow velocity, water depth, water discharge, energy slope, stream power, shear stress, water temperature and strength of turbulence[4]. Bedload transportation in natural rivers is highly complex. At present, no bedload equation is universally applicable under varying flow and grain size distribution characteristics[5]. The channels behave uniformly during high flow, while there is more inherent variability in sediment transportation during low flow[6]. So, it is desirable to do sampling in all possible flows of a river to analyse the channel behaviour from low to high flow.

Driving forces for the movement of sediment particles include not only shear stress but also parameters like mean flow velocity (competency approach), fall velocity (lift concept), specific discharge (discharge concept), channel slope, etc. The turbulence and power of the flowing fluid determine the sediment size that moves as bedload[7]. In general, the bedload of a river is 5–25% of that in suspension[5,8]. The depth-integrated samples are more suitable for quantifying sediment load, as errors produced by vertical averaging are larger when using a few point samples only[9].

The bedload transportation in gravel-bed rivers is highly variable spatially and temporally due to the influence of exposure and hiding factor[10]. In the past, researchers have studied the effect of the non-uniformity of bed materials on sediment transport[11]. In non-uniform sediments, the smaller ones are sheltered by coarser sediments, resulting in large exposure areas for coarser sediments and small exposure areas for finer sediments in a flowing fluid. This signifies an appreciable reduction in critical shear stress for the coarser fraction and an increase in critical shear stress for the finer fraction. In the study of the exposure and hiding effect in bimodal sediments on critical shear stress, an increase of 75% in critical shear stress was found for the sand fraction and a decrease of 64% for the gravel fraction[12].

The 76 mm Helley–Smith (HS) sampler is a direct-point bedload measuring sampler which is easy to use and is widely accepted for bedload sampling[13–17]. Compared to

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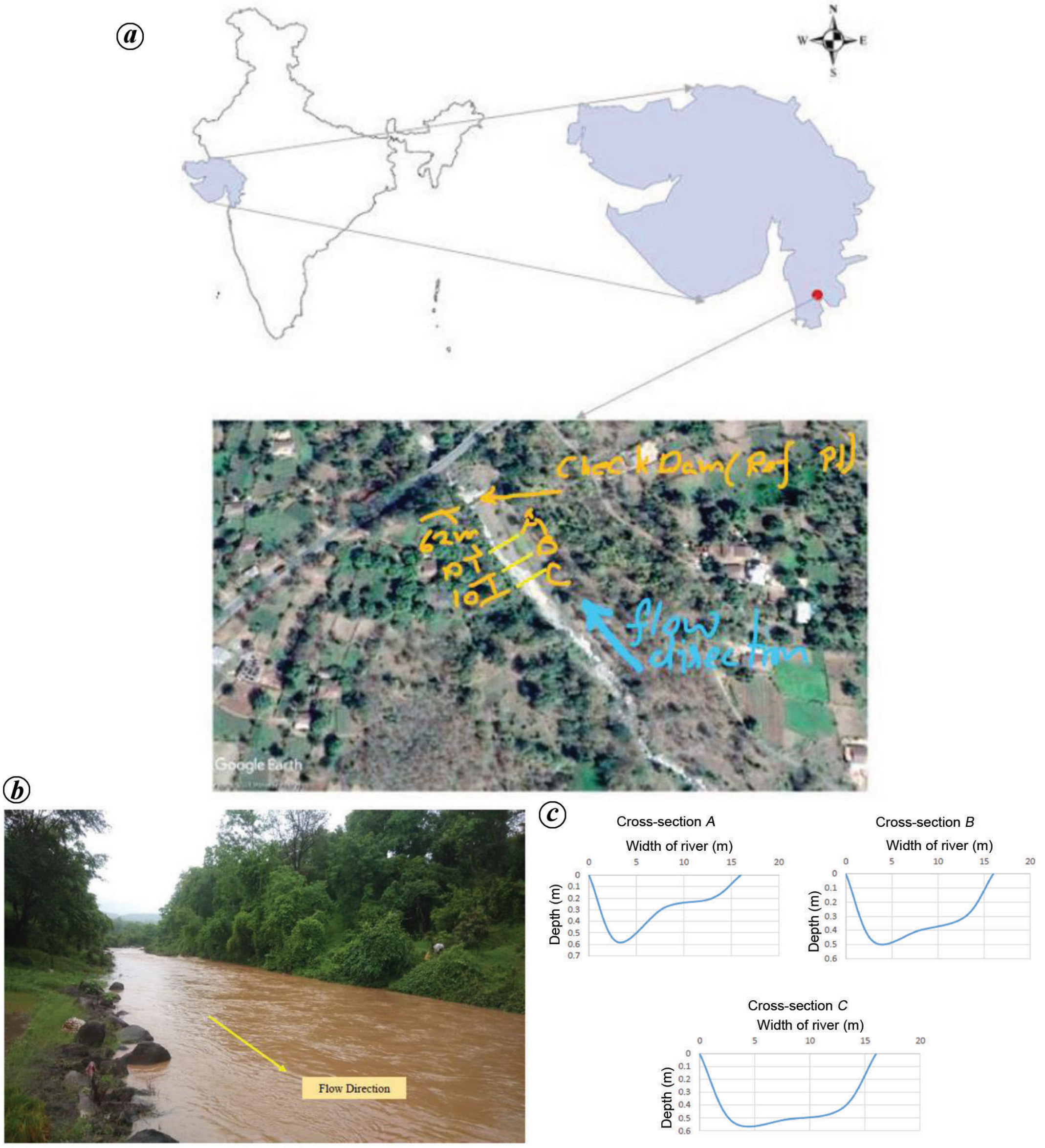

Figure 1. ***a***, Index map of Kharera, Gujarat, India and sampling sections. ***b***, Kharera stream in full flow. ***c***, Cross-sectional profile.

multiple points sampling and reach averaging method, sampling at a single-point location gives more reliable results provided data are sufficiently large to cover the range of possible flow conditions[15].

In the present study, bedload was measured at selected points across the sections using the 76 mm HS sampler. A bedload rating curve against specific discharge was also developed. The performance of the selected bedload transport equations was assessed using the measured bedload and other hydraulic parameters. The equation of Recking (2013) was calibrated for a more accurate prediction of bedload in study the reach. The proportion of suspended load and bedload in the total load for a mountain ephemeral alluvial stream was analysed to validate the results of Waikhom and Yadav[18].

Study site and field measurements

The Ambica River is a west-flowing river having its catchment in Maharashtra and Gujarat. Kapri, Wallan, Kaveri and Kharera are the important tributaries of the western Ambica River basin. The Kharera riverbed contains sand gravel and cobble. Bedforms are not present and the river planform is governed by the valley rather than sediment movement and has witnessed less change over the years.

The planform can be classified as single-phase irregular width variation (AGU classification). The channel width changes slightly due to bank erosion in some places. The Kharera basin contains 65% crop land, 10% forest and shrubs, and 23% plantation. The basin soil is mostly alluvial debris washed down from the hills in the region (Water Resources

Information System). Rainfall during the monsoon season is from late June to early September, with an annual average of 1700 mm. The selected reach is 96 m amsl having lat. 20°42′21.00″–20°42′19.07″N and long. 73°18′30.74″–73°18′32.21″E. Figure 1 *a* shows the index map and sampling sections in the study reach of the Kharera stream. Figure 1 *b* shows the Kharera during full flow condition and Figure 1 *c* shows the profile of cross-sections *A–C*.

These cross-sections are situated upstream of the check dam at a distance of 62, 72 and 82 m respectively. They are comparatively straight, stable and suitable for multiple measurements. At each cross-section, depth of flow, velocity, bedload and suspended load were measured at 3, 8 and 13 m lateral distances from the right bank of the stream. A pygmy cup-type current meter was used to measure velocity. The average velocity of flow was between 0.38 and 0.87 m/s in the selected stretch. The suspended load samples were collected using a Punjab bottle sampler at 0.6 depth from the water surface and oven-dried in the laboratory to determine the concentration of the suspended sediment load. Standard equipment was used to measure geometrical parameters. Figure 2 shows the slope of the study reach, which was computed as 0.0045 (1 in 223).

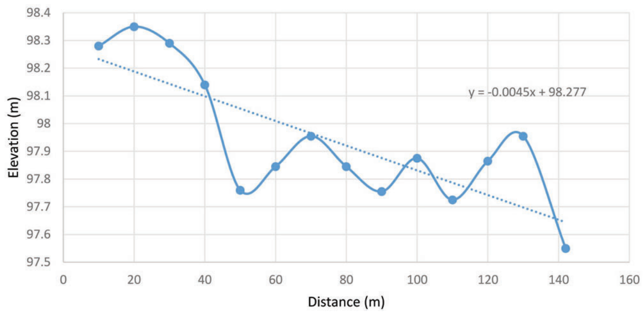

Figure 2. Bed slope measurement in the river reach.

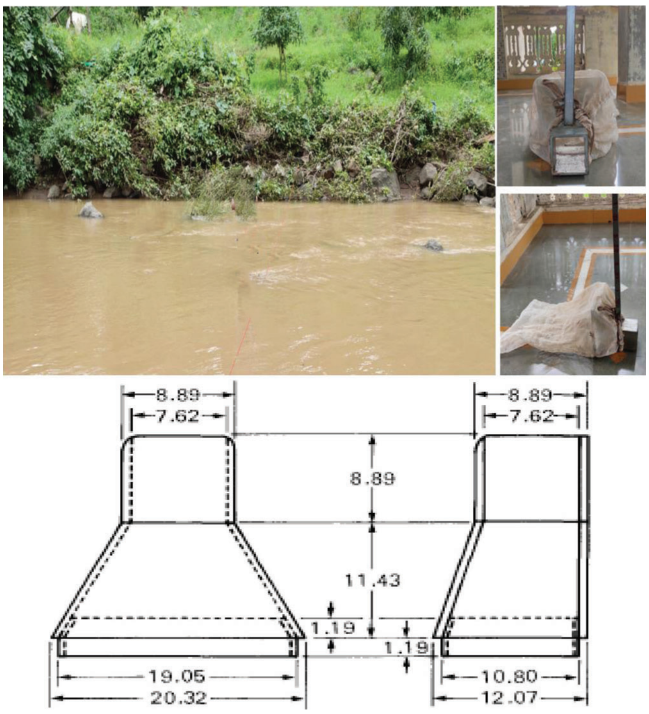

Figure 3. Measurement of bedload using Helley–Smith sampler. (Source: ref. 13.)

Bedload was measured using a locally fabricated HS sampler with a square entrance nozzle of size 76.2 mm × 76.2 mm (Figure 3). The sampling bag was made up of polyester mesh having 0.25 mm size openings.

This sampler has an expansion ratio (ratio of exit area to entrance area) of 3.22 and provides an adjustable handle for easy use over a range of depths. The trapping efficiency of the sampler is the ratio of the collected bedload weight at a given time to the bedload weight passing through the sampler width at the same time[19]. The HS sampler's trapping efficiency reduces as the size of the particle increases. For particle sizes ranging from 0.5 to 16 mm, the HS sampler gave a hydraulic efficiency of 0.9–1.1, provided it was not filled more than 30% (ref. 13).

Bedload and suspended load transport analysis

Measurement and calculation of bedload transport rate

The Kharera stream is an ephemeral stream with the flow in the monsoon season only. The bedload was collected on different days from July to September. The minimum sampling time for the HS sampler is 60 sec. Sampling time can be increased for a low bedload transport rate to 300 sec (ref. 20). In the present study, a sampling time of 20 min was selected to collect a sufficient quantity of bedload samples for analysis. The collected bedload samples were dried and sieved in the laboratory to analyse sediment gradation of bedload. Figure 4 shows the gradation curves for bedload sample collected at cross-section *A*.

Table 1 shows the grain size distribution of the collected bedload samples at cross-sections *A–C*. Table 2 summarizes

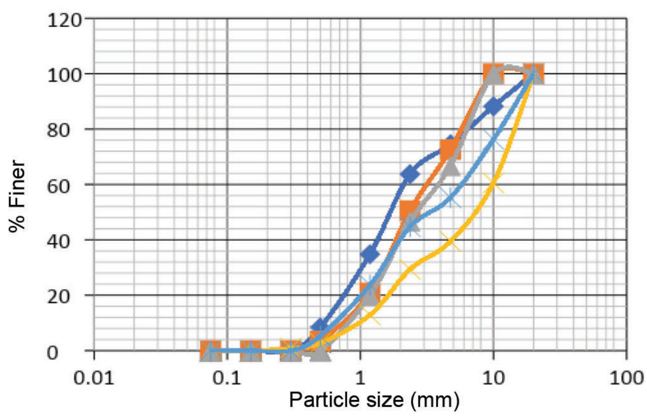

Figure 4. Gradation curves for bedload samples collected at cross-section *A*.

Table 1. Grain size distribution of bedload material

River section	Distance from right bank (m)	Sediment diameter (mm)					
		D_{10}	$D_{15.9}$	D_{35}	D_{50}	$D_{84.1}$	D_{90}
A	3	1.30	1.37	1.59	1.77	2.17	2.24
	8	0.54	0.69	1.19	1.80	8.42	11.50
	13	1.42	1.71	2.82	4.05	8.55	9.43
B	3	0.42	0.49	0.82	0.89	6.24	7.64
	8	0.45	0.57	1.04	1.67	8.17	9.83
	13	0.48	0.61	1.02	1.52	6.19	7.60
C	3	0.83	1.02	1.85	2.84	15.23	8.43
	8	2.19	2.85	5.44	9.67	16.74	17.95
	13	0.94	1.32	2.54	4.73	11.68	14.77

Table 2. Measured and computed hydraulic parameters for cross-sections *A*, *B* and *C*

Run no.	River section	Slope ($\times 10^{-3}$; (m/m))	Width (m)	Hydraulic radius (m)	Area (m^2)	Froude number	Bedload transport rate (tonnes/day)	Mean flow velocity (m/s)	Shear velocity (m/s)	Shear stress (N/m^2)	Discharge (m^3/s)
1	*A*	4.5	16	0.25	3.97	0.31	1.85	0.46	0.10	10.91	1.98
2	*A*	4.5	16	0.24	3.90	0.28	1.02	0.46	0.10	10.71	1.64
3	*B*	4.5	16	0.32	5.17	0.34	0.47	0.46	0.12	14.22	2.99
4	*B*	4.5	16	0.30	4.83	0.33	0.64	0.44	0.12	13.28	2.66
5	*C*	4.5	16	0.41	6.53	0.20	0.83	0.39	0.13	17.92	2.86
6	*C*	4.5	16	0.44	7	0.30	1.10	0.36	0.14	19.21	2.34
7	*A*	4.5	16	0.55	8.83	0.39	1.96	0.87	0.16	24.05	10.06
8	*A*	4.5	16	0.18	2.83	0.34	1.39	0.40	0.09	7.78	1.69
9	*A*	4.5	16	0.18	2.83	0.25	0.81	0.39	0.09	7.78	1.24
10	*B*	4.5	16	0.27	4.36	0.47	1.04	0.62	0.11	11.99	3.38
11	*C*	4.5	16	0.35	5.63	0.21	0.14	0.41	0.12	15.47	2.27

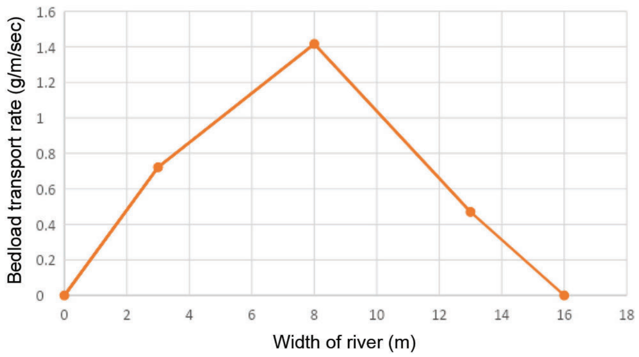

Figure 5. Bedload variation at cross-section *A*.

variously measured and computed hydraulic parameters at these cross-sections *A*–*C*. Figure 5 shows the lateral variation of bedload at cross-section *A*.

Bedload discharge was determined using the following formula[21]

$$Q_b = (1/2)[W_{tb1}L_1 + (W_{tb1} + W_{tb2})L_2 + \cdots + (W_{tbi} + W_{tbi+1})L_i], \quad (1)$$

$$W_{tb} = M/(W_s N_s T_s), \quad (2)$$

where Q_b is the bedload discharge (g/s), L the length between two points (m), W_{tb} the dry weight per unit time per unit width (g/s/m), M the dry bedload mass (g), W_s the width of intake nozzle of sampler (m), N_s the number of repetitions, T_s is the sampling time (s).

Selected bedload equations for calculating bedload transport rate

The five widely employed bedload equations were used to compute bedload transport rate in the Kharera stream (Table 3).

Evaluation and comparison of bedload equations

The bedload transport rate was computed using the reach-average method. Flow and sediment parameters were averaged over a cross-section. These average parameters were utilized to predict the bedload transport rate using the bedload equations of Schoklitsch[22], Kalinske[23], Meyer-Peter and Mueller[24], Brown[25] and Recking[26].

The standard statistical parameters were calculated to check the performance of the bedload equations. The discrepancy ratio (DR) was computed in eq. (3), an average of variation coefficient (V_c) in eq. (4) and root mean square error (RMSE) in eq. (5).

$$\text{DR} = \frac{\text{Calculated bedload discharge}}{\text{Measured bedload discharge}}, \quad (3)$$

Table 3. Bedload equations

Approach to compute bedload	Year	Formula
Schoklitsch	1934	$q_b = 2500 S_o^{1.5}(q - q_c),\ q_c = 0.26(G-1)^{5/3} d^{1.5} / S_o^{7/6}$
Kalinske	1947	$\frac{q_{bv}}{\sqrt{(G-1)gd_{50}^3}} = 10.0\left(\frac{\tau_0}{(\gamma_s - \gamma)d}\right)^{2.5}$
Meyer-Peter and Muller	1948	$\phi = 8(\theta - 0.047)^{3/2},\quad \theta = \frac{SR}{(G-1)d_{50}}$
Brown	1950	$q_{bv} = F_1 q_* \sqrt{(G-1)gd_{50}^3}$ $F_1 = \sqrt{\frac{2}{3} + \frac{36}{d_*^3}} - \sqrt{\frac{36}{d_*^3}}$ $\tau_* = \frac{SR}{(G-1)d_{50}}$ If $\tau_* < 0.09$, then $q_* = 2.15\ \exp\left(-\frac{0.391}{\tau_*}\right)$ If $\tau_* \geq 0.09$, then $q_* = 40\tau_*^3$
Recking	2013	$\phi = \frac{14(\tau_{84}^*)^{2.5}}{\left[1 + \left(\frac{\tau_m^*}{\tau_{84}^*}\right)^4\right]}$ $\tau_m^* = (5S + 0.06) \times \left(\frac{d_{84}}{d_{50}}\right)^{4.4\sqrt{S} - 1.5}$ $\tau_{84}^* = \frac{SR}{(G-1)d_{84}}$

q_b is the bedload transport rate in mass per unit time and width (kg/m/s), q_{bv} the bedload transport rate in volume per unit time and width (m^3/m/s), q the water discharge per unit width (m^3/s/m), q_c the critical water discharge per unit width (m^3/s/m) corresponding to sediment threshold, d the sediment size, s the bed slope, ϕ_b the bedload transport intensity, θ the Shields parameter, θ_c the threshold Shields parameter, F_1 the fall velocity parameter, q_* the dimensionless bed flux, d_* the dimensionless particle size, τ_* the dimensionless shear stress parameter, τ_0 the average bed shear stress, ν the kinematic viscosity of the fluid, G the specific gravity of sediment, g gravity acceleration, γ_w the unit weight of water, γ_s the unit weight of sediment particle, ρ the density of flowing fluid, R the hydraulic radius and S/S_0 is the channel bed slope.

Table 4. Statistical parameters for selected bedload equation

Bedload equation	Schoklitsch (1934)	Kalinske (1947)	Meyer–Peter and Muller (1948)	Brown (1950)	Recking (2013)
Average of variation coefficient	197.26	3028.28	4002.43	7276.08	1279.94
RMSE	2.42	20.84	31.34	48.05	8.95
Discrepancy ratio	>2	>2	>2	>2	>2

$$V_c = \frac{\sum_{i=1}^{n} \mathrm{DR}}{n}, \quad (4)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(Q_{bc} - Q_{bm})^2}{n}}, \quad (5)$$

where Q_{bc} and Q_{bm} are the computed and measured bedload discharge respectively, where n is the total number of observations.

Table 4 presents the performance of the selected five bedload equations.

All five bedload equations overpredicted the bedload transport rate compared to the measured bedload transport rate. Figure 6 compares measured and computed bedload transport rates for the selected bedload equations. Most of the data points lie above and far from the line of equality, indicating significant overprediction of the bedload transport rate.

The Schoklitsch[22] equation performed better than the other equations. None of the bedload equations gave consistent

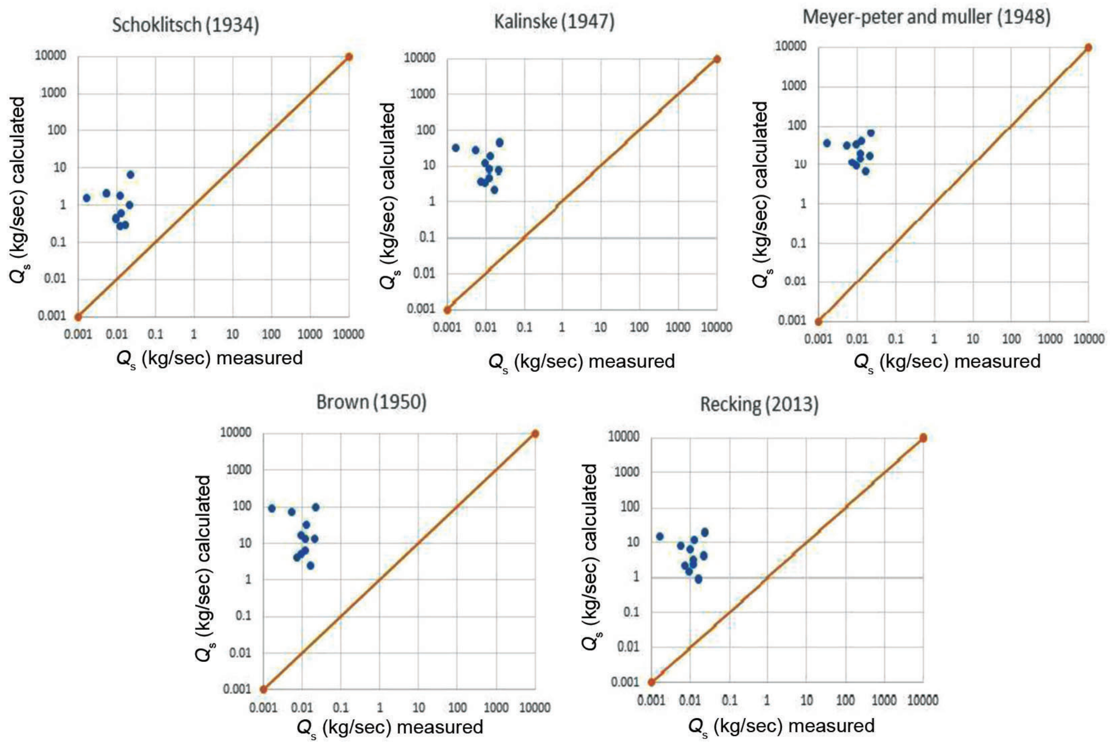

Figure 6. Comparison of computed and measured bedload rate for Kharera stream.

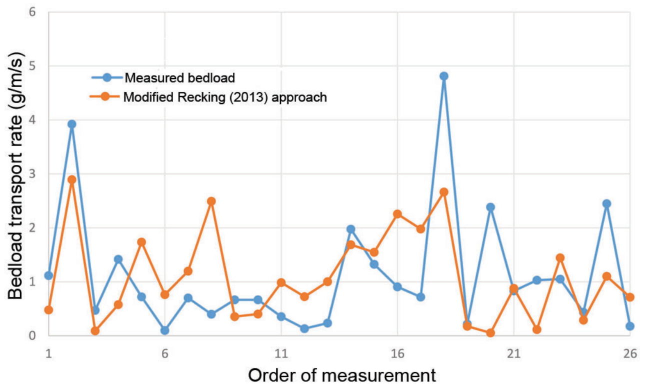

Figure 7. Comparison of calibrated Recking (2013) relation and measured bedload rate.

results. This may be due to the hiding and sheltering effect in rivers resulting in low bedload transportation rates. The other reasons for such variations could be the unaccountability of parameters like channel roughness, the viscosity of the fluid, temperature, sediment composition of the bed material, active channel width, supply and availability of sediments, composition of active bed layer, etc.

Calibration of Recking (2013) equation

In non-uniform sediments, bedload rate is controlled by large-diameter particles because of exposure and hiding effect. To Recking[26] equation was developed for gravel and cobble bed considering the exposure and hiding effect. A calibration coefficient ξ was introduced by trial-and-error approach in the Recking[26] bedload equation to improve its predictability accuracy for the selected river reach, as given in eq. (6).

$$\phi = \xi \frac{14(\tau_{84}^{*})^{2.5}}{\left[1+\left(\dfrac{\tau_m^{*}}{\tau_{84}^{*}}\right)^{4}\right]}, \qquad (6)$$

where ϕ is the bedload transport intensity, τ_m^* the mobility shear stress and τ_{84}^* is the shield shear stress corresponding to d_{84} sediment size.

The minimum average discrepancy ratio was achieved for the calibration coefficient value of 0.00167. Figure 7 shows a comparison of the calculated bedload transport rate using the calibrated Recking[26] equation and the measured bedload rate. The value of the calibration coefficient varies from one site to another depending upon discharge and gradation of bed material.

The performance of the calibrated Recking[26] equation was analysed using the selected statistical parameters (Table 5). The discrepancy ratio varied from 0.022 to 7.751, but the average variation coefficient was 1.921 and RMSE reduced significantly, showing good agreement between predicted and measured bedload discharge.

Table 5. Statistical parameters for modified Recking (2013) approach

Bedload model	Average of variation coefficient	RMSE	Discrepancy ratio
Modified Recking (2013) approach	1.92	1.35	Ranges from 0.02 to 7.75

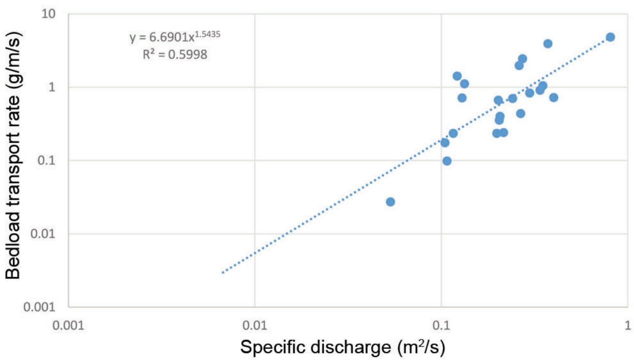

Figure 8. Bedload rating curve of Kharera river.

Bedload prediction by rating curve

The bedload rating curve was developed using the specific discharge (m^2/s) and bedload transport rate (g/m/sec), as given in eq. (7). The rating curve was derived by measuring the flow parameters and bedload at a point location. Specific discharge was computed by multiplying the depth and average velocity at a point location and bedload was collected simultaneously at the same point. Figure 8 shows the bedload rating curve developed using the collected bedload samples. The best-fit line reveals the coefficient of determination to be 0.5686.

$$Q_b = 6.690q^{1.5435}, \quad (7)$$

where Q_b is the bedload transport rate (g/m/s) and q is the specific discharge (m^2/s).

Measurement and calculation of suspended sediment load

The suspended sediment load was measured using a handheld Punjab bottle sampler (IS-3912:2014). Samples were collected at 0.6 depth from the water surface, at three verticals (lateral distance) of 3, 8 and 13 m from the right bank of the stream. These samples were oven-dried after filtering to determine the concentration of suspended sediment. The concentration of suspended sediment load varied between 50 and 540 ppm for different flow conditions.

The river cross-section was divided into three segments with a width of 3, 10 and 3 m. The segmental discharge was calculated by multiplying the flow area and velocity. Finally, eq. (8) was used to determine the suspended sediment load (Table 6).

$$\text{SSL} = \sum_{i=1}^{n} (C_i Q_i) \times 0.0864, \quad (8)$$

where SSL is suspended sediment load (tonnes per day), C the concentration of the suspended sediment (mg/l) and Q is the segmental discharge (m^3/s).

Bedload proportion in total load

Table 6 shows the measured bedload, suspended load, total load and the ratio of bedload to suspended load. The measured average bedload transport rate for the Kharera stream was 1.02 tonnes/day. The bedload was approximately 3.96% of that of the suspended load.

From Table 6, it can be seen that the obtained average percentage value of 3.97 for suspended load to be taken as bedload transport rate, lies between 0% and 5%, recommended by Waikhom and Yadav[18].

Discussion and conclusion

The applicability and validity of the bedload equations were assessed based on the generality of the assumptions used in the derivation and the agreement between the measured and calculated results[4]. Most of the derived bedload equations have general assumptions: (a) flow parameter and sediment properties are invariant and the bedload transport rate is in a steady state, (b) the bedload transport rate is a function of sediment and flow parameters and (c) a maximum possible amount of bedload is being transported[27]. These assumptions do not relate exactly to the field conditions, which may be a reason for overprediction by all the selected bedload equations. Parameters like discharge, flow depth, velocity and bedload rate vary spatially and temporally in a river. The sediment transport equations typically overpredict the bedload transport rate by several orders of magnitude. These equations do not account for the limited conditions of sediment supply[28]. Turbulence near the riverbed affects the bedload rate significantly, an increase in the turbulence level will increase the bedload rate[29].

The bedload sampling is challenging during high flow conditions due to safety concerns. The Kharera, being a river in a mountainous region, the response to catchment rainfall is

Table 6. Measured bedload, suspended load and total load

Run no.	River section	Measured suspended load (tonnes/day)	Measured bedload (tonnes/day)	Total load (tonnes/day)	Bedload as the percentage of suspended load	Bedload as the percentage of total load
1	*A*	28.98	1.85	30.83	6.37	5.98
2	*A*	9.48	1.02	10.50	10.80	9.75
3	*B*	52.19	0.47	52.66	0.91	0.90
4	*B*	29.90	0.64	30.54	2.15	2.10
5	*C*	43.08	0.83	43.91	1.93	1.89
6	*C*	37.69	1.10	38.78	2.91	2.84
7	*A*	29.01	1.39	30.40	4.80	4.57
8	*B*	55.82	1.04	56.85	1.86	1.83
	Average				3.97	3.73

very fast. Flow depth and velocity vary rapidly in a short period. Such variation in hydraulic parameters during the sampling period affects the performance of bedload transport equations significantly. Compared to laboratory experimentation, the steady-state condition in mountainous rivers, does not exist or prevail for a short period. Since the bedload discharge measurements are expensive and time-consuming, formulas have been favoured over collecting and analysing field data despite the limitations in replicating complex bedload sediment transport processes in rivers[30]. In some cases, the prediction of empirical equations deviates from the measured bedload by three orders of magnitude[31].

The measured average bedload transport rate for the Kharera stream was found to be 1.02 tonnes/day and the flow was subcritical (Froude number < 1). A calibration coefficient of 0.00167 in the Recking (2013) approach results in a satisfactory prediction of the bedload transport rate in the Kharera stream. The developed bedload rating with the coefficient of determination value of 0.5686 can be used for predicting bedload in the study reach. The bedload of the Kharera stream is about 3.96% of that of the suspended sediment load. From the observations and results, it can be concluded that up to 5% of suspended load can be taken as bedload in the absence of measured bedload data for the mountain ephemeral rivers.

Data availability statement: Some or all data, models and codes that support the findings of this study are available from the corresponding author upon reasonable request (hydraulic and sediment data).

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