Evaluation and Calibration of Bed Load Equation for the mountain ephemeral Stream of Gujarat

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Abstract

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

Keywords: bed load, suspended load, mountain river, ephemeral river, Helley Smith sampler

Introduction

Prediction of bedload is important for the design, planning, management, and operation of hydraulic projects such as dams, hydropower plants, and canals. Sediment movements are affected by a variety of factors including construction of the reservoir, change in land use and land cover, other types of land disturbance which include mining activities, land and water management, climate change, and sediment control programs.[1] The delivery of sediment 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 the bedload transport rate. Most of the bedload equations were derived using experimental flume data. Reliable applicability of these equations in the different field conditions is still not established. Consequently, it becomes of greater significance to quantify the sediment transport rate using a direct sampling technique in the field. Incorporating the field observed data with these equations will help to develop the sediment transport model, which demonstrates the actual field condition and produce the result with low discrepancy. The collection of the bedload from the river is a time consuming and expensive matter. [3] In India, bed loads are rarely measured as a regular practice. [28] 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, till now no bedload equation is universally applicable under varying flow and grain size distribution characteristics.[5] The channels behave uniformly during high flow, while more inherent variability in sediment transportation is produced during low flow.[6] So, it is desirable to do sampling in all possible flows of the river, to analyze the channel behavior from low flow to high flow.

Driving forces for movement of sediment particle not only includes shear stress but also include 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 the river is 5% to 25% of that in suspension. [5, 8] The depth-integrated samples are more suitable for quantification of sediment load, as errors produced by vertical averaging are larger when using a few point samples only.[9]

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

76 mm Helley-Smith sampler is a direct point bedload measuring sampler, which is easy to use and it is widely accepted for bed load sampling. [13-17] Compared to multiple points sampling and reach averaging method, the sampling at a single point location produces more reliable results provided data is sufficiently large to cover the whole range of possible flow conditions.[15]

In the present study, the bed load was measured at selected points across the sections using 76 mm HS Sampler. A bed load 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 more accurate prediction of bed load in study reach. The proportion of suspended and bed load in total load for a mountain ephemeral alluvial stream was analyzed to validate the results of Waikhom and Yadav, (2017).

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. Kharera river bed contains sand, gravel, and cobble. Bed forms are not present and the river plan form is governed by the valley rather than sediment movement and see very 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 at some places. The kharera basin contains 65 % crop land, 10 % forest and shrubs and 23 % plantation. The basin soil is mostly alluvial debris washed from the hills in the region (WRIS). Rainfall is in monsoon season spanning from late June to early September with annual average of 1700 mm. The selected reach is 96 m above the M.S.L. having latitude 20°42'21.00"N to 20°42'19.07"N and longitude 73°18'30.74"E to 73°18'32.21"E. The index map and sampling sections in study reach of the Kharera stream is shown in Fig. 1 (a), kharera during the full flow condition in Fig. 1 (b) and profile of Cross-sections A-C in Fig. 1 (c).

Fig. 1 a. Index Map of Kharera and sampling sections b. Kharera stream in full flow c. Cross-sectional Profile

These cross-sections were situated upstream of the check dam at a distance 62 m, 72 m, and 82 m respectively. These sections were selected as 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 m, 8 m and 13 m lateral distances from the right bank of the stream. Pygmy cup type current meter was used to measure the velocity. The average velocity of flow was between 0.38-0.87 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 lab to compute the concentration of suspended sediment load. Standard equipments were used to measure geometrical parameters. Fig. 2 shows the slope of study reach which was computed as 0.0045 (1 in 223).

Fig. 2 Bed slope measurement in river reach

Bedload was measured using a locally fabricated Helley-Smith bedload sampler having a square entrance nozzle of size 76.2 mm × 76.2 mm as shown in Fig. 3. The sampling bag was made up of polyester mesh having 0.25 mm size openings.

Fig. 3 Measurement of bedload using Helley-Smith sampler

This sampler has an expansion ratio (ratio of exit area to entrance area) of 3.22 and it is provided with an adjustable handle for easy use over a range of depths. Trapping efficiency of the sampler is the ratio of collected bedload weight in a given time to the bedload weight passing through sampler width in the same time.[18] Trapping efficiency of the Helley-Smith bedload sampler reduces as the size of particle increases. For particle size ranging from 0.5 – 16 mm, Helley-Smith bedload sampler gives a hydraulic efficiency of 0.9-1.1, provided the sampler should not fill more than 30%.[19]

Bedload and suspended load transport analysis

Measurement and calculation of Bedload Transport Rate

Kharera stream is an ephemeral stream and have flow in the monsoon season only. The bedload was collected on different days from July to September. The minimum sampling time for a Helley-Smith sampler is 60 seconds. Sampling time can be increased for a low bedload transport rate to 300 seconds.[20] In the present study, a sampling time of 20 minutes is selected to collect sufficient quantity of bed load sample for analysis. Collected bedload samples were dried and sieved in lab to analyze sediment gradation of bed load. Fig. 4 shows the gradation curves for bedload sample collected at cross-section A.

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

Table 1 shows the grain size distribution of collected bedload samples at cross-section A, B, and C. Table 2 summarizes various measured and computed hydraulic parameters at cross-sections A, B, and C.

Table 1. Grain size distribution of bedload material.

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

Lateral variation of bed load is shown in Fig. 5.

Fig. 5 Bedload variation at cross-section A

Bedload discharge is determined by using the following formula:[21]

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

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

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

Selected Bedload Equations for calculating bed load transport rate

The five widely acclaimed bedload equations were used to compute the bedload transport rate in Kharera stream as listed in Table 3.

Table 3. Bedload equations

Evaluation and Comparison of Bedload Equations

The bedload transport rate was computed using reach average method. Flow and sediment parameters were averaged over a cross-section. These average parameters were used to predict the bedload transport rate using bedload equation of Schoklitsch (1934), Kalinske (1947), Meyer-Peter and Mueller (1948), Brown (1950), and Recking (2013). [22-26]

The standard statistical parameters were calculated to check the performance of bedload equation. The discrepancy ratio (DR) was computed as Eq. 3, Average of variation coefficient (V_c) as Eq. 4 and Root Mean Square Error (RMSE) as Eq. 5.

$$\mathrm{DR} = \frac{\text{Calculated bed load discharge}}{\text{Measured bed load discharge}} \quad (3)$$

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

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

Where, Q_{bc} and Q_{bm} are computed bedload discharge and measured bedload discharge respectively, where ‘n’ is the total no. of observations.

The performance of the selected five bed load equations is presented in Table 4.

Table 4. Statistical parameters for selected bedload equation

All five bedload equations overpredicted the bedload transport rate, as compared to measured bedload transport rate. Fig. 6 shows the plots between measured and computed bedload transport rates for the selected bed load equations. Most of the data points lie above and far from the line of equality indicating significant overprediction of the bedload transport rate.

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

Schoklitsch (1934) equation has performed better among other equations. None of the bedload equations produced consistent results. This may be due to the hiding and sheltering effect in rivers resulting in low bedload transportation rates. Other reasons for such variation can be the unaccountability of parameters like channel roughness, viscosity of fluid, temperature, sediment composition of bed material, active channel width, supply and availability of sediment, composition of active bed layer, etc.

Calibration of Recking (2013) equation

In non-uniform sediment, bedload rate is controlled by large diameter particles because of exposure and hiding effect. Recking (2013) equation was developed for the gravel and cobble bed considering the exposure and hiding effect. A calibration coefficient, 'ξ' has been introduced by trial-and-error approach in the Recking (2013) bedload equation to improve its predictability accuracy for the selected river reach as given in Eq. 6.

$$\emptyset = \xi \frac{14(\tau_{84}^{*})^{2.5}}{\left[1 + \left(\frac{\tau_{m}^{*}}{\tau_{84}^{*}}\right)^{4}\right]} \quad (6)$$

Where, $\emptyset$ is the bedload transport intensity, τ_{m}^{*} is mobility shear stress and τ_{84}^{*} is the shield shear stress corresponding to d_{84} size.

The minimum average discrepancy ratio is achieved for the calibration coefficient value of 0.00167. Fig. 7 presents the comparison of the calculated bedload transport rate using the calibrated Recking (2013) equation and measured bed load rate. The value of the calibration coefficient may vary from one site to another depending upon discharge and gradation of bed material.

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

The performance of the calibrated Recking (2013) equation is analyzed using the selected statistical parameters as shown in Table 5. The values of the discrepancy ratio vary from 0.022 to 7.751, but the value of the average variation coefficient is 1.921 and RMSE is reduced significantly, which shows good agreement between predicted and measured bedload discharge.

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

Bedload Prediction by Rating Curve

The bedload rating curve was developed using the specific discharge (m^2/s) and bedload transport rate (gm/m/s) as given in Eq. 7. This rating curve is derived by measuring the flow parameters and bedload at a point location. Specific discharge is computed by multiplying the depth and average velocity at a point location and bedload is collected simultaneously on the same point. Fig. 8 shows the bedload rating curve developed using collected bedload samples. The best fit line reveals the coefficient of determination value equals to 0.5686.

Fig. 8 Bedload rating curve of the Kharera river

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

Where Q_b is bedload transport rate (gm/m/s) and q is specific discharge (m^2/s).

Measurement and calculation of Suspended Sediment Load

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

River cross-section was divided into three segments having a width of 3 m, 10 m, and 3 m. The segmental discharge was calculated by multiplying the flow area and velocity. Finally, Equation (8) was used to compute the suspended sediment load as tabulated in Table 6.

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

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

Bedload Proportion in Total Load

Measured bedload, suspended load, total load, and the ratio of bedload to suspended load are tabulated in Table 6. The measured average bedload transport rate for the Kharera stream is 1.02 t/day. The bedload of the Kharera stream is approximately 3.96% that of the suspended load.

Table 6. Measured bedload, suspended load, total load and ratio of bedload to suspended load and total load

From Table 6, it can be seen that the average percentage value of 3.967 for suspended load to be taken as bed load transport rate lies between 0-5 % of suspended load, which conforms with the findings of Waikhom & Yadav (2017).[27]

Discussion and Conclusions

The applicability and validity of the equations are assessed based on the generality of the assumptions used in the derivation and the agreements 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 steady-state (b) the bedload transport rate is a function of sediment and flow parameters (c) a maximum possible amount of bedload is being transported.[28] These assumptions do not relate exactly with the field conditions which may be a reason for overprediction by all selected bed load 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 the sediment supply.[29] Turbulence near the river bed affects the bedload rate significantly, an increase in the turbulence level will increase the bedload rate.[30]

The sampling of bedload is a challenging task during high flow conditions due to safety concerns. Being a river in a mountainous region, response to catchment is 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 considerably. Compared to laboratory experimentation, the steady-state condition in mountainous rivers, either don't exist at all or prevail for very short period. Due to the high cost and time-consuming nature of bedload discharge measurements, formulas have been favored over collecting and analyzing field data despite the limitations in replicating complex bedload sediment transport processes in rivers.[31] In some cases, the prediction of empirical equations deviates from measured bed load by three orders of magnitude.[32]

The measured average bedload transport rate for the Kharera stream was found to be 1.02 t/day and the flow was subcritical (Froude number<1). A calibration coefficient of 0.00167 in Recking (2013) approach results in 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 bed load in study reach. The bedload of the Kharera stream is about 3.96% that of the suspended sediment load. From the observations and results, it can be concluded that, upto 5 % of suspended load can be taken as bed load in the absence of measured bed load data for the mountain ephemeral rivers.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (Hydraulic and sediment data).

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Table 1. Grain size distribution of bedload material

River Section	Distance from right bank (m)	Sediment Diameter					
		D_{10} (mm)	$D_{15.9}$ (mm)	D_{35} (mm)	D_{50} (mm)	$D_{84.1}$(mm)	D_{90} (mm)
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 (m/m) (x 10^{-3})	Width(m)	Hydraulic radius (m)	Area (m^2)	Froude number	Bedload transport rate (ton/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

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	$\frac{q_{bv}}{\sqrt{(G-1)g d_{50}^3}} = 10.0\left(\frac{\tau_0}{(\gamma_s - \gamma)d}\right)^{2.5}$
Meyer-Peter and Muller	1948	$\emptyset = 8(\theta - 0.047)^{3/2}$ $\theta = \frac{SR}{(G-1)d_{50}}$
Brown	1950	$q_{bv} = F_1 q_* \sqrt{(G-1)g d_{50}^3}$ $F_1 = \sqrt{\frac{2}{3} + \frac{36}{d_*^3}} - \sqrt{\frac{36}{d_*^3}}$ $\tau_* = \frac{SR}{(G-1)d_{50}}$ 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	$\emptyset = \frac{14(\tau_{84}^*)^{2.5}}{\left[1 + \left(\frac{\tau_m^*}{\tau_{84}^*}\right)^4\right]}$ $\tau_m^* = (5S + 0.06) \times \left(\frac{d_{84}}{d_{50}}\right)^{4.4\sqrt{S} - 1.5}$ $\tau_{84}^* = \frac{SR}{(G-1)d_{84}}$

Where q_b is bedload transport rate in mass per unit time and width (Kg/m/s), $q_{bv}$is bedload transport rate in volume per unit time and width (m^3/m/s), q is water discharge per unit width (m^3/s/m), q_c is the critical water discharge per unit width (m^3/s/m) corresponding to sediment threshold, d is sediment size, $\emptyset_b$is bedload transport intensity, $\theta$is shields parameter and θ_c is threshold shields parameter, $F_1$is fall velocity parameter, q_* is dimensionless bed flux, d_* is the dimensionless particle size τ_* is dimensionless shear stress parameter,$\tau_0$is average bed shear stress, v is the kinematic viscosity of the fluid, G is the specific gravity of sediment, g is gravity acceleration, γ_w is the unit weight of water, γ_s is the unit weight of sediment particle, ρ is the density of flowing fluid, R is the hydraulic radius and S/S_o is the channel bed slope.

Table 4. Statistical parameters for selected bedload equation

Bedload equations	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

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

Table 6. Measured bedload, suspended load, and total load

Run No.	River Section	Measured Suspended load (ton/day)	Measured Bedload (ton/day)	Total load (ton/day)	Bedload as the % of suspended load	Bedload as % 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**

Fig. 1 a. Index Map of Kharera and sampling sections b. Kharera stream in full flow c. Cross-sectional Profile

Fig. 2 Bed slope measurement in river reach

Fig. 3 Measurement of bedload using Helley-Smith sampler

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

Fig. 5 Bedload variation at cross-section A

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

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

Fig. 8 Bedload rating curve of the Kharera river

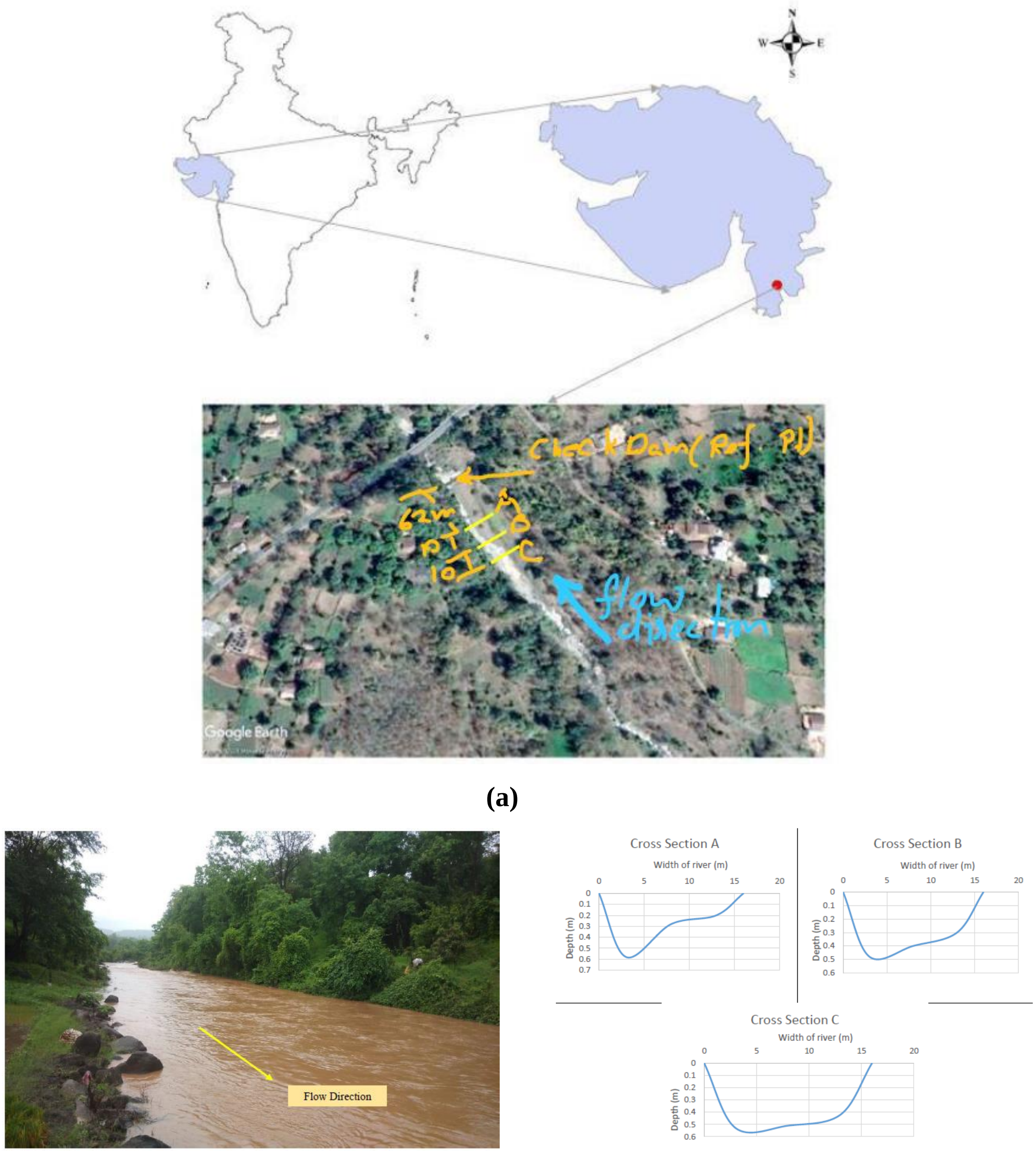


Fig. 1 a. Index Map of Kharera and sampling sections b. Kharera stream in full flow c. Cross-sectional Profile

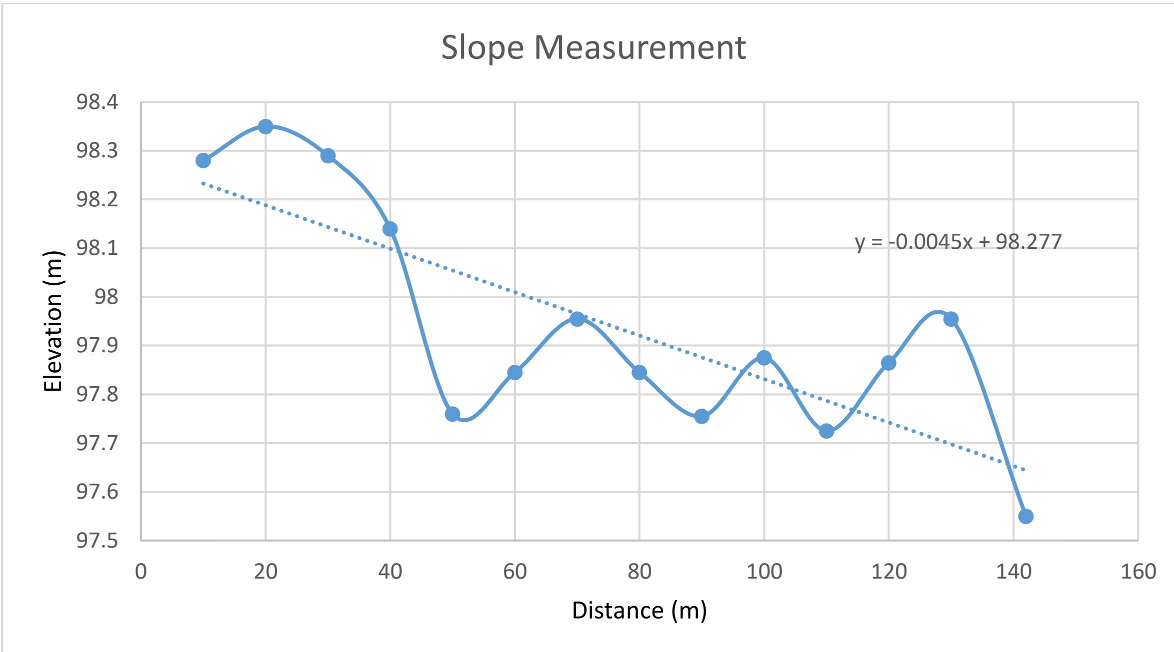
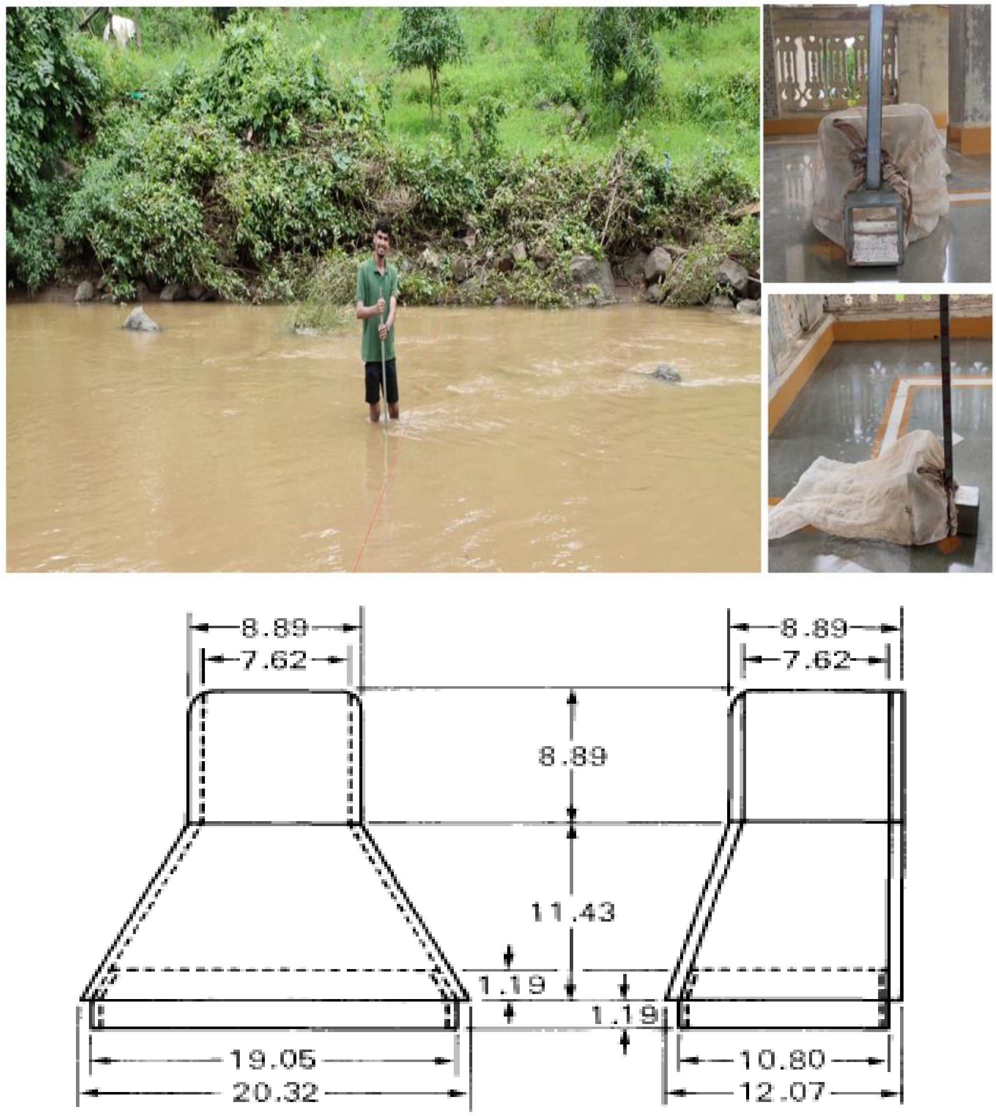


Fig. 2 Bed slope measurement in river reach



(***Source:** Emmett, W. W., 1979*)

Fig. 3 Measurement of bedload using Helley-Smith sampler

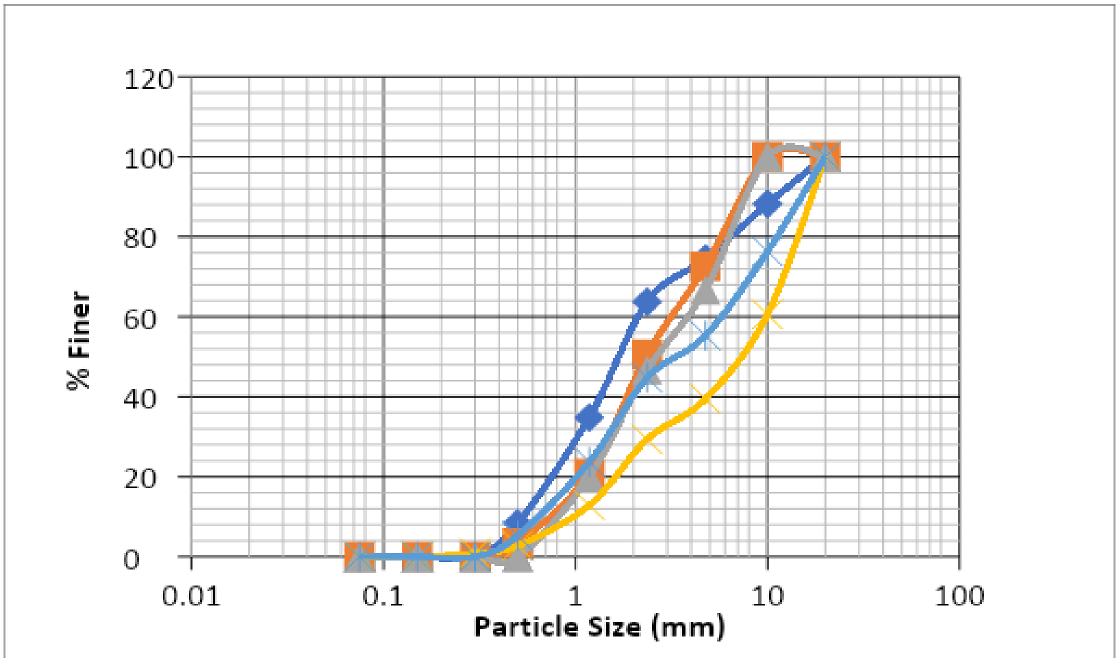


Fig. 4 Gradation curves for bedload samples collected at cross-section A

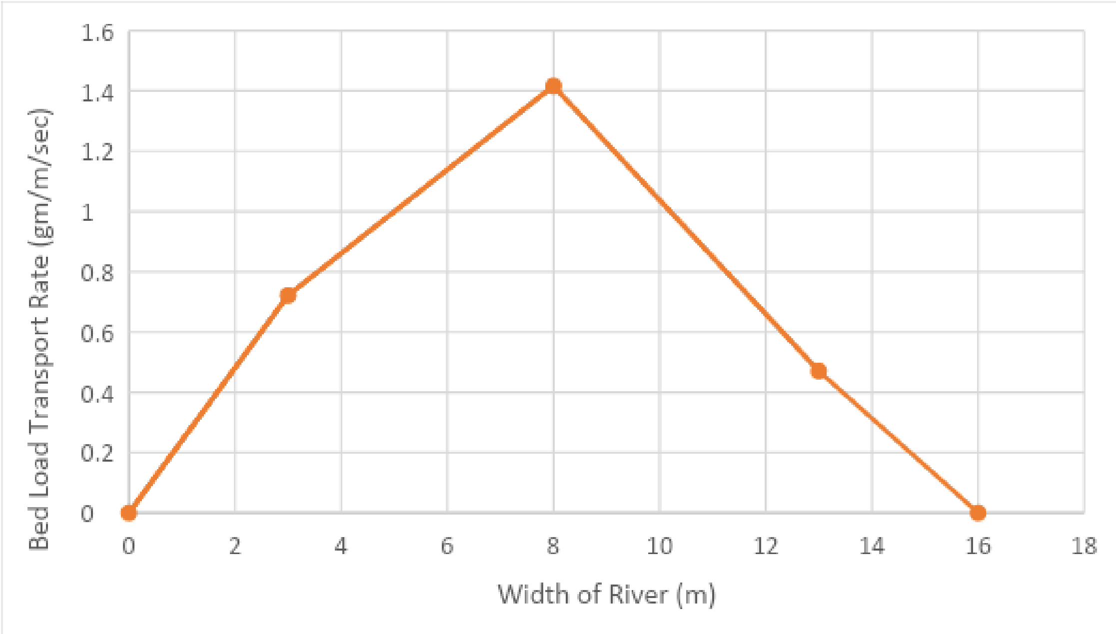


Fig. 5. Bedload variation at cross-section A

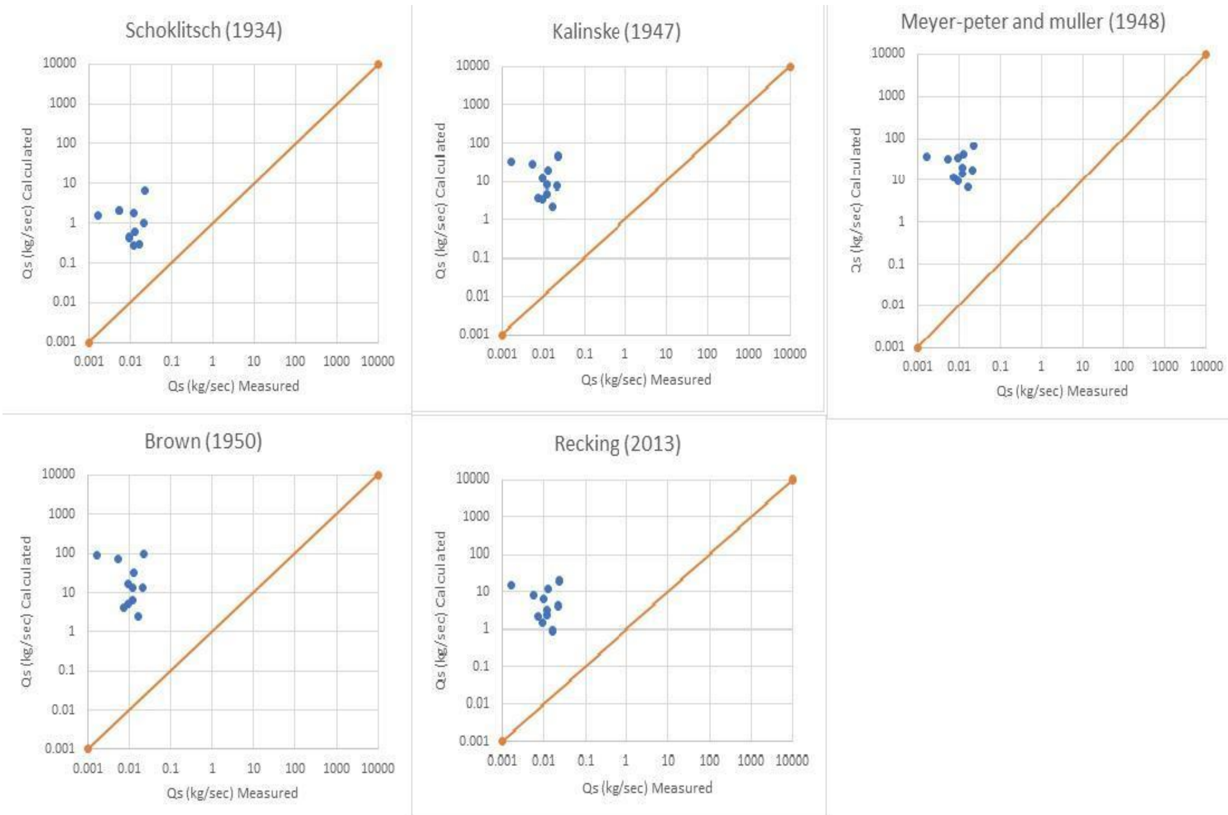


Fig. 6 Comparison of computed and measured bedload rate for Kharera stream.

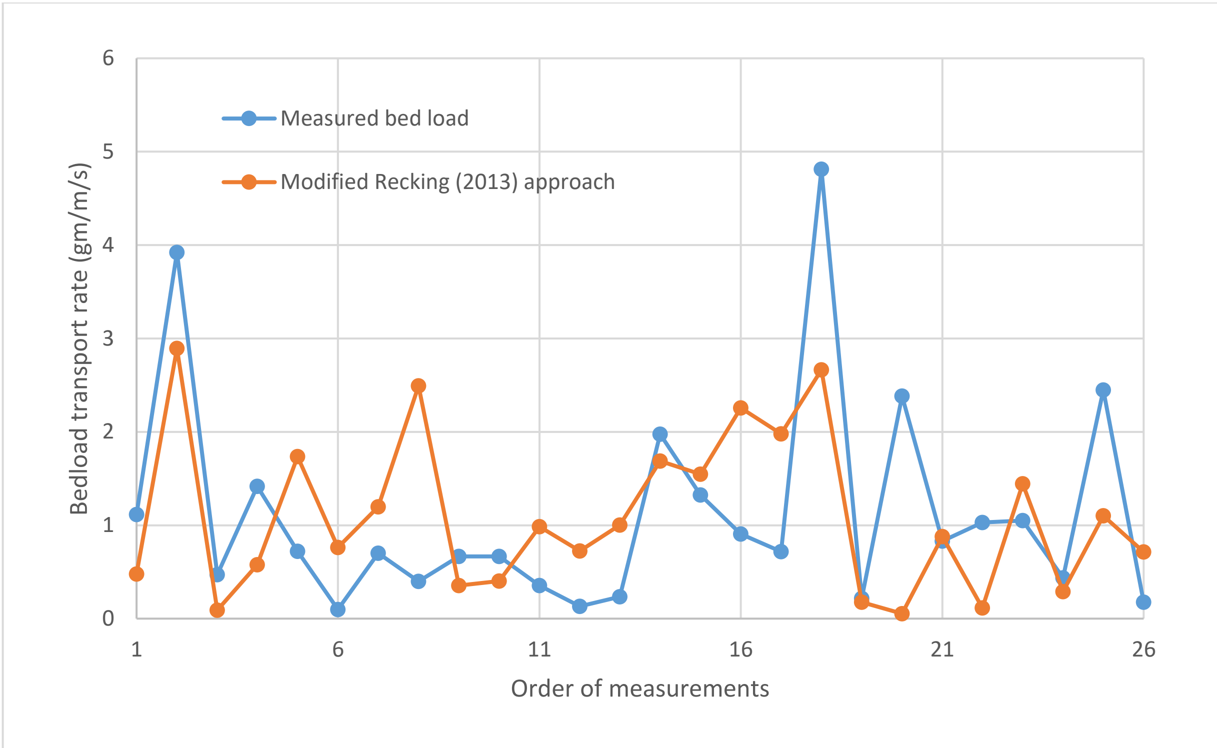


Fig. 7 Comparison of calibrated Recking (2013) relation and measured bedload rate

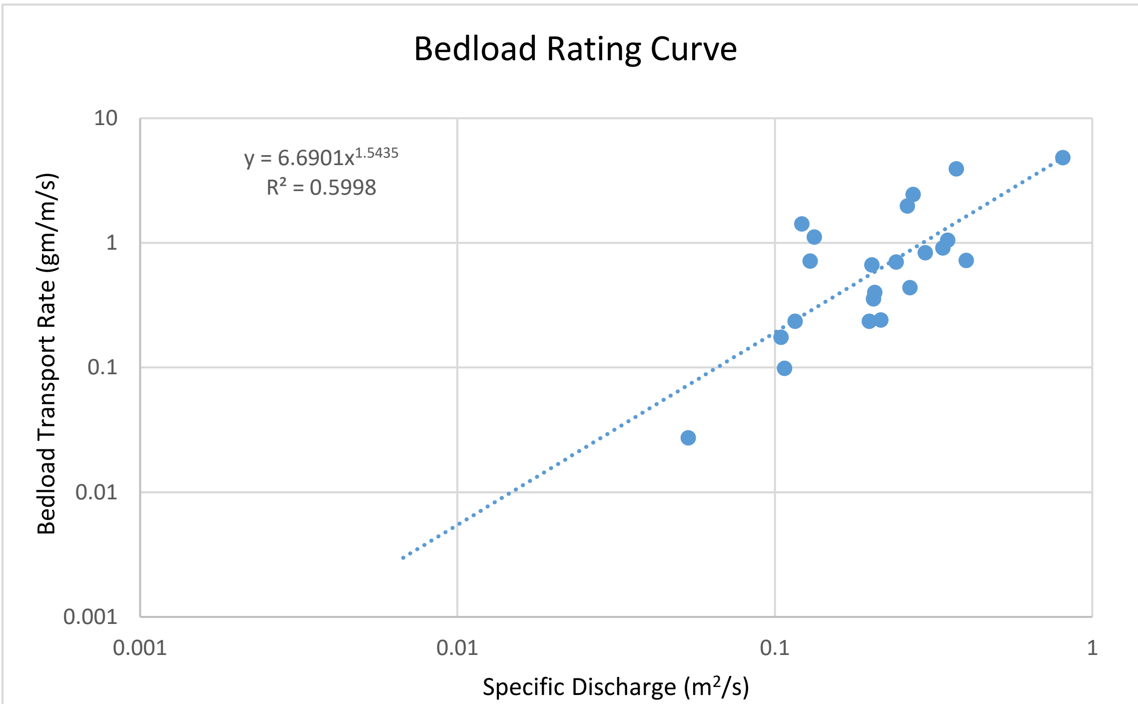


Fig. 8. Bedload rating curve of the Kharera river