Chapter 6
Estimating Sediment Rate Through Stage-Discharge Rating Curve for Two Mountain Streams in Sikkim, India

Sonu Kumar, Santosh Rangrao Yadav, and Triambak Baghel

Abstract Sediment transport in streams is associated with a wide variety of environmental and engineering issues. Rates of sediment discharge are related to the sources, transport, and storage of sediment and erosion hazards within a watershed, which are related to the tectonic regime, climate, land cover, land use, and river setting. In the present study, an attempt has been made to estimate the rates of sedimentation in two tributaries Ranikhola and Busuk-khola of the Teesta River in Sikkim, India. The river water sampling was done on weekly basis for monsoon months, and suspended sediment concentration was estimated. To obtain rates of sedimentation, river discharge is required. For this purpose, a stage-discharge rating curve was developed by measuring flow discharge (Q) using standard current meter method, whereas stage (h) obtained by automatic water level recorder. The developed stage-discharge rating curve equations $h = 1.8196$ Q0.168 (Ranikhola) and $h = 1.9184$ Q0.156 (Busuk-khola) are useful for computing flow discharge from the river stages that will aid in the estimation of sediment discharge in the rivers. The result shows that the total sediment load in the Ranikhola and Busuk-khola rivers was ranged between 18.00–4071.51 and 1.92–603.73 tonnes per day, respectively.

Keywords Suspended sediment · Bed load · Stage · Discharge · Rating curve · Ranikhola · Busuk-khola

6.1 Introduction

The prediction of river sediment load constitutes an important issue in hydraulic and sanitary engineering. Sediment is responsible for transporting a significant proportion of many nutrients and contaminants including their uptake, storage, release, and

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transfer between environmental compartments. Most sediment in surface waters is derived from surface erosion and comprises a mineral component, arising from the erosion of bedrock, and an organic component arising during soil-forming processes including biological and microbiological production and decomposition. An additional organic component may be added by biological activity within the water body.

Sedimentation in rivers has long been an issue of serious concern worldwide, which has broad effects upon both terrestrial and aquatic aspects of life within a river basin. The study of river suspended sediments is becoming more important, nationally and internationally, as the need to assess fluxes of nutrients and contaminants to lakes and oceans, or across international boundaries, increases. River suspended sediment concentrations are most important with respect to pollution, channel navigability, reservoir filling, hydroelectric-equipment longevity, fish habitat, river aesthetics, and scientific interests and provide insights to the erosion and transport of materials from a landscape, and changes in concentrations with time that result from landscape processes or human disturbance. Moreover, it is also used to evaluate the erosion hazard, management of water resources, water quality, hydrology project management (dams, reservoirs, and irrigation), and to determine the extent of the damage that occurred in the catchment. Sediment carried in a stream is classified as either suspended load (fine-grained soils, e.g. clay and silt) or bed load (coarser fractions like sand and gravel). Coarser sediments will be deposited first and suspended sediment load moves at the approximately same velocity as that of the flowing water (Martin and Meybeck 1979).

The stage-discharge rating curve at a river cross-section is a fundamental technique in hydrology employed for determining discharge from catchments. It is a common practice to measure the discharge of streams at suitable times, usually by a current meter or other methods and the corresponding stage followed by plotting and fitting stage against discharge data with a power or polynomial curve. The traditional and simple way to gather information on flow discharge is then to measure the stage with gauges and to use the stage-discharge curve to estimate the flow discharge (Rantz 1982; Braca 2008; Chen 2013).

Recently, many researchers worldwide have estimated rating curves for rivers by measuring velocities either with a cup type current meter (Alfa et al. 2018) or an ultrasonic current meter (Adegbola and Olaniyan 2017). Alexandrov et al. (Alexandrov et al. 2003) analysed relations between suspended sediment concentration and water discharge during flash floods in an ephemeral stream.

In Sikkim, India, the two perennial rivers, viz. Ranikhola and Busuk-khola, are tributaries of Teesta River on which two large hydro-power projects are operational. Annually, these projects need to be closed due to high inflow of sediment with large flow discharge during four monsoon months from June to September. Therefore, it is utmost important to estimate the sediment rates of those tributaries which has considerable contribution to sediment rates in the Teesta river. To estimate these sediment rates, river discharge was required to be measured, and it is mostly difficult to measure flow discharge directly during monsoon months because of high river stages coupled with chaotic turbulence. Therefore, an attempt was made to arrive at a stage-discharge rating curves for channel cross-sections below two bridges on the selected rivers. For this purpose, two sites were selected, viz. Ranipool Bridge (27° 17′ 37″ N latitude, 88° 35′ 19″ E longitude and altitude of 867.77 m above mean sea level (AMSL)) on Ranikhola River and Jalipool Bridge (27° 17′ 26″ N latitude, 88° 35′ 44″ E, longitude and altitude of 829 m AMSL) on Busuk-khola River.

6.2 Materials and Methods

6.2.1 Stage-Discharge Rating Curve

To measure flow velocity in the selected rivers, the standard current meter method was used which is a velocity area method that involves measuring flow velocity in the flow cross-section with the help of a vertical axis cup type current meter and flow cross-section area by using automatic water level recorder. At the selected gauging sites, the bridge spans of 23 m and 11 m were divided into 23 and 11 segments, respectively, each being 1 m wide. To measure depth from bridge span, measuring tape attached with a galvanized iron (G.I.) wire was lowered down after attaching a sounding weight to its one end. This assembly of G.I. wire, measuring tape, and sounding weight was lowered down to the river water by using a pulley arrangement and reading was taken when the sounding weight touched to the river bed. This was necessitated by inaccessibility of the selected gauging sites during high flood conditions. Whereas, during low flow conditions, measurements were done directly by using a staff gauge. To measure flow depth in the channel, water surface depth from the bridge span was measured randomly at six different points and average of six readings was taken as the water surface depth from the bridge span. To convert depth measured from the bridge span into water surface elevation, the datum was taken at 15 m depth from the bridge span because the maximum depth of river bed observed from the bridge span was 13.9 m. The river stage was computed by deducting the depth of water surface at each segment from the datum.

As per criteria given by Subramanya (2013), the flow velocity at each segment was measured at the depth of 0.6 times the depth of flow because the depth of water is less than 3 m. The discharge in each segment estimated by measuring velocities was found to be about 8% of total discharge in the river, which was within 10% of the total discharge. After measuring flow velocity in each segment with the current meter, total flow discharge in the river was computed by using mean section method as illustrated in Fig. 6.1 in which following formulae were used.

$$d_{\mathrm{m}} = \frac{d_2 + d_3}{2} \tag{6.1}$$

$$V_{\mathrm{m}} = \frac{V_2 + V_3}{2} \tag{6.2}$$

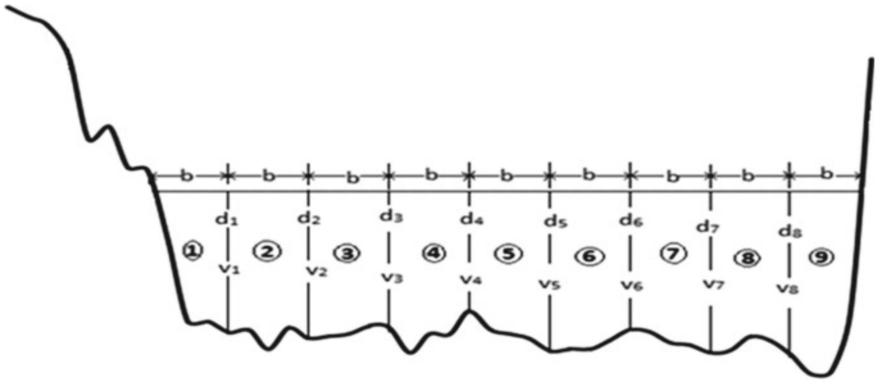

Fig. 6.1 Measuring flow discharge by mean section method

$$\Delta Q = b \times d_{\mathrm{m}} \times V_{\mathrm{m}} \tag{6.3}$$

$$Q = \sum \Delta Q \tag{6.4}$$

where b = width of a segment (m), d_2 = depth of water flow at point 2 (m), d_3 = depth of water flow at point 3 (m), V_2 = flow velocity at point 2 (m/s), V_3 = flow velocity at point 3 (m/s), d_{m} = mean depth of a segment (m), V_{m} = mean flow velocity in a segment (m/s), ΔQ = discharge in a segment (m^3/s), and Q = total discharge in river (m^3/s).

The stage and corresponding discharge values were plotted along Y-axis and X-axis, respectively, on arithmetic and logarithmic scales to get the stage-discharge rating curves.

6.2.2 River Sedimentation Rate

In the present study, water samples were collected on weekly to fortnightly basis from the Ranikhola and Busuk-khola rivers by using two litre plastic sampling bottles from 28 July 2018 to 25 November 2018 to measure suspended sediment load. While collecting samples, it was assumed that the suspended sediment was distributed uniformly across the entire cross-section of the river and samples were collected at a depth of six-tenth of the depth of river flow. After thoroughly stirring, the samples were taken into a pre-weighed aluminium container (weight of empty aluminium container = W_1) that was kept into a hot air oven which was set at 110 °C until all water evaporated. The container was allowed to cool till it reached room temperature, and its weight was measured again by using an electronic balance (weight of container and suspended sediment = W_2). The difference in the above-mentioned two weights divided by two gave suspended sediment concentration (C in g/L) in the sample. The rate of suspended sediment (also known as suspended sediment load, SSL in tonnes per day) was estimated by Eq. (6.5).

$$\mathrm{SSL} = Q \times C \times 86.4 \tag{6.5}$$

where Q = flow discharge (m^3/s), C = suspended sediment concentration (g/L).

As for mountainous rivers, the bed load in a stream lies in the range of 20–40% of the SSL (Schroder and Theune 1984; Dadson et al. 2003; Turowski et al. 2008), in the present study, bed load is assumed to be 20% of the SSL; considering the lowest value of the above-mentioned range. Total sediment rates in the Ranikhola and Busuk-khola rivers during monsoon months were estimated by adding SSL and bed load.

6.3 Results and Discussion

6.3.1 Measurement of Channel Dimensions

To compute flow discharge in the Ranikhola and Busuk-khola rivers, the cross-sectional details of the two selected rivers were measured before taking each reading. Sample readings taken on 28 July 2018 and 28 July 2018 at Ranipool and Jalipool bridges are given in Tables 6.1 and 6.2, respectively.

The measured channel cross-sections of the Ranikhola and Busuk-khola rivers at Ranipool and Jalipool bridges were plotted (Figs. 6.2 and 6.3). In Figs. 6.2 and 6.3,

Table 6.1 Depth of river bed measured from the bridge span at Ranipool Bridge (28 July 2018)

Distance (m)	Depth of river bed from bridge span (m)	Distance (m)	Depth of river bed from bridge span (m)
3	15.84	14	17.5
4	15.9	15	17.6
5	16.42	16	17.1
6	16.15	17	16.8
7	16.34	18	15.45
8	16.9	19	15.4
9	16.8	20	16.41
10	17	21	16.8
11	17.11	22	16.5
12	17.35	23	16
13	17.4	–	–

Table 6.2 Depth of river bed measured from the bridge span at Jalipool Bridge (29 July 2018)

Distance (m)	Depth of river bed from bridge span (m)	Distance (m)	Depth of river bed from bridge span (m)
0	7.8a>9.95	6	15.7
1	3.39a>15.65	7	15.1
2	15.15	8	15.1
3	15.65	9	14.95
4	15.8	10	14.95
5	15.6	11	14.95

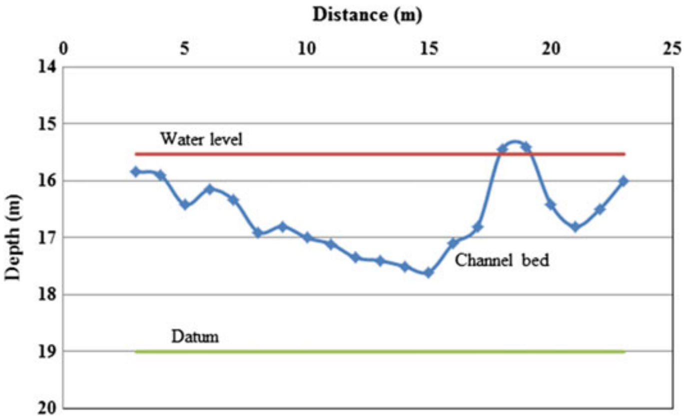

Fig. 6.2 The Ranikhola River cross-section at Ranipool Bridge

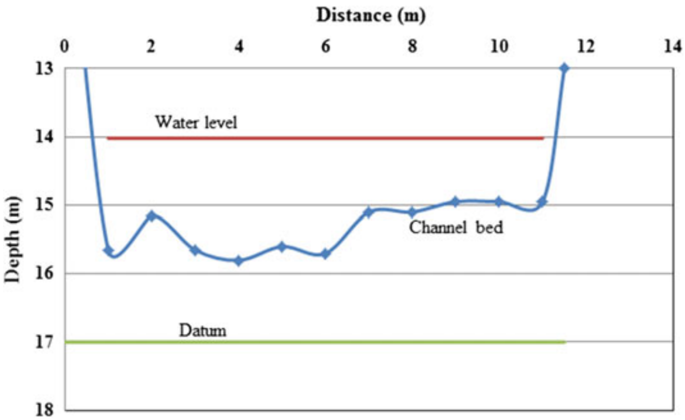

Fig. 6.3 The Busuk-khola River cross-section at Jalipool Bridge

the distance from the left-hand side while facing upstream is plotted on the X-axis, whereas depths of the river bed and that of water surface (both measured from the bridge span) are plotted on Y-axis.

6.3.2 Flow Velocities and Discharge Measurement

To estimate the flow discharge in the Ranikhola and Busuk-khola rivers, the flow velocity measurements were made by using current meter at the frequency of about a week and daily basis based on discharge variation in the rivers. One of the sample reading and corresponding computational procedure is shown in Table 6.3, in which the flow velocity (V) was estimated by using calibration equations ($V = 0.719$ Ns + 0.009 and $V = 0.8649$ Ns, where Ns = revolution per second of the current meter) of the two current meters used in the present study.

6.3.3 Stage-Discharge Relationship

The river stage and corresponding flow discharge measurements were taken for about four months duration, i.e. from 28 July 2018 to 27 November 2018. The stage-discharge data generated through the present study are given in Tables 6.4 and 6.5. The measured river stages were plotted against the corresponding estimated flow discharge values in arithmetic and logarithmic plots with stage as ordinate and discharge as abscissa (Figs. 6.4, 6.5, 6.6 and 6.7). After plotting the stage versus discharge to the arithmetic scale, a smooth curve through the plotted points was drawn, whereas a straight line was drawn for logarithmic plots and power form equations were chosen. The coefficients of determination (R^2) values for the above-mentioned plots were observed to be about 0.968 and 0.989 for Ranikhola and Busuk-khola rivers, respectively. The corresponding power form equations for the two rivers are given in Eqs. (6.6) and (6.7).

$$h = 1.8196\, Q^{0.168} \tag{6.6}$$

$$h = 1.9184\, Q^{0.156} \tag{6.7}$$

where h = river stage (m) and Q = flow discharge (m^3/s).

Table 6.3 Discharge computation by mean section method (28 July 2018)

Distance (m)	Depth of river bed from bridge span (m)	Depth of water level from bridge span (m)	Depth of water (m)	Revolutions of current meter	Time (s)	Velocity (m/s)	Avg. velocity (m/s)	Avg. depth (m)	Elemental discharge (m3/s)
3	15.84	15.5	0.31	40	30	1.15	1.59	0.34	0.54
4	15.9	15.5	0.37	70	30	2.02	2.36	0.63	1.49
5	16.42	15.5	0.89	94	30	2.71	2.36	0.76	1.78
6	16.15	15.5	0.62	70	30	2.02	1.85	0.72	1.32
7	16.34	15.5	0.81	58	30	1.67	2.19	1.09	2.39
8	16.9	15.5	1.37	94	30	2.71	2.65	1.32	3.5
9	16.8	15.5	1.27	90	30	2.59	2.67	1.37	3.65
10	17	15.5	1.47	95	30	2.74	2.75	1.53	4.2
11	17.11	15.5	1.58	96	30	2.77	2.93	1.7	4.97
12	17.35	15.5	1.82	107	30	3.08	2.84	1.85	5.24
13	17.4	15.5	1.87	90	30	2.59	2.36	1.92	4.54
14	17.5	15.5	1.97	74	30	2.13	2.1	2.02	4.25
15	17.6	15.5	2.07	72	30	2.08	1.86	1.82	3.38
16	17.1	15.5	1.57	57	30	1.64	1.66	1.42	2.35
17	16.8	15.5	1.27	58	30	1.67	0.84	0.64	0.53
18	15.45	15.5	–	–	30	–	–	–	–
19	15.4	15.5	–	–	30	–	0.58	0.44	0.25
20	16.41	15.5	0.88	40	30	1.15	0.92	1.08	0.99
21	16.8	15.5	1.27	24	30	0.69	0.63	1.12	0.71

(continued)

Table 6.3 (continued)

Distance (m)	Depth of river bed from bridge span (m)	Depth of water level from bridge span (m)	Depth of water (m)	Revolutions of current meter	Time (s)	Velocity (m/s)	Avg. velocity (m/s)	Avg. depth (m)	Elemental discharge (m3/s)
22	16.5	15.5	0.97	20	30	0.58	0.72	0.72	0.52
23	16	15.5	0.47	30	30	0.86	0.43	0.235	0.1
Total discharge									46.72

Table 6.4 Stage-discharge data for the Ranikhola River at Ranipool Bridge

Date	Discharge	Stage	Date	Discharge	Stage
7/29/2018	46.72	3.47	11/7/2018	4.2	2.31
8/11/2018	38.76	3.23	11/8/2018	4.22	2.3
8/13/2018	42.11	3.42	11/9/2018	3.67	2.29
8/19/2018	32.61	3.3	11/10/2018	3.65	2.27
8/21/2018	25.31	3.14	11/11/2018	3.386	2.28
8/23/2018	22.51	3.08	11/12/2018	3.66	2.33
8/25/2018	37.55	3.4	11/13/2018	4.07	2.29
8/27/2018	27.88	3.2	11/14/2018	3.41	2.25
8/29/2018	20.1	3.04	11/18/2018	3.57	2.27
8/31/2018	13.09	2.9	11/20/2018	3.31	2.21
9/3/2018	11.23	2.71	11/22/2018	2.74	2.2
9/13/2018	7.80	2.5	11/24/2018	2.48	2
9/17/2018	17.61	2.88	11/25/2018	2.5	2.1
11/5/2018	3.44	2.26	11/27/2018	2.4	2.11

Table 6.5 Stage-discharge data for the Busuk-khola River at Jalipool Bridge

Date	Discharge	Stage	Date	Discharge	Stage
8/11/2018	17.9	3.01	11/9/2018	4.29	2.41
8/13/2018	19.41	3.1	11/10/2018	4.19	2.43
8/22/2018	18.34	2.98	11/11/2018	3.71	2.35
8/26/2018	13.88	2.9	11/12/2018	3.63	2.34
8/31/2018	21.61	3.2	11/14/2018	3.25	2.33
9/10/2018	10.2	2.72	11/18/2018	3.29	2.32
9/20/2018	7.86	2.59	11/20/2018	3.23	2.31
9/18/2018	12.14	2.75	11/22/2018	3.07	2.3
10/8/2018	6.05	2.55	11/23/2018	3.16	2.31
10/15/2018	15.85	2.96	11/25/2018	2.97	2.27
11/5/2018	5.46	2.5	11/28/2018	2.51	2.2
11/7/2018	4.3	2.42	12/2/2018	1.85	2.11
11/8/2018	4.13	2.41	–	–	–

6.3.4 Sediment Discharge in Two Rivers

The suspended sediment concentration was estimated through laboratory analysis, and the resultant data is given in Table 6.6. The suspended sediment load in the Ranikhola River was computed by using Eq. (6.5).

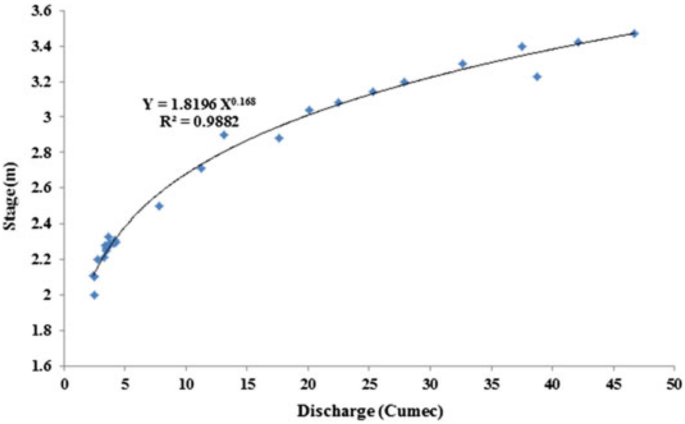

Fig. 6.4 Stage-discharge rating curve for the Ranikhola River at Ranipool Bridge (arithmetic)

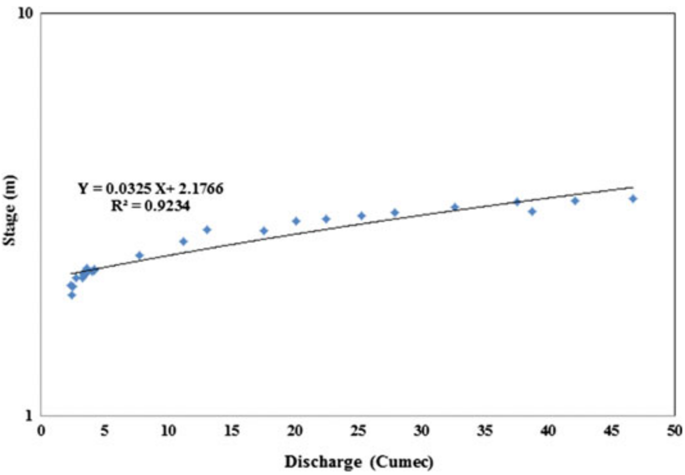

Fig. 6.5 Stage-discharge rating curve for the Ranikhola River at Ranipool Bridge (logarithmic)

From Tables 6.6 and 6.7, it was observed that during the study period of four months, the total sediment loads in the Ranikhola and Busuk-khola rivers were ranged between 18–4071.51 and 1.92–603.73 tonnes per day, respectively.

6.4 Conclusions

The developed stage-discharge rating curve equations are: $h = 1.8196\ Q^{0.168}$ and $1.9184\ Q^{0.156}$ with coefficients of determination (R^2 values) of 0.968 and 0.989 which

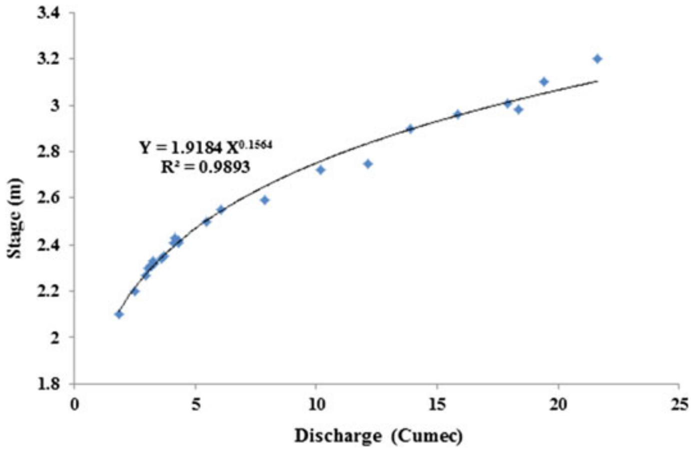

Fig. 6.6 Stage-discharge rating curve for the Busuk-khola River at Jalipool Bridge (arithmetic)

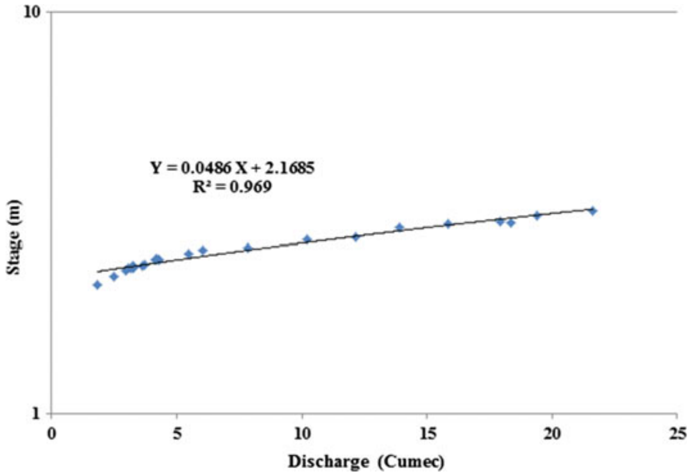

Fig. 6.7 Stage-discharge rating curve for the Busuk-khola River at Jalipool Bridge (logarithmic)

may be useful for computing flow discharge in the Ranikhola and Busuk-khola rivers for the measured stages at Ranipool and Jalipool bridge cross-sections, respectively. It was observed that at smaller stages, increase in discharge is comparatively lesser than the same at higher stage values, which can be attributed to the more increase in flow cross-sectional area at higher stage values as compared to the lower increase at lesser stage values. The range of sediment rates in the two rivers was observed to be 18–4071.51 tonnes per day in Ranikhola River and 1.92–603.73 tonnes per day in Busuk-khola River. These large sediment inflow rates into the Teesta River necessitates the large-scale catchment area treatment programmes including both

Table 6.6 Sediment load in the Ranikhola River

Date	Flow discharge (m^3/s)	Sediment concentration (g/L)	Suspended load (tonnes/day)	Bed load (tonnes/day)	Total load (tonnes/day)
7/29/2018	46.72	0.53	2139.59	427.92	2567.5
8/11/2018	38.76	0.41	1373.23	274.65	1647.87
8/13/2018	42.11	0.88	3201.71	640.34	3842.05
8/19/2018	32.61	0.62	1746.85	349.37	2096.22
8/21/2018	25.31	0.33	721.64	144.33	865.97
8/23/2018	22.51	0.31	602.91	120.58	723.49
8/25/2018	37.55	0.34	1103.07	220.61	1323.68
8/27/2018	27.88	0.2	481.77	96.35	578.12
8/29/2018	20.1	0.21	364.69	72.94	437.63
8/31/2018	13.09	3	3392.93	678.59	4071.51
9/3/2018	11.23	0.2	194.05	38.81	232.87
9/13/2018	7.8	0.3	202.18	40.44	242.61
9/17/2018	17.61	0.19	289.09	57.82	346.9
11/5/2018	3.44	0.4	118.89	23.78	142.66
11/7/2018	4.2	0.47	170.55	34.11	204.66
11/8/2018	4.22	0.8	291.55	58.31	349.86
11/9/2018	3.7	2.6	830.94	166.19	997.13
11/10/2018	3.65	0.3	94.61	18.92	113.53
11/11/2018	3.39	0.45	131.67	26.33	158
11/12/2018	3.66	0.1	31.65	6.33	37.98
11/13/2018	4.07	0.25	87.91	17.58	105.49
11/14/2018	3.41	0.45	132.62	26.52	159.14
11/18/2018	3.57	0.24	74.03	14.81	88.83
11/20/2018	3.31	0.3	85.87	17.17	103.05
11/22/2018	2.74	0.2	47.35	9.47	56.82
11/24/2018	2.48	0.07	15	3	18
11/25/2018	2.5	0.08	17.28	3.46	20.74
11/27/2018	2.4	0.20	41.47	8.29	49.77

structural and non-structural control measures in the watershed areas of the two selected rivers so that the sediment rates may be reduced. Further, it is necessary to control the landslides during monsoon season that are prime source of sediments apart from the erosion of terraced agricultural fields.

Table 6.7 Sediment load in the Busuk-khola River

Date	Flow discharge (m^3/s)	Sediment concentration (g/L)	Suspended load (tonnes/day)	Bed load (tonnes/day)	Total load (tonnes/day)
8/11/2018	17.9	0.23	355.71	71.14	426.85
8/13/2018	19.41	0.3	503.11	100.62	603.73
8/22/2018	18.34	0.21	332.74	66.55	399.29
8/26/2018	13.88	0.3	359.77	71.95	431.72
8/31/2018	21.61	0.1	186.73	37.35	224.07
9/10/2018	10.2	0.11	96.98	19.4	116.37
9/20/2018	7.86	0.1	67.94	13.59	81.53
9/18/2018	12.14	0.15	157.33	31.47	188.8
10/8/2018	6.05	0.2	104.49	20.9	125.39
10/15/2018	15.85	0.12	164.33	32.87	197.2
11/5/2018	5.46	1	471.74	94.35	566.09
11/7/2018	4.3	0.45	167.11	33.42	200.53
11/8/2018	4.14	0.3	107.18	21.44	128.62
11/9/2018	4.29	0.12	44.5	8.9	53.4
11/10/2018	4.19	0.2	72.37	14.47	86.84
11/11/2018	3.71	0.8	256.64	51.33	307.97
11/12/2018	3.63	0.4	125.38	25.08	150.46
11/14/2018	3.25	0.31	86.99	17.4	104.39
11/18/2018	3.29	0.13	36.95	7.39	44.34
11/20/2018	3.23	0.1	27.92	5.58	33.5
11/22/2018	3.07	0.5	132.67	26.53	159.2
11/23/2018	3.16	0.32	87.28	17.46	104.74
11/25/2018	2.97	0.11	28.2	5.64	33.84
11/28/2018	2.51	0.09	19.53	3.91	23.44
12/2/2018	1.85	0.01	1.6	0.32	1.92

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