Journal of Agroecology and Natural Resource Management
p-ISSN: 2394-0786, e-ISSN: 2394-0794, Volume 4, Issue 3; April-June, 2017, pp. 238-242

http://www.krishisanskriti.org/Publication.html

Stage-Discharge Rating Curve for a Perennial River in Sikkim, India

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Abstract—The accurate information about stage and discharge of a river are very important for various hydrological applications such as water resources planning, reservoir operation, sediment handling as well as hydrologic modeling. As routine plotting of the stage-discharge rating curve for a river cross-section is very much essential to get the flow discharge data in quick time, the present study was undertaken with an objective of developing a rating curve for the Ranikhola river, a tributary of the Teesta river in Sikkim, India.

For this purpose, the gauging station was selected at Aadampool bridge on the Ranikhola river and the standard current meter method was employed to measure river stage and corresponding flow discharge at a frequency of about 5-days for the study period of 96 days (from August 27 to November 29, 2011). The seventeen values of measured stage and corresponding discharge were plotted to get the desired stage-discharge rating curve. The power form of equation [$Q = 0.406 (h - h_o)^{0.314}$, h = river stage (m) and Q = flow discharge (m^3/s); $R^2 = 0.968$] was observed to be the best fit and it was concluded that the stage varied roughly as the square root of the discharge. The developed stage-discharge rating curve may be used in future for computing flow discharge in the Ranikhola river for the measured stage at Aadampool cross-section.

Introduction

Measurement of discharge through a river draining a catchment area is one of the most important aspects for hydraulic engineers because such data are needed for: planning and management of water resources in the basin, evaluation of water balance at the catchment scale, design of water control and conveyance structures, and rainfall-runoff and flood-routing model calibration and validation. The accurate information about discharge and stage are very important for various hydrological applications such as water resources planning, reservoir operation, sediment handling as well as hydrologic modelling. The stage-discharge relationship, also known as the rating curve or simply rating, is a very important tool in surface hydrology because the reliability of discharge data is highly dependent on a satisfactory rating curve at the gauging station. The rating curve uncertainty may be due to errors in stage and velocity measurements, extrapolation of the rating curve [10, 8], and cross-section change due to vegetation growth and/or bed movement [7, 1].

Stream discharge can be measured by two methods viz. direct and indirect. In direct method, flow velocity and flow cross-sectional area are directly measured in field, which is a time consuming and costly procedure. Therefore, at least in medium and large rivers, in most studies around the world, indirect method is preferred which is a two-step procedure: first, the stream discharge is plotted against the corresponding elevation of the water surface (called stage) through a series of careful measurements and in second step, the stage of the stream is observed routinely, and the discharge is estimated by using the previously established stage-discharge relationship. Further, such an approach can be considered adequate for all rivers under steady-flow conditions, when flood waves show a marked kinematic behavior, which generally corresponds to rivers with steep bed slopes (>10^{-3}) [2, 3].

Although, the preparation of rating curves seems to be an essentially empiric task, a wide theoretical background is needed to create a reliable tool to switch from measured stage to discharge. Discharge depends upon the nature of rainfall in the catchment area which is purely stochastic. Due to stochastic nature of discharge, stage varies accordingly [5]. Stages are measurable at any time whereas it needs sufficient preparation to measure the discharge that may not be handy. Hence, to predict the discharge from measured stage, there should be specified relation between them. The stage-discharge relationship at a particular river cross-section, even under conditions of meticulous observations, is not necessarily unique as rivers are often influenced by factors neither always understood nor easy to quantify [9]. This is due to the fact that, in reality, discharge is not a function of stage alone. Discharge also depends upon longitudinal slope of river, channel geometry, bed roughness, etc. However, the measurement of these parameters in every time steps and sections is not reliable. Therefore, it is in the practice that usually discharge is forced to show the dependency with stage alone and hence, the accurate relationship between discharge and stage has an established importance in hydrology [4].

In the above context, in the present study, an attempt has been made to arrive at a stage-discharge relationship for the channel cross-section at the *Aadampool* bridge on the *Ranikhola* River in Sikkim, India.

2. Materials and methods

2.1. Study area

The *Ranikhola* River, a tributary of Teesta River in Sikkim State of India, is a perennial river that originates near a place called Penlong (Figure 1) in Ranipool Forest Block, about 5 km north-eastwards from Gangtok, the capital of Sikkim and it merges into the Teesta River near Singtam, about 20 km south-westwards from Gangtok. For establishing stage-discharge rating curve, a reconnaissance survey along the length of the *Ranikhola* River was carried out to select a suitable gauging station below an existing bridge that enabled easy use of current meter in the mountainous stream having very high flow velocity with tremendous turbulence, especially in rainy season. Through the survey, the gauging station on the *Ranikhola* River selected for the present study was *Aadampool* bridge (27° 18′ 36″ N latitude, 88° 35′ 6″ E longitude and an altitude of 925.68 m above mean sea level (MSL)). The *Ranikhola* River's channel is V-shaped that has abundance of big boulders and rocks in its bed along its length both upstream and downstream of the selected gauging station. The area of the *Ranikhola* watershed that drains at the *Aadampool* bridge is about 60 km^2 whereas the stream length from the most remote point (MRP)/ ridge line (27° 21′ 55″ N latitude, 88° 38′ 18″ E longitude and an altitude of 2458 m above MSL) to the outlet point of the watershed is about 10 km. The width of the *Ranikhola* River measured manually at various reachable places along the river length ranges between 3 and 12 metres. The longitudinal profile (i.e. L-section) of the *Ranikhola* River (Figure 2) from the ridge line to the outlet at the *Aadampool* bridge indicates that very steep slope (>30 %) exists from the chainage of 6 km to the ridge line whereas towards the outlet, the channel bed slope is about 9 %; the average channel bed slope is about 15 %.

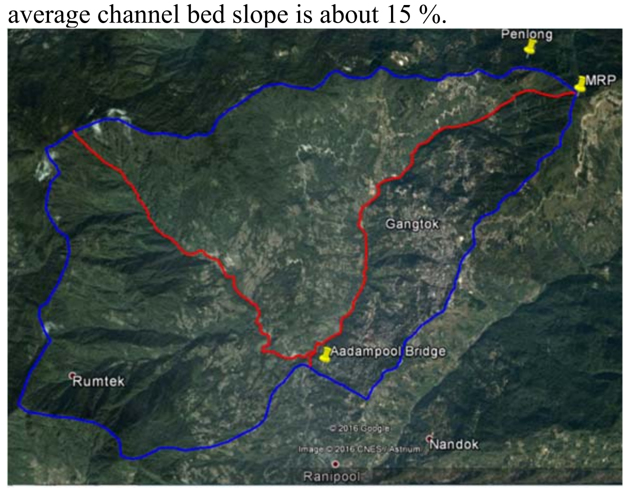

Figure 1. The *Ranikhola* watershed showing its two major streams (Source: [6]).

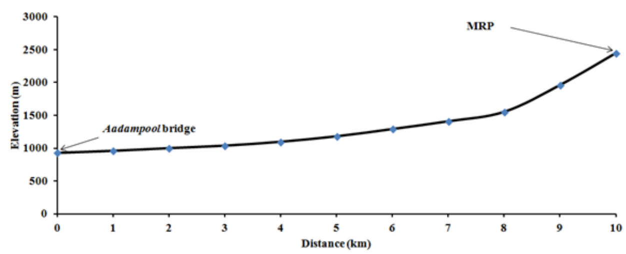

Figure 2. Longitudinal profile of the *Ranikhola* River from the ridge line to the *Aadampool* bridge.

2.2. Measurement of stage and discharge

To measure flow velocity in the *Ranikhola* River, the standard current meter method was used which is a velocity-area method that is amongst the direct methods of flow discharge measurement in which flow velocity at a point in the flow cross-section is measured with the help of a current meter. The current meter used in this study was vertical axis type current meter, for which the calibration equation was:

$V = 0.0112\ N_s + 0.0178$ (equation 1)

where, V = flow velocity at the instrument location (m/s), and N_s = revolution per minute of the current meter.

At the *Aadampool* bridge, in order 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 into the river water by using a pulley arrangement and readings were taken when the sounding weight made contact with the river bed.

For taking such readings, the segment width of 0.5 m was used for measurements vis-à-vis channel cross-section whereas segment width of 2 m was used for measurements vis-à-vis flow velocity.

The top width of flow cross-section was measured with a measuring tape on bridge span whereas water surface depth from the bridge span was measured by using an electronic water level meter. The water surface depth from the bridge span was estimated as an average of six randomly measured depths. To convert the water surface depth measured from the bridge span to the water surface elevation, the datum selected was 14 m depth from the bridge span i.e. 925.68 – 14 = 911.68 m above MSL as the maximum depth of river bed measured from the bridge span was 13.48 m. The river stage elevations were then computed by deducting the average depth of water surface at each segment from the elevation of the datum (911.68 m).

The bridge span of 26 m was divided into 13 segments, each being 2 m wide. For this purpose, following standard guidelines were used as given in [11]:

(a) The discharge in each segment should be less than 10 % of the total discharge.
(b) The difference in velocities in adjacent segments should be less than 20 %.

The flow velocity at the end of each segment was measured separately at the depth of 0.6 times the depth of flow as the depth of water in the *Ranikhola* River was less than 3 m [11]. The discharge in each segment estimated by measuring velocities was found to be about 8 % of total discharge in the river, which was within the above-mentioned criteria (a).

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 Figure 3 in which dark line showing channel cross-section was plotted for the data recorded on August 27, 2011.

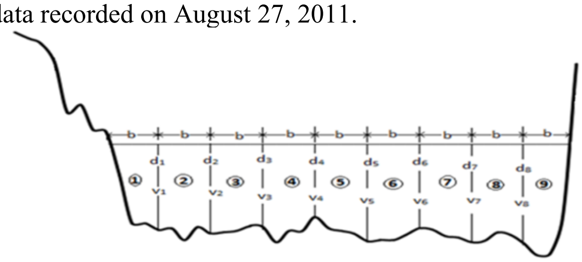

Figure 3. The *Ranikhola* River flow discharge estimation by mean section method.

The formulae used in mean section method are given below:

$$d_m = \frac{d_2+d_3}{2} \quad \text{(equation 2)}$$

$$V_m = \frac{V_2+V_3}{2} \quad \text{(equation 3)}$$

$$\Delta Q = b \times d_m \times V_m \quad \text{(equation 4)}$$

$$Q = \sum \Delta Q \quad \text{(equation 5)}$$

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).

2.3. Stage-discharge relationship

The measured values of the stages and the corresponding discharges plotted on arithmetic and logarithmic scales gives the required stage-discharge relationship that represents the integrated effect of a wide range of channel and flow parameters. The combined effect of these parameters is termed as 'control'. If the stage-discharge relationship for a gauging section does not change with time, the control is said to be 'permanent'. If it changes with time, it is called 'shifting control'. Majority of non-alluvial/ mountainous rivers (like the *Ranikhola* River) exhibit permanent control for which stage-discharge relationship is a single-valued relation that is expressed as:

$$Q = a\,(h - h_o)^b \quad \text{(equation 6)}$$

where, Q = discharge (m^3/s), h = stage (m), 'a' and 'b' are rating curve constants, h_o = stage corresponding to zero discharge (m).

The real 'h_o' is the gauge height of the lowest point in the control cross-section. For natural channels, this value can sometimes be measured in the field by measuring the depth of flow at the deepest place in the control section, and subtracting this depth from the gauge height at the time of measurement. The 'h_o' is instead a value that, when subtracted from the mean gauge heights of the discharge measurements, will cause the logarithmic rating curve to plot as a straight line. This is the reason why the 'h_o' is sometimes referred to as the logarithmic scale offset. In the present study, the 'h_o' is taken as the elevation of the lowest point in the river channel at the *Aadampool* cross-section i.e. h_o = 912.2 m above MSL.

Considering logarithmic scale, equation 6 becomes log Q = log a + b × log (h – h_o). A linear trend line equation between 'log Q' values (on Y-axis) and 'log (h – h_o)' values (on X-axis) was fitted, the slope of the line gives 'b' and the Y-intercept gives 'log a' (and thereby 'a'). Thus, the stage-discharge relationship was developed as in the equation 6.

3. Results and discussion

3.1. Measurement of channel dimensions

To compute flow discharge in the *Ranikhola* River, the details of the cross-section at the *Aadampool* bridge were measured before taking each reading. The measured river cross-section at *Aadampool* bridge was plotted by taking the distance along the bridge span from the right hand side while facing upstream on the X-axis whereas depth of the river bed and that of water surface (both measured downward from the bridge span) on the Y-axis (Figure 4). The measured stage of 1.39 m (on August 27, 2011) from the datum (of 911.68 m) has been shown in Figure 4.

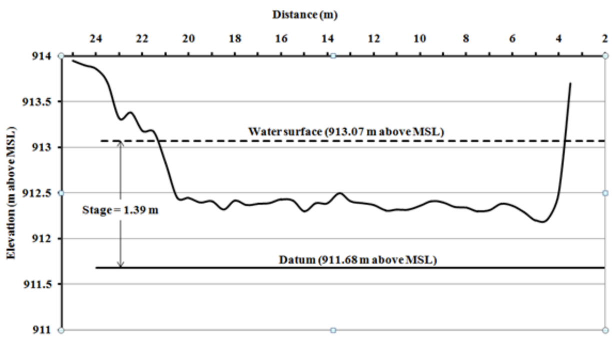

Figure 4. The *Ranikhola* River cross-section and stage measured on August 27, 2011.

3.2. Flow velocity and discharge measurement

To estimate the flow discharge in the *Ranikhola* River, the flow velocity was measured at the frequency of about twice a week. One of the sample reading and corresponding computational procedure is shown in Table 1, in which the flow velocity was estimated by using equation 1.

Table 1. Discharge computation by mean-section method (August 27, 2011).

Distance from the left corner of the bridge (m)	Depth of river bed from bridge span (m)	Depth of water surface from bridge span (m)	Depth of water (m)	Revolutions per minute of the current meter (N_s)	Flow velocity (m/s)	Average flow velocity (m/s)	Average flow depth (m)	Segmental discharge (m^3/s)
5.5	13.	12.	0.5	21	0.25	-	-	-
7.5	13.	12.	0.7	49	0.56	0.41	0.64	0.525
9.5	13.	12.	0.7	58	0.66	0.61	0.72	0.888
11.5	13.	12.	0.7	75	0.85	0.76	0.72	1.098
13.5	13.	12.	0.7	107	1.20	1.03	0.70	1.454
15.5	13.	12.	0.6	88	1.00	1.10	0.69	1.524
17.5	13.	12.	0.6	97	1.16	1.08	0.66	1.428
19.5	13.	12.	0.6	93	1.05	1.12	0.64	1.432
21.5	13.	12.	0.6	83	0.94	1.00	0.63	1.274
								Total discharge = 9.623

3.3. Stage-discharge relationship

The data of river stage and corresponding flow discharge in the *Ranikhola* River measured for 96 days (during August 27 to November 29, 2011) are given in Table 2. The measured stage (in m) was plotted in Microsoft Excel worksheet against the corresponding estimated flow discharge in an arithmetic plot with stage as ordinate and discharge as abscissa. After plotting the stage versus discharge to the arithmetic scale, a smooth curve through the plotted points is drawn (Figure 5). To get the rating curve equation in its standard form, as discussed in section 2.3, a linear trend line equation between 'log Q' (on Y-axis) and 'log $(h - h_o)$' (on X-axis) was also plotted (Figure 6). The developed stage-discharge relationship is the equation 7. The coefficient of determination (R^2) for the logarithmic plot was observed to be 0.977.

$$Q = 0.406\,(h - h_o)^{0.314} \quad \text{(equation 7)}$$

where, h = river stage elevation (m above MSL), Q = flow discharge (m^3/s), and h_o = 912.2 m above MSL.

Table 2. Stage-discharge data for the *Ranikhola* River.

Date	Stage elevations, h (m above MSL)	Stage (m)	Discharge, Q (m^3/s)	Square root of discharge
27-Aug-11	913.07	1.39	9.623	3.102
3-Sep-11	912.94	1.26	7.704	2.776
13-Sep-11	912.92	1.24	5.518	2.349
16-Sep-11	912.96	1.28	7.249	2.692
22-Oct-11	912.76	1.08	2.959	1.720
28-Oct-11	912.70	1.02	2.360	1.536
2-Nov-11	912.68	1.00	1.841	1.357
5-Nov-11	912.71	1.03	1.917	1.385
9-Nov-11	912.64	0.96	1.308	1.144
11-Nov-11	912.63	0.95	1.140	1.068
15-Nov-11	912.71	1.03	2.105	1.451
17-Nov-11	912.65	0.97	1.696	1.302
19-Nov-11	912.64	0.96	1.410	1.187
23-Nov-11	912.64	0.96	1.330	1.153
24-Nov-11	912.62	0.94	0.908	0.953
26-Nov-11	912.61	0.93	0.968	0.984
29-Nov-11	912.60	0.92	0.900	0.949

To check the relationship between stage and discharge, the stage values were plotted against the square root of the discharge values (Figure 7) and it was observed that the river stage roughly varies as the square root of the corresponding flow discharge, which is evident from very high value of the coefficient of determination (R^2) of 0.984 for the line fitted through the data points plotted in Figure 7.

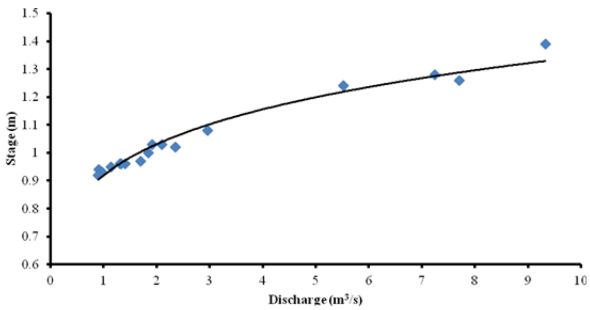

Figure 5. Stage-discharge rating curve for the *Ranikhola* River (arithmetic scale).

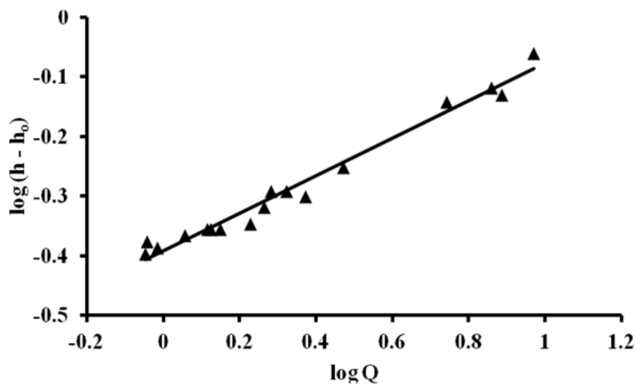

Figure 6. Stage-discharge rating curve for the *Ranikhola* River (logarithmic scale).

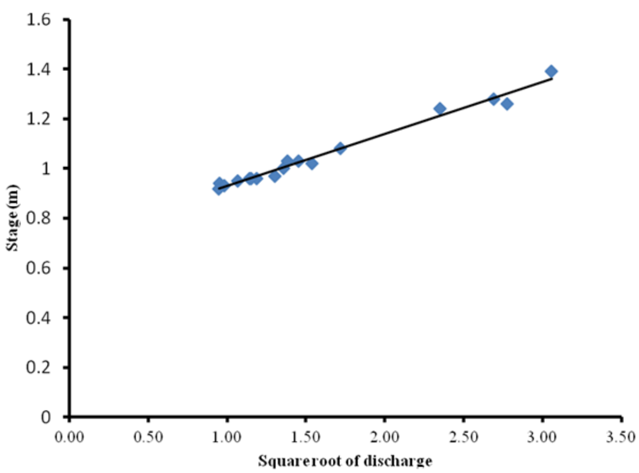

Figure 7. Stage versus square root of discharge.

4. Conclusions

The specific conclusions drawn from the present study are:

1. The developed stage-discharge relationship (equation 7) can be used for computing flow discharge in the *Ranikhola* River for the measured stage at *Aadampool* cross-section.
2. The range of the stage has been observed to be 0.92 to 1.39 m corresponding to the estimated flow discharge range of 0.90 to 9.34 m^3/s.
3. It was observed that at smaller stage values, increase in the discharge is comparatively lesser than the same at higher stage values, which can be attributed to more increase in flow cross-sectional area in V-shaped channel at higher stage values as compared to its lower increase at lesser stage values.
4. It was concluded that the stage varies roughly as the square root of the discharge.
5. The main limitation of the present study is that in the absence of an automatic gauging station, round the year data was not generated. For this purpose, it is suggested that an automatic gauging station needs to be established on the *Ranikhola* River.

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