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Rating Curve Development and Validation on Tordzie Watershed

Mexoese Nyatuame[1, 2, *], Sampson Agodzo[1], Leonard Amekudzi[3], Bismark Mensah-Brako[1]

[1]Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

[2]Department of Agricultural Engineering, Ho Technical University, Ho, Ghana

[3]Department of Physics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

Email address:

doga_nyatuame@yahoo.com (Mexoese Nyatuame)

[*]Corresponding author

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Abstract: Basin discharge is a crucial hydrological parameter in water resources management. However, its direct measurement is a difficult task to a hydraulic engineer. The quality of the data was examined employing regression analysis to check correlation between the discharge (Q) and stage (H). The mean values of the two variables were then adopted to find the difference of value between zero gauge and level of zero flow, "H_0", and locality constants ("K" and "n") to fit into rating curve equation and plotted the stage-discharge rating curve. The generated equations for the network stations were $Q = 7.4716(H-0.1096)^{1.024}$ for Honuta, $Q= 8.2105\ (H-0.30)^{1.2415}$ for Kpetoe and for Tordzinu $Q = 3.937\ (H-0.48)^{1.3178}$. The formulated equations were validated with historical stage and discharge data. The correlation coefficients were 99.78%, 99.85% and 98.73% for Honuta, Kpetoe and Tordzinu respectively. The Correlation coefficients indicated percent of original uncertainty explained by the analysis. The standard deviations (and standard errors) were 1.81% (0.34%), 15.58% (4.50%) and 14.25% (4.11%) for Honuta, Kpetoe and Tordzinu, respectively, on Tordzie watershed. The calculated rating curve has several advantages. Among them, it is able to estimate accurate discharge during the flood based on extrapolation which is difficult to measure directly.

Keywords: Discharge, Rating Curve, Stage, Tordzie Basin, Volta Region

1. Introduction

The discharge (stream flow) of a basin or stream is explained as volume of water passing from one section to another section per unit time measured in cubic meters per second. Discharge measurement is a prerequisite for any water infrastructure development. The water supply for whatever purpose, irrigation water management, hydro power generation, flood disaster structures all requires the knowledge of the rate of flow of water. Stream flow and stage measurements are two essential hydrological parameters required to be measured in any hydrological station in a basin. Stage is the height of water surface of any water body observed in relation to a reference point. The mean sea level is usually taken as the reference point or an arbitrary reference point [1].

There is a stage-discharge relation or rating curve relation existing between the surface of water (water level) and the instantaneous stream flow in an open channel. In the establishment of water balance of a basin, stream flow is one of the key hydrological parameters that must be considered. The rating curve is a very essential scientific tool in surface hydrology as the dependability of stream flow data values is highly reliant on an acceptable stage-stream flow relations at the hydrological station.

Stage measurement is comparatively not difficult; precise results can be obtained, and not particularly expensive. The stream flow observations required for the conceptual rating curve development, however, is full of drudgery, costly, and sometimes risky. The aforementioned accounted for the difficulty to actually measure stream flow at certain hydrological stations directly for rating curve development.

The reasons for the difficulty are (1) locations experiencing high stream flows during rainfall are risky to be measured with current meter; (2) locations with turbulent flows; (3) inaccessible locations; (4) ungauged stations or existing one destroyed by high flows during a heavy storm [2]. For unstable flow situations usually encountered in small basins, the basin flow can vary substantially during measurement. A rating curve represents a correlation of the stage of a cross section of a basin with the rate of basin flow at that section. The rating curve lessens the drudgery and expensive direct basin flow measurements [3].

In the words of Beven [4] and Beven et al [5], errors occurred in direct discharge data measurements and other water balance terms thus rendering the closing of water balance very difficult using the measured data. Additionally, Di Baldassarre and Claps [6] reported that the usual procedure adopted in river discharge measurement interpolation fail to replicate the discharge-stage relationship in the extrapolation zone. This, they revealed, results in physically implausible values. Thus, they suggested the use of hydraulic method in deriving the stage-discharge curves and the related uncertainty. Besides, Di Baldassarre and Montanari [7] presented analysis of uncertainty of rating curve regarding direct measurements, their interpolation and extrapolation of unsteady flow conditions and seasonal changes in roughness.

The reliability of the calculated stream flow data, according to Mosley and McKerchar [8] is determined by the quality of stage-discharge relationship. However, the unique stage-discharge relationship exists only for ideal case of stable uniform flow [9]. Tordzie basin is very important river basin in the volta region of Ghana due to its economic importance to its catchment dwellers. The water from the basin serves the purpose of domestic uses such as washing, drinking and as well as agricultural usages of irrigation and animal watering and fire fighting and other industrial usages [10]. According to GSS [11], the population of people settling in and around the catchment is over 5000 and the population is increasing at the rate of 2.4% per annum. There is also an emergence of small and medium rural industries in the catchmet or vicinity of the basin that uses the water from the basin for their enterprises. The water resouces engineers, planners and policy makers need to plan for the judicious use of the water from the basin in the midst of climate change and variability and also the need to build any hydraulic structures for water storage and conservation requires the knowledge of the basin flow and its characteristics. Thus, establishing the rating curve or the stage-dischrge relation for the Tordzie basin to aid in the discharge computation is a step in the right direction to reduce the drudgery involve in the direct discharge measuremnt and the cost associated with it as mentioned earlier on. The rating curve developed will also serve as baseline for further charactersisation of the hydrology of the basin since not much has been done in terms of hydrological characterisation of the Tordzie basin as compared to other basins in Ghana [12]. Hence the study developed rating curve on the network stations on Tordzie watershed and validated same to serve the aforementioned purposes.

2. Material and Methods

2.1. Study Area

The Tordzie watershed is shown in Figure 1. The Tordzie basin has a catchment area of 1278.3km^3. The study area lies within the transition belt and the Equatorial climate of Ghana. The equatorial climatic zone of the watershed covers the entire outfall of the basin at Tordzinu which is near the coastal belt of the country. The network stations in the Tordzie watershed that were analysed were Honuta (6°83'0"N, $0^0$53'0"E), Kpetoe ($6^0$54'0"N, $0^0$69'0"E) and Tordzinu ($5^0$5'0"N, $0^0$45'0"E), at elevation 221.1 m, 79.0 m and 5.4m respectively. The stream network of the watershed is shown in figure 2.

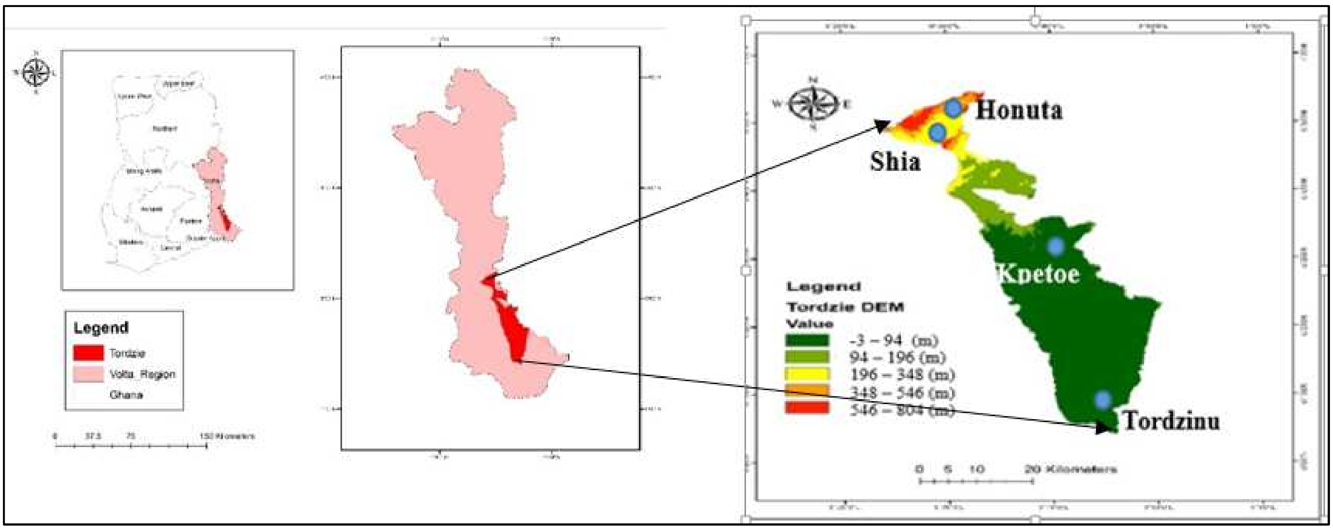

Figure 1. *Map of Ghana Showing Volta Region, Tordzie Watershed and Digital Elevation Model of Tordzie Watershed (Source: generated from field data2017).*

2.2. Data for the Study

The hydrological data obtained from Hydrological Services Department (HSD) was used for the rating curve. The rating curve was developed using hydrological data from March 1975 to February 1976 for Kpetoe and from May 1991 to February 1992 for Tordzinu. These were analysed using iteration method. At Honuta side of the basin, the data used was for the period of May 2002 to March 2003.

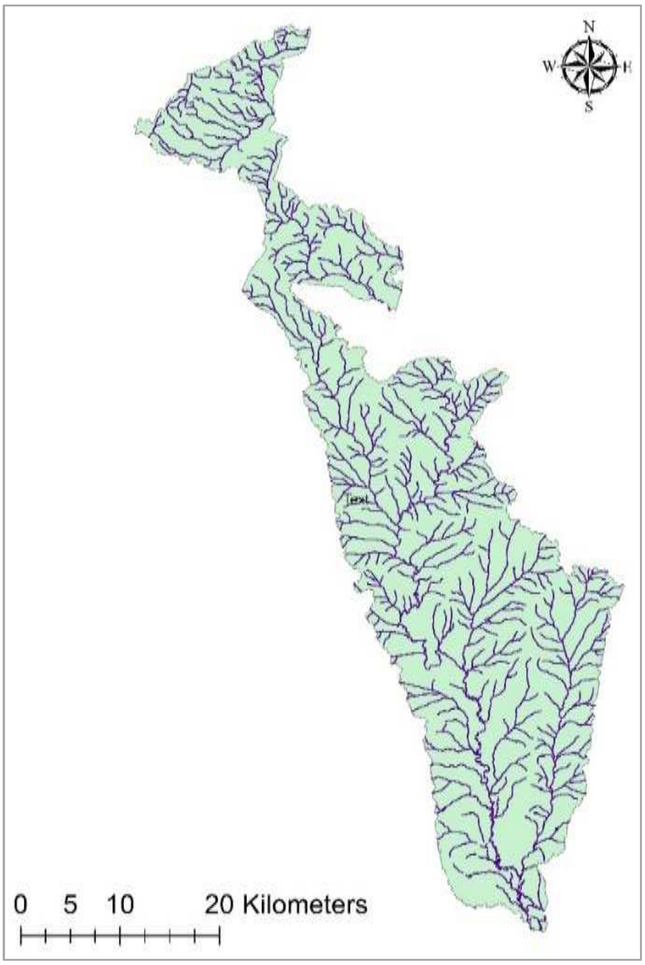

Figure 2. *Tordzie Stream Networks, Source: generated from field data (2017).*

2.3. Stage-Discharge Relationship

The general rating equation is expressed as equation 1 according to [13].

$$Q = K(H - H_o)^n \tag{1}$$

where, H_o = stage corresponding to zero discharge (m), H=gauge depth (m), K and n are coefficients or locality constants and Q= discharge.

Taking log to base 10 of Equation 1, gives

$$LogQ = nLog(H - H_o) + LogK \tag{2}$$

Which is in the form of an equation of a straight line, given as

$$Y = nX + m \tag{3}$$

The unknown variables in Equations 2 and 3 were computed using Equations 4 and 5.

$$n = \frac{N\sum(XY) - \sum(X)(\sum Y)}{N(\sum X^2) - (\sum X)^2} \tag{4}$$

$$m = \frac{\sum Y - n\sum X}{N} = LogK \tag{5}$$

The coefficient of correlation between the stage and discharge was computed employing Equation (6) after [13].

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\left(\sqrt{N(\sum X^2) - (\sum X)^2}\right)\left(\sqrt{N(\sum Y^2) - (\sum Y)^2}\right)} \tag{6}$$

Three points were selected on the stage-discharge curve such that their discharges are in geometric progression

$$\frac{Q_1}{Q_2} = \frac{Q_2}{Q_3} \text{ or } Q_2^2 = Q_1 Q_3 \tag{7}$$

where 1, 2, 3 are points on the stage-discharge relation curve.

The following computation steps were employed for the procedure. Three stage points on the rating curve segment were chosen which correspond to the three discharge points. One of the chosen points was near the lower end of the segment, and one point was near the upper end of the segment. The stage values corresponding to the three discharge points were used to determine the zero flow stage value. Employing the trial and error method and assuming that the lower part of the rating curve is a parabola. The constant H_o in Equation 1 was estimated employing Equation 8.

$$H_o = \frac{H_1 H_2 - H_2^2}{(H_1 + H_3) - 2H_2} \tag{8}$$

Trial and error procedure was adopted until an appropriate H_o value was found to fit the data.

2.4. Statistical Test of Rating Curve for Absence of Bias

The test of absence of bias in the rating curve was conducted, employing the following methods.

1. The mean percentage differences between the observed stream flow and the estimated stream flow from the rating curve must not substantially differ from zero. The *t-test* was employed for the analysis.
2. The number of positive and negative deviations of the observed stream flow from the estimated stream flow from the rating curve ought to be uniformly distributed, i.e. the variance in number of positives and negatives ought not to be more than can be explained as being due to fluctuations. This is tested by the *sign test.*

$$\text{Percentage deviation, } P_d = \frac{Q_m - Q_c}{Q_c} 100 \tag{9}$$

$$\text{Mean deviation, } \bar{d} = \frac{d_1+d_2+d_3+ --\mp d_n}{n} \quad (10)$$

$$\text{Standard deviation of } \bar{d}, S_d = \sqrt{\frac{(P_d-\bar{P}_d)^2}{n-1}} \quad (11)$$

$$\text{Standard error of } \bar{d}, S_E = \frac{S_d}{\sqrt{n}} \quad (12)$$

$$\text{Test statistic, } t = \frac{\bar{d}}{S_E} \quad (13)$$

3. Results and Discussion

3.1. Stage –Discharge Relationships on Tordzie Basin

The stage-discharge relationship was analysed using Equation 2 to compute the zero discharge. The measured stage and discharge were analysed and results presented in Table 1 for Honuta network station using the least square error method.

Table 1. *Rating equation parameters and analysis for Honuta by least square method.*

stage(H)	Q	H_o	$H-H_o$	Log $(H-H_o)$(X)	Log Q(Y)	XY	X^2	Y^2
1.12	8.73	0.11	1.01	0.00	0.94	0.00	0.00	0.89
0.22	0.86	0.11	0.11	-0.97	-0.07	0.06	0.94	0.00
0.32	1.45	0.11	0.21	-0.68	0.16	-0.11	0.46	0.03
0.32	1.47	0.11	0.22	-0.67	0.17	-0.11	0.44	0.03
0.40	2.13	0.11	0.29	-0.53	0.33	-0.17	0.28	0.11
0.32	1.38	0.11	0.21	-0.68	0.14	-0.10	0.46	0.02
0.25	0.91	0.11	0.14	-0.86	-0.04	0.03	0.74	0.00
0.23	0.89	0.11	0.12	-0.91	-0.05	0.05	0.83	0.00
0.24	0.99	0.11	0.13	-0.88	-0.01	0.00	0.77	0.00
0.36	1.90	0.11	0.25	-0.61	0.28	-0.17	0.37	0.08
0.56	3.28	0.11	0.45	-0.34	0.52	-0.18	0.12	0.27
0.21	0.66	0.11	0.10	-1.02	-0.18	0.18	1.04	0.03
0.19	0.55	0.11	0.08	-1.11	-0.26	0.29	1.23	0.07
0.29	1.26	0.11	0.18	-0.74	0.10	-0.07	0.55	0.01
0.26	1.01	0.11	0.15	-0.82	0.00	0.00	0.67	0.00
0.24	0.86	0.11	0.13	-0.89	-0.07	0.06	0.79	0.00
0.28	1.16	0.11	0.17	-0.76	0.06	-0.05	0.58	0.00
0.35	1.66	0.11	0.24	-0.62	0.22	-0.14	0.39	0.05
0.25	0.94	0.11	0.14	-0.85	-0.03	0.02	0.72	0.00
0.20	0.78	0.11	0.09	-1.04	-0.11	0.11	1.08	0.01
0.19	0.55	0.11	0.08	-1.12	-0.26	0.29	1.25	0.07
0.18	0.52	0.11	0.07	-1.14	-0.28	0.32	1.31	0.08
0.19	0.59	0.11	0.08	-1.08	-0.23	0.25	1.17	0.05
0.19	0.60	0.11	0.09	-1.07	-0.22	0.24	1.15	0.05
0.21	0.71	0.11	0.10	-0.99	-0.15	0.15	0.98	0.02
0.23	0.83	0.11	0.12	-0.91	-0.08	0.07	0.83	0.01
0.19	0.55	0.11	0.08	-1.11	-0.26	0.29	1.24	0.07
	1.38			-22.40	0.64	1.33	20.39	1.94

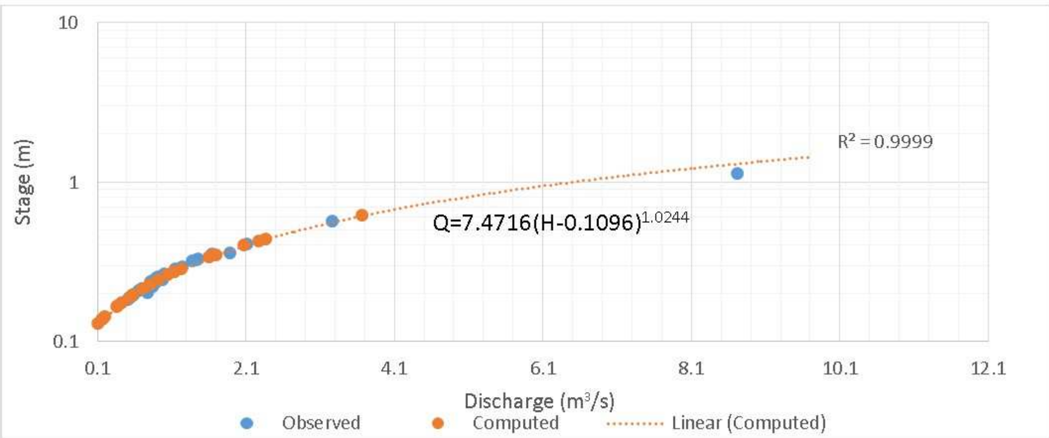

Figure 3. *Stage-Discharge relation curve for Honuta.*

The generated rating curve was calibrated for Honuta, the parameters of the curve are displayed in Table 1. The referred table shows that; $\sum X$= -22.40, $\sum Y = 1.33$, $\sum X^2 = 20.39$, $\sum Y^2 = 1.94$.

The three unknown parameters in Equation 1 were evaluated and they are K= 7.4716, H_o =0.1096 and n = 1.024. The computed coefficients were put into Equation 1 given as

$$Q= 7.4716(H-0.1096)^{1.024}. \quad (14)$$

The coefficient of correlation between the stage and discharge was also computed from Equation 6. The value obtained is 0.99, implying a strong correlation exist between the stage and the stream flow in the hydrological station (Honuta). The gauge and discharge recorded data from May, 2002 to July 2004 was used to develop the Equation 9. The developed equation was validated by the recorded gauge data from August 2004 to October 2006 (Figure 3). The coefficient of determination (R^2) of 99% for both the observed and the calculated rating curve indicated 99% of the original uncertainty was explained by the analysis. The correlation coefficients of the stage-discharge relationship also serve as a validation of the stage-discharge curve. This proves that the equation developed represent an excellent fit. The rating curve performed better at the gauge height between 0.12 and 1.01 m at Honuta gauging station with difference between the computed and the measured discharge being 0.07 m^3/s at higher depths, as seen from Figure 3. The implication is that high flows are associated with measurement errors. At high flows, unsteady flow conditions arises which is at variance with the assumptions of the rating equation. The disparity in discharge values between the observed and computed at higher depths is supported by contemporary literature [2]. The uncertainty inherent in the least squares estimation of the parameters could also account for the error in the equation. Besides, the temporal changes in hydraulic properties governing the rating curve leads to uncertainty in the measured data.

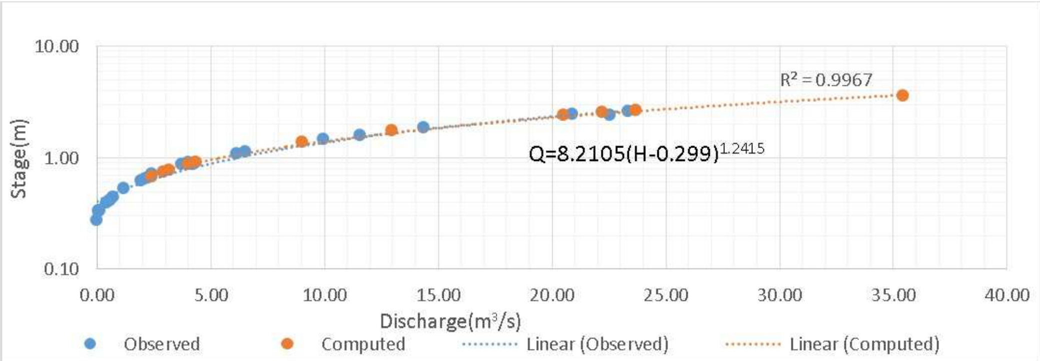

Figure 4. *Stage-Discharge relation curve for Kpetoe.*

The stage-discharge plot for the measured and the computed generated by the derived equation for the Kpetoe reach of the Tordzie basin is very close. The derived Equation for Kpetoe is

$$Q=8.2105(H-0.299)^{1.2415} \tag{15}$$

The coefficient of correlation computed is 0.99, an indication of a good relationship between stage and discharge. The rating curve for Kpetoe performed extremely very well at a gauge height of between 0.3 to 2.6 m with +0.002 difference between the measured and computed discharge at higher depths (Figure 4). The result implies accuracy at the mentioned stage and also that there was no shift in the control of the stream.

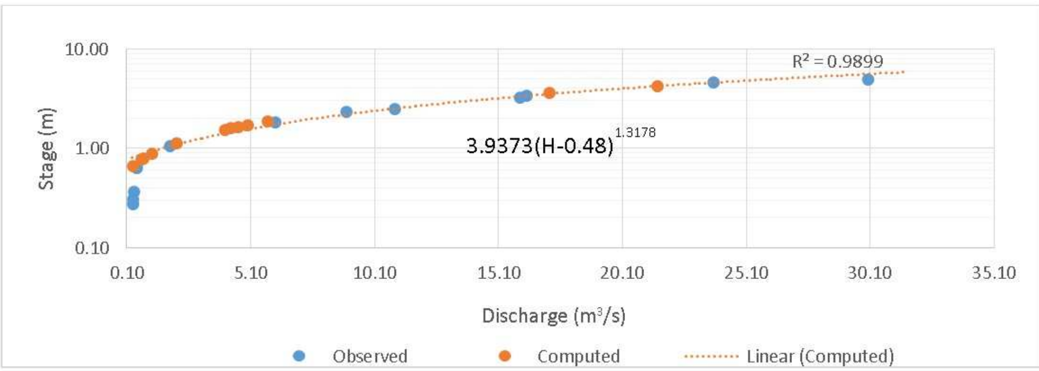

Figure 5. *Stage – Discharge relation curve for Tordzinu.*

The relation between stage and discharge is very close as seen in Figure 5 and depicted by coefficient of determination (R^2). The rating equation for Tordzinu gauge station is,

$$Q = 3.9373\,(H-0.48)^{1.3178} \tag{16}$$

The agreement in performance between the measured and the computed was observed from stage 0.4 m to 2.5 m with + 0.03 m^3/s discharge discrepancy between the computed and the measured discharge. The discrepancy between the measured/observed rating curve and the calculated rating curve could be that the direct discharge measurement is subject to some error. These errors could be observational, instrumental and high flows. This is because high flow measurements are difficult to measure and it takes several years to establish precise experimental high flow ratings.

However, there is a good concord between the measured and the calculated rating curves at the lower depths except from the middle moving up to the high flow depth areas. Some inherent natural randomness associated with direct measurement such as changes in geometry of channel, sediment concentration, wind and turbulent flow results in uncertainty in direct measurement. This assertion is in agreement with the results of [14, 15]. This implies that it is better and more accurate to apply the model generated data for evaluating especially the high flows. However, the rating curve should be validated regularly to ensure its accuracy.

3.2. Validation of the Rating Curve

The rating curve ought to be validated for two reasons, first after the relations are established and secondly when new stages are determined to evaluate if there is variation in rating. Besides, reliability of historical ratings are ascertain through validation.

Table 2. *Paired t-test statistic for validation of a rating curve.*

No	Measurements		Rating Q_c	Percentage deviation, P_d				$(P_d - \bar{d})^2$
				P_d		$P_d - \bar{d}$		
	H	Q_m		+	-	+	-	
1	0.27	8.73	1.14	7.59		7.29		53.14
2	0.61	0.86	3.68		-2.82		3.12	9.73
3	0.42	1.45	2.28		-0.83		1.13	1.28
4	0.28	1.47	1.25	0.22		0.08		0.01
5	0.22	2.13	0.81	1.32		1.02		1.04
6	0.17	1.38	0.44	0.94		0.64		0.41
7	0.13	0.91	0.12	0.79		0.49		0.24
8	0.19	0.89	0.54	0.35		0.05		0.01
9	0.14	0.99	0.19	0.80		0.5		0.25
10	0.16	1.90	0.38	1.52		1.22		1.49
11	0.35	3.28	1.71	1.57		1.27		1.61
12	0.34	0.66	1.68		-1.02		1.32	1.74
13	0.24	0.55	0.93		-0.38		0.68	0.46
14	0.26	1.26	1.05	0.21		0.09		0.01
15	0.34	1.01	1.68		-0.67		0.97	0.94
16	0.21	0.86	0.72	0.14		0.16		0.03
17	0.16	1.16	0.38	0.78		0.48		0.24
18	0.14	1.66	0.21	1.44		1.14		1.30
19	0.12	0.94	0.06	0.88		0.58		0.34
20	0.14	0.78	0.17	0.61		0.31		0.10
21	0.11	0.55		0.55		0.25		0.06
22	0.19	0.52	0.59		-0.06		0.36	0.13
23	0.34	0.59	1.69		-1.1		1.40	1.96
24	0.33	0.60	1.62		-1.02		1.32	1.74
25	0.27	0.71	1.15		-0.44		0.74	0.55
26	0.44	0.83	2.37		-1.54		1.84	3.39
27	0.40	0.55	2.08		-1.53		1.83	3.35
			sum	19.70	11.42	15.57	14.71	85.55

From Equations 9 to 13, mean deviation, $\bar{d}$ = 0.30, Standard deviation, S_D =1.81, standard error, $S_{E=}$ 0.34 and test statistic, t =0.87. The value of t from Table at 5% significant level for a sample size of 27 is found to be 2.056 of two tail test at degree of freedom of n-1 equal to 26. As the computed value of t is less than the tabulated (2.056), the rating curve is free of bias at Honuta gauging station (Table 2). At Kpetoe gauging station the validation result parameters are: mean deviation, $\bar{d}$ =-6.47, Standard deviation, S_D= 15.58, Standard error, S_E =4.50 and test statistic, t =1.44 with tabulated t value of 2.201. The corresponding validation values at the Tordzinu gauging station on Tordzie watershed are: mean deviation, $\bar{d}$ = 3.96, standard deviation, S_D= 14.25, standard error, S_E = 4.11 and t = 0.97 with t (tabulated) = 2.201 at 95% confidence interval. The student's paired t-test was employed to statistically evaluate the distinction between the measured discharge and the computed discharge by the developed rating equation. The mean differences between the two data sets were compared employing the t-test based on paired differences of the data. According to Johnson [16], the test statistic must follow the normality assumption of sampling distribution and independent requirement of discharge magnitude. The t-statistic obtained suggested the rating equation developed is a good one. A good model estimation should result in a t-value of ±1.96 for the highest sampling size and ± 2.23 for the lowest [17]. The implication of the results obtained is that the rating curve could be safely used in estimating discharge for further analysis since the error margin is within acceptable level. However, the standard deviations obtained indicated that the value of the used data is concentrated around the mean at Honuta than at Kpetoe and Tordzinu, meaning there are outliers (extremely low and extremely high) values at the mentioned gauge stations. The implication is that the error associated with high flows (extremely high) is possible to occur in the above gauge stations. A further implication of the error is the under or over estimation of the discharge.

4. Conclusion

The calculated rating curve has several advantages. Among them it is able to estimate accurate discharge during the flood based on extrapolation which is difficult to measure directly. In addition high flood can easily be estimated unlike several years of labourious procedures in direct measurements. Besides, comparatively it is less costly. The rating curve equation developed at the different reaches of the basin can be used to generate flow data given the stage which is easier to measure. However, it is recommended that the developed equation be recalibrated from time to time. It is also recommended for further investigation, the impacts of sediment loads on flow and stage measurement and eventually on the rating curve.

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