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Computation of River Discharge from Formulated Rating Equation in Hydrological Catchments with Inadequate Data: River Omi, South Western Nigeria, as Case Study

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Abstract

River discharge is an important hydrological parameter in any water resources management. Most rivers in Nigeria, with sizeable catchment areas, are poorly gauged and are noted to have histories of frequent flooding experience. Since Stage or Gauge, which is the height of water surface at a relative datum, can be easily measured, it is possible to formulate a rating equation which can predict discharge with a known gauge-depth. This Paper develops a mathematical relationship between gauge heights and discharge, using River Omi, South Western Nigeria, as a case study.

Series of gauge-discharge relationships were established on River Omi from measured values and past records. The water velocities were measured using ultrasonic current meter and geometrical parameters were measured at the gauging station. The stage-discharge relationship, over a period of time, was plotted and a rating equation generated.

The generated rating equation: $Q = 0.1828*(G-0.14)^{0.78,}$ has a coefficient of regression of 97%. The formulated equation was calibrated and validated with discharge data obtained from 2007 to 2012. The rating equation performed better at depth below 0.6 m with less than 1% variation between the simulated and measured discharge. This formulated equation can be adapted to other river catchments with similar hydrological characteristics. It should be noted that below gauging depth of 0.14 m, the rating equation cannot be used.
Keywords: River Discharge, Rating Equation, Gauge Depth, River Omi, Regression

1. Introduction

Ibadan (Oyo state, Nigeria) is the largest city in West Africa and the second largest in Africa, with land size covering an area of 240 km^2. The city is located on geographic grid reference longitude 3º 5E, latitude 7º 20N. It is situated at an average height of 200m above sea level, drained by three major river basins (Ogunpa, Ona and Ogbere) and surrounded by secondary rainforest as well as a savannah. Spatially, it sprawls over a radius of 12-15 km and experiences a mainly tropical climate with an estimated annual rainfall of about 1250 mm (Olaniyan and Adegbola, 2012).

It has a tropical wet and dry climate (Köppen climate classification Aw), with a lengthy wet season and relatively constant temperatures throughout the course of the year.

Ibadan's wet season runs from March through October, though August sees somewhat of a lull in precipitation. This lull nearly divides the wet season into two different wet seasons. November to February forms the city's dry season, during which Ibadan experiences the typical West African harmattan (Goldface - Irokalibe, 2006, Adegbola and Olaniyan, 2012).

This research is designed for River Omi located within Iddo Local Government area of Ibadan. It lies between longitude 3^0 55′ and 4^0 00′ East and Latitude 7^0 00′ and 7^0 05′ North of the equator. The river is about 14.5 km with frequent flooding experience like August, 2011 flooding in Ibadan. The catchment area of the river is 123.53 km^2. The river ranges between 0.50 – 2 m spot height and 19 km from the source to the study area (Kumolu, 2008). River Omi is an alluvial river with channels and floodplains that are self-formed in unconsolidated or weakly-consolidated sediments. The morphology of an alluvial river reach is controlled by a combination of sediment supply, substrate composition, discharge, vegetation, and bed aggradations. River Omi is very useful to the inhabitants for domestic, agricultural and waste disposal purposes. Some of the bridge and culvert on the river has been swept away due to frequent flood occurrence. Figure 1 shows the catchment area around River Omi.

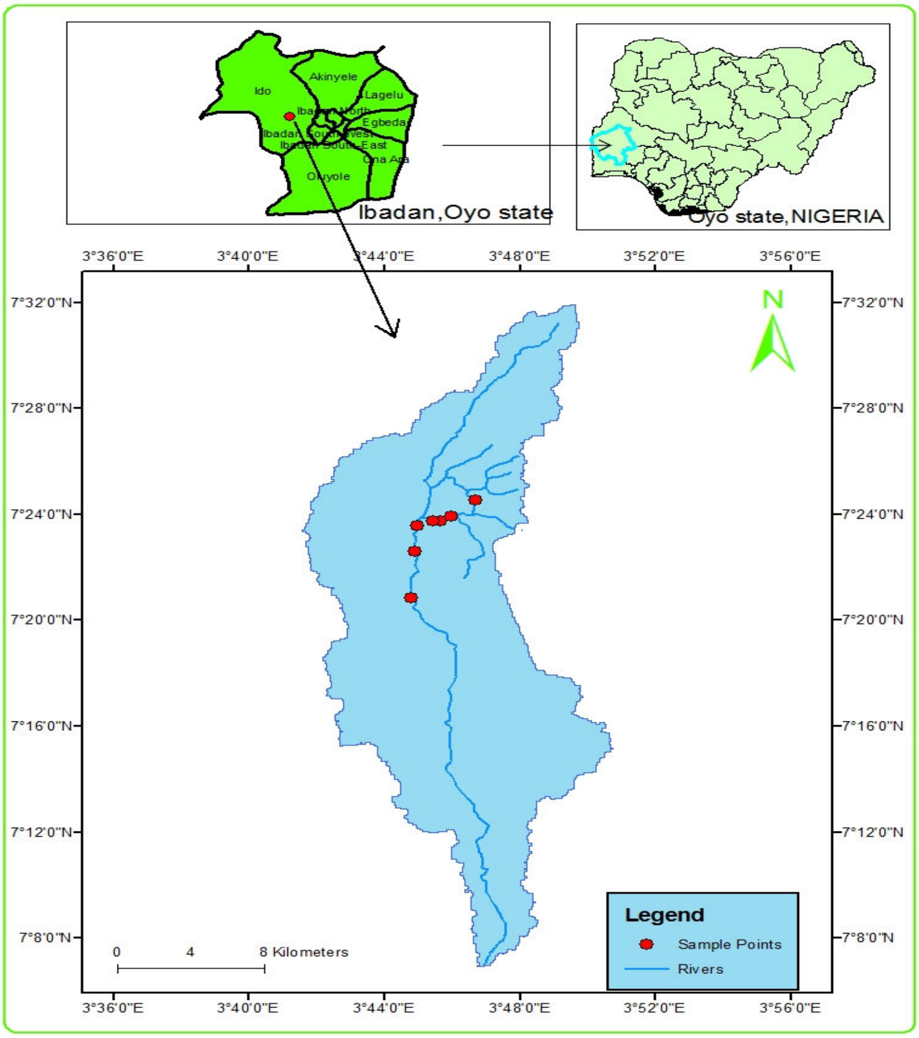

Figure 1 Map of part of Ibadan showing Sampling Stations on River Omi

2. Literature Review

Discharge or rate of flow is the volume of water flowing through a cross section in a unit time such as cubic meters per seconds or cubic feet per seconds. Discharge measurement is imperative in any water system for the development of irrigation and power potentials, water supply, flood control and navigation etc. Discharge and gauge measurement are two hydrological parameters that must be measured at any gauging station. Stage or gauge is the elevation of water surface of a river measured relatively to a datum. The datum can be mean sea level or any arbitrary datum (Sharma and Sharma, 2002).

Gauging site should be permanent irrespective of scouring or silting of sediment and must give same elevation of water surface corresponding to a given discharge (Sharma and Sharma, 2002). Gauge can be a direct or indirect type. Staff gauge are direct type while self-recorder type and crest stage type are indirect gauges. Gauges can be vertical staff gauge, inclined gauge, hook gauge, temporary gauge and crest stage gauge (Subramanya, 2007; Adegbola and Olaniyan, 2012).

Sometimes, discharge and gauge sites may be differ due to site condition. It's very preferable if stage-discharge observations are complementary operations. If discharge measurement site is then differ from gauge site, additional qualities should be possessed by discharge sites. These additional qualities include: it should not be too far from the gauging station, located within straight reach; site should be free from aggradation and degradation among others (Sharma and Sharma, 2002). Discharge measurement can either be direct or indirect measurement. Direct measurement can either be velocity-area method using current meter, floats and dilution method using chemical. Slope-area method using flow measuring structures such as flumes, weir and gated structure is an indirect method of discharge. Velocity increase from the bottom of a channel to the water surface.

Maximum velocity occurs between 0.10 to 0.20 of the depth below water surface. The mean velocity on any vertical section can be obtained at a depth of 0.6 of the total depth (Subramanya, 2007).

However, discharge Computation can be done more accurately by using Velocity-area method which utilized the observed depth and measured velocity by current meter. The two approaches here include mid-section method and mean section method (Subramanya, 2007).

(i) Mid-section methods: the mean velocity is observed at 0.6depths at vertical intervals and flow at edges is omitted. Discharge is computed as:

$$Q = \bar{V}_1 d_1 \left[\frac{b_1+b_2}{2}\right] + \bar{V}_2 d_2 \left[\frac{b_2+b3}{2}\right] + \cdots \quad (1)$$

(ii)Mean section methods: average discharge value is computed for each strip as shown in equation 2

$$q = \left[\left(\frac{d_1+d_2}{2}\right)\left(\frac{\bar{V}_1+\bar{V}_2}{2}\right)\right] \quad (2)$$

$$\sum q = Q \quad (3)$$

where:

Q = discharge (m^3/s), $\bar{V}$= velocity (m/s), b_n = breadth (m), d = depth (m), n = integers

2.1 Stage- Discharge Relationship

The combined effect of gauge and discharge is termed control which is permanent if it does not change with time. The general rating equation is shown in equation 4 which can be expressed as equation 5 and 6 (Subramanya, 2007).

$$Q = C_r(G-a)^{\beta} \quad (4)$$

where:

a = stage for zero discharge (m)

G = Gauge Depth (m)

C_r and β are co-efficients

$$\log Q = \beta \log(G-a) + \log C_r \quad (5)$$

$$Y = \beta X + b \quad (6)$$

The unknown variable in equation 6 can be calculated with equation 7 and 8

$$\beta = \frac{N(\sum XY)-(\sum X)(\sum Y)}{N(\sum X^2)-(\sum X)^2} \quad (7)$$

$$b = \frac{\sum Y - \beta(\sum X)}{N} = \log C_r \quad (8)$$

The coefficient of correlation can be estimated from equation 9 (Subramanya, 2007)

$$r = \frac{N(\sum XY)-(\sum X)(\sum Y)}{\left(\sqrt{N(\sum X^2)-(\sum X)^2}\right)\left(\sqrt{N(\sum Y^2)-(\sum Y)^2}\right)} \quad (9)$$

Subramanya (2007) opined that Running method can be used to estimate constant a. Three points A, B and C on the curve were selected such that their discharges are in geometrical progression i.e.

$$\frac{Q_A}{Q_B} = \frac{Q_B}{Q_C} \quad (10)$$

where:

A, B and C are points on the stage-discharge curve

Running method on the other hand assumed that the lower part of the stage-discharge curve is a parabola. The constant (a) can be estimated using equation:

$$a = \frac{G_1 G_3 - G_2^2}{(G_1+G_3)-2G_2} \quad (11)$$

where:

G_n= Stage depth at a point on the curve

n = exponent

3. Materials and Methods

Water depth was measured at a gauge site and velocity measured with ultrasonic flow meter. Discharge and Stage record from 1970 to 2012 were used in this study. The Stage-Discharge (G-D) curve was plotted using hydrological data from 1970 to 1986 and analyzed using running method. Three points on the curve were selected such that their discharges are in geometrical progression (see equation 10).

The constant "a" in the rating equation, which represents stage for zero discharge, was fixed using two methods. The methods used are running method and graphical method which involves drawing best of fit curve on Plot discharge (Q) against gauge (G).

4. RESULTS AND DISCUSSION

The Rating equation was analyzed using computed zero stage discharge (a) from equation 8. The measured gauge and discharge were analyzed for River Omi as shown in Table 1

TABLE I: Rating Equation Analysis

G	G-A	Q (F^3/S)	X	Y	XY	X^2
0.3	0.09	0.21	-1.04	-0.68	0.71	1.09
0.4	0.19	0.05	-0.72	-1.30	0.94	0.52
0.85	0.64	3.29	-0.19	0.52	-0.10	0.04
1.39	1.18	14.6	0.07	1.16	0.08	0.005
			-5.10	3.76	2.30	5.50

Note that $Y = \log Q$, $X = \log(G - a)$
where:
q = discharge ($m^3 s^{-1}$),
G = stage (m)
The rating equation was developed and calibrated on River Omi watershed as shown in Table 1. From Table 1, $\sum X = -5.51069$, $\sum Y = 3.7567, \sum XY = 2.2957, \sum X^2 = 5.502 , \sum Y^2 = 8.9716$, $a = 0.21$
The three unknown evaluated from the Table 1 are:
$\beta = 1.169, C_r = 6.4569$ *and* $r = 0.769$.
These coefficients were used in the general rating equation shown in Equation 4. The coefficient of regression (r) falls between 0.6 -1.0 which implies a good correlation between discharge and gauge exist on the study area. The developed rating equation developed is:

$$Q = 6.456(G - 0.21)^{1.169} \quad f^3/s \qquad (12)$$
$$Q = 0.1828(G - 0.21)^{1.169} \; m^3/s \qquad (13)$$

where:
Q = discharge ($m^3 s^{-1}$),
G = stage (m)
Equation 12 was calibrated by using gauge records from 2008 to 2010. Trial and error approach was used fix unknown variables of rating equation by using gauging records. The developed rating equation was validated with gauge record between 2011 to 2012 on River Omi. Figure 1 and 2 shows the validation of developed rating equation using Running and Graphical method respectively.

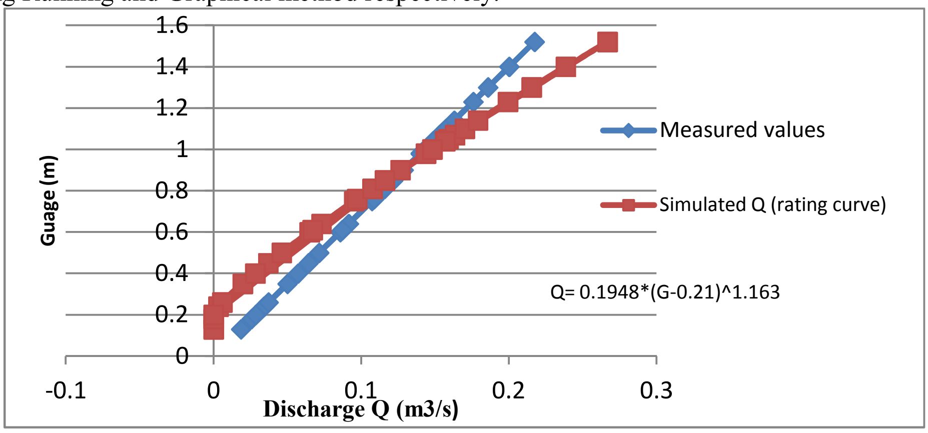

Figure 1. Rating equation validation using Running Method

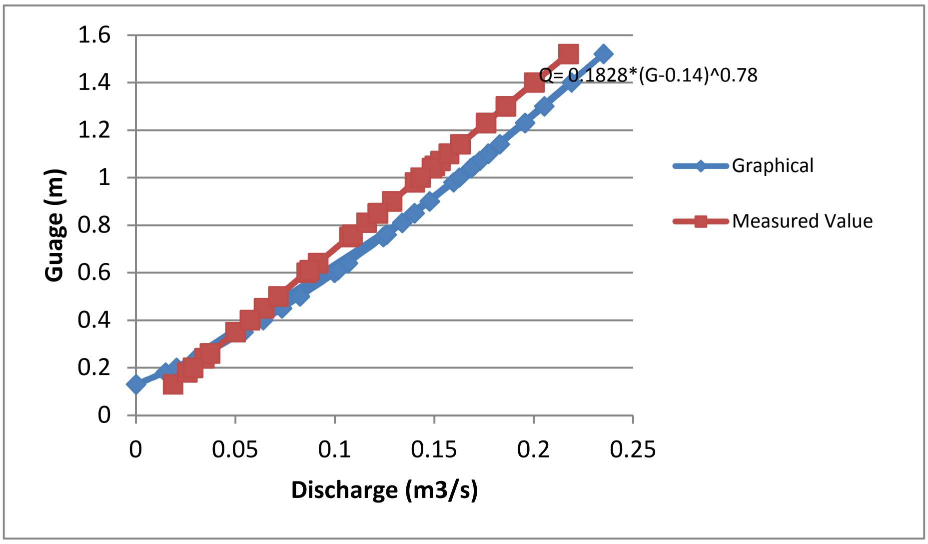

Figure 2. Rating equation validation using Graphical Method

4.1 Discussion of Result

Developing a rating curve entails two steps. The first step involves measuring stage and the corresponding discharges in the river and establishing a relationship. For the second stage, stage of river is measured and discharge is calculated by using the established relationship. Stage is measured by reading a gauge installed in the river. If the stage-discharge relationship doesn't alter with time, it is called permanent control. If the relationship does change, it is called shifting control. Shifting control occurs from erosion or deposition of sediment at the stage measurement site.

Discharge measurement in rivers is a challenging job for hydraulic engineers. A graph of stage versus discharge is known as rating curve. The stage-discharge relationship is an approximate method employed for estimating discharge in rivers, streams and various hydrological applications such as sediment budget analysis. Stages are easy to measure as compared to the measurement of discharge in rivers. Water bodies like is often affected by other factors which are neither always understood, nor easy to quantify. This can be explained from the fact that discharge is not a function of stage alone. Discharge depends on longitudinal slope of river, channel geometry, bed roughness etc. The measurement of these parameters at even and every time step and section is not possible. Thus, there is a need to establish the accurate relationship between stage and discharge.

Running methods assumes that the lower portion of stage-discharge plot is parabolic. This is not totally correct in this study because two sets of constant "a" were obtained. The validated rating equation on River Omi using Running method is:

$$Q = 0.1948(G - 0.21)^{1.163}\ m^3/s \qquad (14)$$

Equation 14 has a coefficient of regression of 77% and performed best between (1-1.1) m depths. The variation between the simulated and measured discharge varies from (1-7) %. The graphical method of fixing constant "a" produced equation 15 with a coefficient of regression of 97%

$$Q = 0.1828(G - 0.14)^{0.78}\ m^3/s \qquad (15)$$

where:
Q = discharge ($m^3\ s^{-1}$),
G = stage (m)

It is easier to measure the stage (or water height) of a stream than its discharge. Discharge can be measured by determining velocity profiles across the width and depth of the stream and adding the discharge from each segment. The rating curve is useful to estimate the discharge from the stage and to forecast higher discharges. The curve may not apply when extrapolated beyond the range of observations.

From Figure 1, the rating equation performed better at gauging height between (0.7 - 1.2) m with ± 0.1 m^3/s differences between simulated and measured discharge. For gauge depth (x) between ($0.21 \geq x \leq 1.4$) m, the difference between simulated and measured discharge is between (0.02-0.03) m^3/s. At a gauging depth ($x > 1.4$ m), the difference between simulated and measured discharge is between (0.03 - 0.05) m^3/s. The rating equation performed better with less than 7% difference between the simulated and measured discharge. It should be noted that below gauging depth of 0.21 m, the rating equation cannot be used.

5. Conclusion

Based on the Obtained result from this study, the following conclusions were made:

(i) The zero discharge in the stream "a" is a hypothetical value that cannot be measure in the field.
(ii) The stage for zero discharge that was deduced graphically gave a better result compared to running method with coefficient of regression of 97% as against 77%.
(iii) The rating equation developed on River Omi was $Q = 0.1828(G - 0.14)^{0.78}\ m^3/s$.

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