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Generalized non-dimensional depth-discharge rating curves tested on Florida streamflow

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Generalized Non-Dimensional Depth-Discharge Rating Curves

Tested on Florida Streamflow

by

Auristela Mueses-Pérez

A dissertation submitted in partial fulfillment
of the requirements for the degree of
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DEDICATION

Mary Kay Ash used to say “If you think you can, you can. If you think you can’t, you’re right”. Today I know “I can” and I owe this fruit of my labor: To God for his strength and support, to Eduardo and my babies, Adriana and Alfonso, for their unconditional love and to my wonderful advisor, Dr. Mark Ross, for his help and encouragement.

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GENERALIZED NON-DIMENSIONAL DEPTH-DISCHARGE RATING CURVES TESTED ON FLORIDA STREAMFLOW

Auristela Mueses-Pérez

ABSTRACT

A generalized non-dimensional mathematical expression has been developed to describe the rating relation of depth and discharge for intermediate and high streamflow of natural and controlled streams. The expressions have been tested against observations from forty-three stations in West-Central Florida. The intermediate-flow region model has also been validated using data from thirty additional stations in the study area. The proposed model for the intermediate flow is a log-linear equation with zero intercept and the proposed model for the high-flow region is a log-linear equation with a variable intercept. The models are normalized by the depth and discharge values at 10 percent exceedance using data published by the U.S. Geological Survey. For un-gauged applications, Q_{10} and d_{10} were derived from a relationship shown to be reasonably well correlated to the watershed drainage area with a correlation coefficient of 0.94 for Q_{10} and 0.86 for d_{10} . The average relative error for this parameter set shows that, for the intermediate-flow range, better than 50% agreement with the USGS rating data can be expected for about 86% of the stations and for the high-flow range, better than 50% for 44% of the stations. Testing the model outside West Central Florida, in some stations at North Florida, and South Alabama and Georgia, show some reasonable relative errors but not as good as the results obtained for West Central Florida. Using a model with a different slope, developed specific for those particular stations improved the results significantly.

1. INTRODUCTION

A discharge rating is a relationship between stage and discharge at a specific point in a river stream or lake outlet structure. The rating relations for a site are created from periodic field measurements of discharge and stage and are the industry standard for continuous flow measurement of streamflow via stream stage. These measurements are used to produce a unique mathematical relation which allows, for a particular location and usually for a period of time, continuous stage measurements to be converted into discharge. The resulting rating curves are useful for interpolating or extrapolating flow measurements and for modeling.

1.1 Description of Simple Rating Curves

The simplest form of a rating curve is a two-parameter stage-discharge relation. Discharge is calculated from field measurements of velocity and channel cross section. To properly develop rating curves, discharges must be measured at all representative stages, using at least 10 to 12 points covering the range of low to high flows (Gupta, 2001). If there is a direct relation between discharge and gage height, the discharge rating is called simple. A simple rating may be only one curve but is more often a compound curve consisting of three segments, one each for the low, medium and high water ranges (Kennedy, 1984).

A simple stage-discharge relation has a power form given by the following equation:

$$Q = A(h \pm a)^n \quad (1)$$

where,

Q = discharge

h = gage height

a = gage height at zero flow

A, n = constants

When plotting this equation in log-log paper, the rating is transformed to a straight line. A straight line is preferred because (1) it can be extended or extrapolated, and (2) it can be described by a simple mathematical equation (Gupta, 2001).

The resulting stage-discharge curve represents Q as a function of stage, datum correction, channel slope and Manning's Coefficient (n). The procedure is costly and time consuming, and dangerous or impractical during high floods. Thus typically, streamflow rating only exists for limited station locations and with limited data at high flow conditions.

1.2 Scope of Research

As it will make clear from the literature review, most of the conventional methods to determine stage-discharge ratings are based on open channel flow, uniform flow and Manning's equation and channel properties. These methods require a roughness coefficient, estimation for the channel cross sectional area and slope, field survey measurements, or some other data specific to the channel. The difficulty in estimating an

adequate Manning's roughness coefficient or discharge coefficient incorporates some uncertainty to these empirical models. Also, channel cross sectional flow data is expensive to acquire and often is not available, particularly for un-gauged streams, limiting the widespread use of these methods.

Although the existing methodologies cited in the references explain general concepts and traditional approaches to determine rating curves such as the variables involved in the ratings, scaling factors and non-dimensional parameters, and discharge as a function of area, none of the mentioned studies investigated non-dimensional discharge rating curves related to watershed characteristics.

This study proposes a generalized mathematical expression to describe non-dimensional depth-discharge relations from the perspective of the watershed characteristics, particular flow indices and the general behavior of stage-discharge curves. Forty-three stations in West-Central Florida have been analyzed. Locations of USGS stations in West Central Florida are shown in Figure 1. Data used in this study were obtained from USGS known rating data reported between 1987 and 1998 and correspond to the best fit rating curves used by USGS to translate stage to discharge. The accuracy of the prediction capability of the proposed model is evaluated using statistical errors of the estimated values compared to USGS rating data.

Figure 1. Location of USGS Stations in the West Central Florida

2. LITERATURE REVIEW

Several methods have been studied to explain the empirical relation among the variables involved in the rating relations. Most of these methods have been developed by the U.S. Geological Survey and are summarized in the work by Kennedy (1984) and Rantz et al. (1982), among others.

Many of the current empirical methodologies that explain the relationship between the variables involved in the rating curves define the relation between the stage and discharge by assuming the discharge as uniform open channel flow with constant slope, and incorporating the Manning's equation and roughness coefficient (Kennedy, 1984; Rantz et al., 1982; Atabay and Knight, 1999; Dawdy et al., 2000). Others have treated the discharge as flow in a constricted weir section (Kennedy (1984), Rantz et al (1982)).

Although the rating curves are commonly used to convert stage into discharge, the literature recognized that there are errors associated with the development of ratings curves. Dymon and Christian (1982) identified three types of errors influencing the random error of a single discharge measurement. These were rating curve error, water level measurement errors and an error caused by ignoring the physical parameters that affect discharge. They reviewed the methods for evaluating the three types of errors. Similarly, Tillery et al. (2001) derived potential errors for individual measurements and rating relations for 17 stations in Arizona. In the study, they explored the errors

associated with developing rating curves based on direct measurements of discharge and stage, indirect measurements of discharge and theoretical weir and culvert computations. They concluded that errors are greater when based on indirect measurements.

In more recent attempts at defining a theoretical relation based on the channel properties Dingman et al. (1997) proposed a multiple-regression equation that is independent of the roughness coefficient. The discharge is described in terms of the cross sectional area, hydraulic radius and water surface slope. Dingman (1999) extended his work to incorporate acquisition of remotely sensed channel data. The method can be applied to un-gauged streams in the New Hampshire area, with values of width and slope similar to the ones considered in developing the model.

The idea of non-dimensional stage-discharge rating curves has not been widely studied. Some investigations involving scaling factors for discharge were made by Ervine et al. (1993), Savage et al. (2001), and Sivapalan et al. (2001). Ervine et al. (1993) used a non-dimensional discharge coefficient to quantify the effect of the main parameters affecting conveyance in meandering compound river channels. Bruce et al. (2001) used non-dimensional discharge curves to compare results from their study on flow parameters calculation over a standard ogee-crested spillway using a physical model, a numerical model and existing literature. Sivapalan et al. (2002) used a scaling relationship based on area to explain the non-linear response of the watershed due to the dependence of a catchment hydrological property on area. A recent investigation by Shesha et al. (2003) developed a generalized linear head-discharge relationship for flow over sharp-crested inclined inverted V-notch weirs. In those studies, the scaling factor was introduced to present and compare their results and not as part of the methodology.

Another investigation describing a theoretical expression for non-dimensional rating relations was made by Kamula (2000). He established a new procedure for fish ways design and suggested a different equation for each of the main existing fish way types. In his procedure, he created a general scaling equation for dimensionless discharges, based on the depth of flow over the weir and the effect of pool length (Kamula, 2000).

The determination of discharge from theoretical ratings considering the effect of unsteady, non-uniform flow in the stage-discharge relation was examined by Schmidt (2002). In his work, Schmidt addressed the rating hysteresis problem and the effects of different downstream backwater conditions. The rating relations are calculated from Hydraulic Performance Graphs (HPG) curves and require the channel cross section and the stage data points at each end of a stream reach. Westphal et al. (1999) also explored the hysteresis effect by recognizing that stage-discharge relations for the rating curve are not single-valued, in measurements in the Middle Mississippi River. He also attributed to replication errors as the possible cause for the stage-discharge pattern.

Some investigations present methodologies to determine discharge and stage in ungauged stations. Moramarco and Singh (2001) proposed a simple method for relating local stage and remote discharge. The method reconstructs the discharge hydrograph at a river section, based on water level recorded at the cross section and a discharge value recorded at another upstream cross section. Results show the method as reliable when the hydraulic conditions at the site are unknown. Similarly, Franchini et al. (1999) proposed a methodology for synthesizing the rating curve provided with stage data, when a reliable rating curve and stage data is available in an upstream cross section. The proposed

methodology uses the Muskingum-Cunge model for routing the flood wave to the site of interest. Szilagyi et al. (2003) proposed a similar approach but using a reservoir-cascade-type formulation. The method allows for stage predictions using physically based flow routing of known discharges from an upstream station, in river sections where no values of discharge are available.

Some studies explored the adequacy of the rating curves in converting water levels to flow rates for high flows. Fenton and Keller (2001) found that rating curves errors impose severe limitations in developing methods to estimate floods due to the bias introduced at site and regional flood frequency estimates. They proposed some improvements in the existing practices to be able to obtain a more reliable estimate of high flows. On the same topic, Lewis (1998) proposed some enhancements of river flood forecasts by using a dynamic hydraulic flow routing technique to properly extend the rating curve to account for hydraulic conditions that may cause overbank flow.

Jothityangkoon and Sivapalan (2003) investigated changes in the rating curve due to the effects of overbank flows during the transition from normal to high flows. The authors attributed the changes in the rating to the effects in the interactions between the main channel and floodplain sections and proposed a distributed flood routing model based on non-linear storage-discharge relationship to account for the effects.

Discharge has also been calculated based on channel characteristics of streams. This is particularly useful for ungauged streams where a bankfull channel can be identified by use of field indicators and related to discharge. Cinotto (2003) used channel dimensions to develop regional curves from the regression analyses of the relations between drainage area and the cross-sectional area, mean depth, width, and streamflow of

the bankfull channel (Cinotto, 2003) at 14 stations in Pennsylvania and Maryland. The analysis showed bankfull cross sectional area and bankfull discharge with the strongest correlation to drainage area. Bankfull width and depth showed a moderate linear correlation to area.

Leopold and Maddock back in 1953 already recognized the physiographic implications of the hydraulic geometry of stream channels. In their study, they related discharge and some hydraulic characteristics of a given cross section – depth, width, velocity and suspended load – with a power function. They found that in a hydrologically homogeneous region there is a pattern when plotting these hydraulic characteristics against discharge. Interestingly, they also found that among the stations, the respective lines are generally parallel. The station curves differed much in ordinate but were similar in slopes. The rest of the study focused on exploring the relations of depth, with and velocity as a function of the load transported in the channel.

Some studies involving basin characteristics were developed using the U.S. Geological Survey (USGS) flood-regionalization procedures (in Florida, Hammet and DelCharco, 2005) that relate flood characteristics to watershed and climatic characteristics through the use of regression analysis. These equations use hydrologic characteristics like drainage area, channel slope, percent wetlands and rainfall, to estimate the magnitude of flows for specific recurrence interval, such as the 2-, 10-, 25-, 50-, 100-, and 500-year. These procedures are particularly useful for predicting or estimating flood flows at stream sites where little or no streamflow information is available. These equations do not represent a stage-discharge rating relation and are limited to specified recurrence intervals.

Mazvimavi et al. (2006) also explored the influence of basin characteristics on the spatial variation of river flows. The study investigated the correlation of three basin characteristics and river flows. The study identified mean annual precipitation, mean annual potential evaporation and median slope as the most important basin characteristics affecting the variation of river flows.

More complex analyses have been done using artificial neural network (ANN) and fuzzy neural network (FNN). ANN has been widely used in water-related research with reasonable good results. Bhattacharya and Solomatine (2000) applied ANN to develop a stage-discharge relationship for river Bhagirathi in India. The model provided a solution to the random fluctuations often exhibited by the ratings by using more data generated from the ANN model. Deka and Chandramouli (2003) presented a FNN model to derive a stage-discharge relationship. The study shows the advantage of using a FNN approach by simplifying the amount of information required in terms of the number of inputs. The study also shows that the FNN model has a better prediction ability than the single ANN and conventional methods. However, despite the high efficiency of ANN's and FNN's in modeling non-linear relationships, creating and training the network is still complex and difficult to interpret.

3. DATA

Forty-three stations located in West-Central Florida were used to develop the model as the calibration-data set. The verification data-set consisted of thirty additional stations, also within the West Central Florida study area. Following standard practice, the stations in the verification data set were not used to develop the model. Stations in the calibration and verification data set were selected randomly, based on the stations where rating and basin characteristics data were available.

Table 1 gives the range of values for hydraulic parameters for the calibration data set. Locations of all USGS stations in the study area are shown in Figure 1. The rating data for the calibration set corresponds to USGS known data reported between 1987 and 1998. Data for the verification set corresponds to the rating data actually in use by the USGS for 2005-2006.

Table 1. Ranges of Values for Hydraulic Parameters for Calibration Data

Parameter		Units	Mean	Std Dev	Minimum	Maximum
Discharge	Q	CMS	31	64	0	790
Depth	d	m	1.99	1.44	0.03	6.65
Drainage Area	A	Sq. mi	138.32	214.31	4.3	1373
Channel Slope	ChS	%	3.41	1.62	1.23	7.01
Watershed Slope	S	m/m	0.00743	0.00426	0.001	0.025
% Wetland	W	%	18.58	8.22	5.1	36.82
DTWT	WT	m	1.19	0.24	0.92	2.07

4. METHODOLOGY

4.1 Identification of Most Significant Variables

To identify all variables that could be considered as most significant predictors for the model, a statistical analysis was performed using the SAS statistical software package. The six watershed characteristics considered as potential predictors of discharge were: water depth, drainage area, percent wetlands, depth to water table, watershed slope and channel slope. A correlation matrix was constructed using values of Q_{10} for discharge and d_{10} for depth, because these were measured values at each station. The average 10% exceedence discharge values, Q_{10} , and corresponding depths, d_{10} , are readily available (i.e. normally reported) for measured flow stations from annual data summaries and published rating tables, respectively. The Q_{10} value was taken from the station record, from the Water Resources Data of Florida, USGS (2003). The average depth corresponding to that discharge was calculated from the published USGS rating for that station. Table 2 summarizes the correlations among the variables in the calibration data; results showed water depth and drainage area with the highest correlation to discharge. However, the correlation was very low to other expected parameters including basin slope and percent wetlands.

A least square regression analysis was used to develop the discharge model. The stepwise procedure “maximum R^2 improvement” in SAS was used to identify which of the potential predictor variables besides water depth, would be included in the regression

model. The stepwise procedure combines the variables to develop the best two-variable model, three-variable model and so forth, that produces the highest correlation coefficient R^2 . Other statistical measurements as Cp and F-value were also used to define the best model. The stepwise procedure was performed using the rating data from the 43 stations in the study area. Results from this analysis (Table 3) showed that, again, the most significant variables are water depth and drainage area; any additional variable included did not improve the R^2 significantly. Thus, the model development focused on a two-variable model including only water depth and drainage area.

Table 2. Matrix Correlations for Discharge for Variables in the Calibration Data

	Q	d	A	ChS	Slope	W	WT
Q	1.00	0.77	0.97	-0.42	0.07	-0.07	0.02
d	0.77	1.00	0.70	-0.26	-0.13	-0.14	0.06
A	0.97	0.70	1.00	-0.45	0.21	-0.05	0.08
ChS	-0.42	-0.26	-0.45	1.00	-0.06	-0.45	0.09
S	0.07	-0.13	0.21	-0.06	1.00	-0.20	0.57
W	-0.07	-0.14	-0.05	-0.45	-0.20	1.00	-0.07
WT	0.02	0.06	0.08	0.09	0.57	-0.07	1.00

Table 3. Results from the Stepwise Procedure “Maximum R^2 Improvement”

	Variables	R^2	Cp	F value
Q	d	0.46	203.2	802.4
	d, A	0.55	12.3	576.5
	d, A, S	0.55	8.7	388.0
	d, A, S, ChS	0.55	7.8	292.4
	d, A, S, ChS, W	0.55	5.3	235.6
	d, A, S, ChS, W, WT	0.55	7.0	196.3

4.2 Approaches for the Determination of the Non-Dimensional Ratings

Three different approaches were examined for the determination of a non-dimensional relationship between discharge and depth. The approaches are explained below.

4.2.1 Approach 1: Normalization by Drainage Area

It was first hypothesized that discharge and depth could be normalized as a function of basin drainage area and total annual rainfall. The logic for this was that discharge would increase by increasing drainage area and/or increased long term annual rainfall if all other factors were equal. Hence, the stream cross section characteristics and resulting rating would be function of these variables. The general non-dimensional equations for discharge and depth for this hypothesis are given by:

$$Q' = \frac{Q}{RA} \quad (2)$$

$$d' = \frac{d}{A^{0.5}} \quad (3)$$

where Q' is dimensionless (relative) discharge, Q is measured discharge (L^3T^{-1}), R is annualized rainfall intensity (LT^{-1}), A is watershed area (L^2), d' is dimensionless (relative) water depth and d is stream water depth (L). For the analysis, annualized rainfall intensity was assumed constant, considering that the long-term annual rainfall intensity in West-Central Florida was fixed and readily determined from gage record.

A fundamental departure from USGS rating curves was that the proposed relation in Equation (2) uses depth of water instead of stage elevation. This is desirable because:

- The stream stage is measured from an arbitrary datum that is not always defined to a standard datum, e.g., National Geodetic Vertical Datum of 1929 (NGVD-29).

This makes it difficult to correlate to a reference when using a generalized relation in an un-gauged stream (i.e., the streambed elevation are not known).

- Equations that define the hydraulic behavior of streams are based on depth, thus this would be more realistic in terms of the physical representation of the system.
- Live bed environments typical of natural streams are always changing, greatly affecting low flows. However, it was hypothesized that the streambed inverts change while, on a long-term basis in natural channels, similar slope and friction conditions prevail. Thus, absolute depths should be similar in long-term record to maintain a fixed $Q(d)$ relationship.

The use of water depth instead of stage is inconvenient since a change in depth (as hydraulic depth) does not necessarily produce the corresponding change in discharge, as opposed to measured stage. For example, the average hydraulic depth may decrease as the flow transitions out-of-banks in increasing flood flow conditions. This will result in a misrepresentation of the rating relation. To overcome this inconvenience, an effective depth (d) related to stage was defined using the following equation:

$$d = d_0 + (h - h_0) \quad (4)$$

where,

d = effective depth (L)

d_0 = minimum hydraulic depth (L)

h = stage (L)

h_0 = stage at zero flow (L)

The minimum hydraulic depth was estimated from USGS field data, where depths are the average values calculated from cross sectional area and channel width. The stage is the data point from the USGS rating curves and the relative stage at zero flow was determined from the USGS rating data.

The relative discharge and depth were used to derive a log-linear relation of the form:

$$\log Q' = m \log d' + b \quad (5)$$

In this general relationship, the values of the parameters m and b must accurately represent the overall behavior of the stage-discharge ratings for a great number of stations. Figure 2 shows the relative discharge versus relative depth for all stations used in this study, using the USGS rating data. Noteworthy is that most of the stations have similar slopes. This gives credibility to the idea that a unique relation can be determined to represent the depth-discharge characteristics of many stations. An average value of the slopes and intercepts was used as the m and b parameters for the generalized non-dimensional relation. The final equation is defined as:

$$\log Q' = 1.72 \log d' + 6.79 \quad (6)$$

Results from this model were compared to the USGS rating data. Some stations provided a “good fit” for only a portion of the data, other stations differed completely. Discharge values estimated with the model were subtracted from the USGS known rating data and divided by the USGS data to obtain the relative error. The average relative error

compared to the USGS data varied from 18% to 50% for 46% of the stations, 51% to 100% in 30% of the stations and more than 100% in the remaining 24%.

Figure 2. Relative Discharge Versus Relative Depth for Stations in West-Central Florida for Approach 1

4.2.2 Approach 2: Normalization by Discharge and Depth at Full Channel

Discharge and depth were normalized as a function of discharge and depth at full channel flow within banks. These two parameters were approximated from the rating data, as the point where a change in the rating slope occurs (rating break point). The general non-dimensional equations for discharge and depth are given by:

$$Q' = \frac{Q}{Q_{full}} \quad (7)$$

$$d' = \frac{d}{d_{full}} \quad (8)$$

where Q' is dimensionless (relative) discharge, Q is measured discharge (L^3T^{-1}), Q_{full} is discharge at full channel bank flow (L^3T^{-1}), d' is dimensionless (relative) water depth, d is stream water depth (L) and d_{full} is water depth at full channel bank flow (L). As in the first approach, equation (7) is described in terms of depth of water instead of stage.

The generalized relation based on relative discharge and depth was defined with a log-linear equation as in Approach 1. For this model, the non-dimensional discharge-depth relation was defined with zero intercept. Figure 3 shows the relative discharge versus relative depth for all stations under study, using the USGS rating data. A general value for slope was defined and the final equation for this approach is:

$$\log Q' = 1.9 \log d' \quad (9)$$

Figure 3. Relative Discharge Versus Relative Depth for Stations in West-Central Florida for Approach 2

A value of discharge and depth at full channel banks is required to generate the rating in un-gauged stations. Known values of discharge at full channel banks were related to drainage area and known values of depth were related to the square root of the drainage area. The resulting trend line showed a small correlation of the two parameters, 0.45 for discharge and 0.20 for depth.

Results from this model were compared to the USGS rating data. As in the first approach, some stations matched a portion of the data, while other stations completely differed. The average relative error compared to the USGS data varied from 8 to 50% for 33% of the stations, 51 to 100% in 26% of the stations and more than 100% in the remaining 41% (poorer performance than Approach 1).

4.2.3 Approach 3: Normalization of Discharge and Depth at Ten Percent

Exceedence Flow

Discharge and depth were normalized as a function of the value of the discharge reported to be exceeded ten percent of the time and the corresponding depth. The rationale for selecting the ten percent exceedance value as the scaling factor, is that most rivers in the West Central Florida area have well defined incised channels and most discharges at or below the 90th percentile (10% exceedance) are contained within banks (Lewelling, 2004). Because bankfull discharge typically increases with drainage area, high flow values as Q_{10} in this case, were considered to represent a better relation to drainage area. For streams with relatively high friction of groundwater flow, Q_{10} is also indicative of a runoff dominated flow period.

The general non-dimensional equations for discharge and depth are given by:

$$Q' = \frac{Q}{Q_{10}} \quad (10)$$

$$d' = \frac{d}{d_{10}} \quad (11)$$

where Q' is dimensionless (relative) discharge, Q is measured discharge (L^3T^{-1}), Q_{10} is discharge exceeded ten percent of time (L^3T^{-1}), d' is dimensionless (relative) water depth (L), d is stream water depth and d_{10} is water depth corresponding to the 10% discharge exceedance (L). As in the previous approaches, the relative depth is described in terms of depth of water instead of stage.

The generalized relation based on relative discharge and depth was also defined with a log-linear equation with zero intercept. Table 4 shows data of discharge and depth for the 10% discharge exceedance and the slope of the corresponding relative discharge versus relative depth rating, for the thirty-five stations where data were available. A very high correlation coefficient of 0.996 was obtained from the fitted USGS data for this approach using specific slopes ($Slope_{10}$ in Table 4). Thus, these slopes represent the rating of each particular station quite well. Plots of these ratings are shown in Figure 4. The slope was defined and the final equation for this approach is:

$$\log Q' = 1.77 \log d' \quad (12)$$

A value of discharge and depth exceeded 10% of the time was required to generate the rating in un-gauged stations. Known values of discharge as Q_{10} were related to drainage area and values of depth as d_{10} were related to the square root of the drainage

area. The resulting trend line showed a better correlation of the two parameters, 0.94 for discharge and 0.62 for depth. Figures 5 and 6 show data and trend line for discharge and depth, respectively.

Table 4. Discharge and Depth for the 10% Discharge Exceedance and the Slope of the Corresponding Rating for Calibration Data Set

ID	USGS Station Name	USGS Gage #	Slope ₁₀	Q ₁₀ (CMS)	d ₁₀ (m)
5	Payne Creek Nr Bowling Green, Fl	2295420	1.34	7.5	1.3
6	Peace River At Fort Meade, Fl	2294898	1.73	15.5	1.8
7	Peace River At Arcadia Fl	2296750	1.74	76.5	2.8
8	Little Manatee River Nr Wimauma, Fl	2300500	1.72	11.0	1.9
9	Little Manatee River Nr Ft. Lonesome Fl	2300100	1.72	2.2	1.3
10	North Prong Alafia River At Keyville Fl	2301000	2.1	8.5	1.8
11	Alafia River At Lithia Fl	2301500	1.67	20.5	1.9
12	Peace River At Bartow Fl	2294650	2.57	17.1	1.6
13	Horse Creek Nr Myakka Head Fl	2297155	1.6	2.1	0.8
15	Charlie Creek Nr Gardener, Fl	2296500	1.98	21.2	2.4
16	South Prong Alafia River Nr Lithia , Fl	2301300	1.9	6.3	1.5
17	Horse Creek Nr Arcadia, Fl	2297310	1.9	15.0	2.4
18	Peace River At Zolfo Spring, FL	2295637	1.61	41.1	2.6
19	Trout Creek Near Sulphur Springs Fl	2303350	2.34	1.6	0.7
20	Cypress Creek At Worthington Gardens FL	2303420	2.37	3.6	1.3
21	Peace Canal Nr. Wahneta	2293987	2.48	9.0	1.3
22	Bowlegs Creek Nr. Ft. Meade	2295013	2.27	2.2	0.9
24	Joshua Creek @ Nocatee	2297100	2.19	7.8	1.7
28	Myakka River Nr Sarasota	2298830	2.71	19.4	2.0
29	Deer Prairie @Power Line	2299120	2.6	3.8	1.3
30	Big Slough Canal Nr Myakka	2299410	2.29	2.7	1.0
31	Walker Creek Nr Sarasota	2299861	1.92	0.4	0.4
35	Braden River Nr Lorrane	2300032	1.91	2.4	1.2
38	Bullfrog Creek Near Wimauga	2300700	1.95	2.3	1.0
41	Blackwater Ck Nr Knights	2302500	1.84	5.3	0.9
42	Hills R. Nr Zephyrhills	2303000	1.96	14.9	1.6
43	Baker Creek At McIntosh Ro	2303205	2.22	1.2	0.5
48	Delaney Creek Nr Tampa	2301750	2.74	0.7	0.4
50	Tiger Creek Nr Babson Park	2268390	2.53	1.9	0.9
51	Livingston Ck Nr Frostproof	2269520	1.91	3.7	1.1
52	Carter Creek Nr Sebring	2270000	2.64	1.5	1.0
53	Josephine Ck Nr Desoto	2271500	2.3	4.8	1.1
57	Brooke Creek @ Van Dyke	2307200	2.85	0.3	0.4
62	Anclote River Near Elfers	2310000	2.1	4.9	1.7
63	Pitha R. Nr Fivay Junction	2310280	2.7	0.5	0.4

Figure 4. Relative Discharge Versus Relative Depth for Stations in West-Central Florida for Approach 3

Results from this model were compared to the USGS rating data. As in the previous approaches, some stations provided a good fit while others completely differed. However, in this approach, the general model matched a larger portion of the data compared to the other approaches. This supports the idea that this model could better represent a larger range of the stream depth-discharge behavior. The average relative error compared to the USGS data varied from 20 to 50% for 42% of the stations, 51 to 100% in 48% of the stations and more than 100% in the remaining 10%.

Figure 5. Correlation Between Discharge as Q_{10} and Drainage Area for Approach 3

Figure 6. Correlation Between Depth as d_{10} and Square Root of the Drainage Area for Approach 3

5. MODEL DEVELOPMENT

From the analysis of the three different approaches, it is recognized that even though the slopes in the intermediate-flow region have a similar behavior, they vary within a specific range (Figure 7). Also, the high-flow regions exhibited log-linear behavior with considerably different slopes than the intermediate-flow regions (Figure 8). Based on this, two different mathematical relationships are proposed for each of the flows regions.

5.1 Theoretical Background for Model Development

Certain physical characteristics at the gauging section or in the channel bed, known as station controls, stabilize the stage and discharge relation (Gupta, 2004). It is common practice to locate the streamflow gauging station in a section control with the purpose of making the rating more stable. A section control can be a natural or man-made obstruction, such as a riffle, rock, weir or spillway. For engineered structures as in the case of weirs and spillways, by creating an obstruction, critical depth is forced to occur and a unique relationship between stage and discharge results. This simple relation between stage and discharge also exists for natural obstructions. The control characteristics of the station will determine the particular features of the gauging site rating curve, including the rating slope.

Figure 7. Relative Discharge ($\text{Log } Q'$) Versus Relative Depth ($\text{Log } d'$) for the Intermediate-Flow Region

Figure 8. Relative Discharge ($\text{Log } Q'$) Versus Relative Depth ($\text{Log } d'$) for the High-Flow Region

Hence, the difference in streamflow behavior (ie. rating slope) between the two regions and within the same flow region can be examined by presuming simple control at stream sections.

5.1.1 Analysis for Simple Control Sections

Consider that streamflow is downstream controlled at a section by one of the following cases: sharp crested uncontracted; sharp crested contracted; V-notch; Broad crested weir.

All weir relations are represented by $Q = f(K, H^n)$, with K being all the constant parameters (discharge coefficient, weir length, contraction) and $n=3/2$ for uncontracted, moderately contracted rectangular and trapezoidal weirs and $5/2$ for V- notches. Using some hypothetical data for stage and discharge and normalization parameters, non-dimensional rating curves (Q' vs. H') were developed for the assumed control sections. The dimensional form of C was used for the weir equations.

Assuming a horizontal_uncontracted section, the weir equation is:

$$Q = CLH^{\frac{3}{2}} \quad (13)$$

with C values between 3.2 and 4.4 and a typical value of 3.3. Figure 9 shows the non-dimensional discharge and depth, plotted on log-log scale for this case. Data used in this figure is shown in Appendix A.

Figure 9. Q' vs. H' for Horizontal_Uncontracted Section for Varying Coefficients C

For a horizontal_contracted section, the weir equation is:

$$Q = C(L - 0.2H)H^{\frac{3}{2}} \quad (14)$$

with C values between 3.2 and 4.4 and a typical value of 3.3. Figure 10 shows the non-dimensional discharge and depth, plotted on log-log scale for this case. Data used in this figure is shown in Appendix B.

For a V-Notch Section section, the weir equation is:

$$Q = CH^{\frac{3}{2}} \quad (15)$$

with C values between 2 and 4.3 with a typical value of 2.5 for 90° V-Notch. Figure 11 shows the non-dimensional discharge and depth, plotted on log-log scale for this case. Data used in this figure is shown in Appendix C.

Figure 10. Q' vs. H' for Horizontal_Contracted Section for Varying Coefficients C

Figure 11. Q' vs. H' for V-Notch Section for Varying Coefficients C

For a Broad Crested Weir section, the weir equation is:

$$Q = CLH^{\frac{3}{2}} \quad (16)$$

with C values between 2.34 and 3.3 and a typical value of 2.63. Figure 12 shows the non-dimensional discharge and depth, plotted on log-log scale for this case. Data used in this figure is shown in Appendix D.

Results for the typical C value for each of the evaluated control sections are shown in Figure 13.

Figure 12. Q' vs. H' for Broad Crested Weir Section for Varying Coefficients C

From Figures 9 to 12, the effect of varying the discharge coefficients for each control section shape is basically a shift in the resulting rating. The discharge coefficient lumps together the effects of the approach velocity head with the contraction and head losses. Even though the analysis did not consider the variation of C with head, both the velocity head and discharge coefficient increase with stage. Thus, for the same head and crest length, a larger discharge coefficient will result in a larger discharge.

Figure 13. Q' vs. H' for All Control Sections for Typical Values for C

Figure 13 presents the results for all control section shapes. Similarly to the effect of varying C , the effect of varying the section shape is a shift in the resulting rating except for the V notch. The discharge capacity of a rectangular versus a broad crested weir is different, therefore the shift in the ratings, however the three equations use the same exponent. The exponent in the V-Notch section is different/larger than the rectangular and broad crested sections which is reflected in the different and in this case steeper slope.

It is worth to notice that the slope of the non-dimensional relations does not change with the varying C for the same control section shape. This is a clear indicative that the relation slope is a direct function of the exponent and is not affected by all the constant parameters included in K .

By observing the slopes in the non-dimensional rating curves for each of the stations being studied, most of the values fall between 1.5 and 2.5. Therefore, the degree of contraction could easily explain the variation in slope within the intermediate-flow region.

Thus, from the weir equation for the control section:

$$\log Q = \log K + \log H^n \quad \text{or} \quad \log Q = \log K + n \log H \quad (17)$$

Where $n=3/2$ or $5/2$ is the slope of the non-dimensional relations.

It can also be shown that uncontracted (e.g., uniform) wide flows approach n values of $5/3$ as an upper limit for turbulent flows. To explore this, a plot with the uncontracted and V-notch sections and non-dimensional curves using Manning's equation was created (Figure 14) for a rectangular and trapezoidal section. The behavior of the Manning's relation is similar to the weirs' behavior but with a different slope.

5.1.2 Analysis for Compound Control Sections

In compound control sections, the low/normal flows are managed by, for example, a V-notch, and larger flows would require, for example, a trapezoidal weir. For these cases, the two profiles would form a compound weir. The simplest way to calculate the discharge over a compound weir is applying the discharge equation corresponding to each segment of the weir and up to the head of that segment.

Assuming a compound weir consisting of a V-Notch or Horizontal and a Trapezoidal (Cipottelli) Weir (standard equations follow), the non-dimensional relation was created. Figure 15 show results, using typical values for C . Data used in this figure is shown in Appendix E.

Figure 14. Q' vs. H' for Uncontracted and V-Notch Weirs and Manning's Equation

The equation for a trapezoidal section is:

$$Q = CLH^{\frac{3}{2}} \quad (18)$$

Figure 15 could explain the different/steeper slopes observed in the high-flow regions. In compound high-flow control sections (channel and out-of banks flood plain sections) there is a different degree of contraction. The low/normal flows are managed by cross sections with a relative degree of contraction (similar to a V-notch or uncontracted weir), and larger flows would be managed by cross sections with a higher degree of

contraction (similar to a trapezoidal weir). For these cases, when plotting Q vs. H , the two profiles would form a compound weir as shown in Figure 15. This will result in a break in the resulting rating at the point where the flow changes from channel flow (low and intermediate) to floodplain flow (high); there is a break in the rating curve, with the high-flow range having a steeper slope.

Figure 15. Q' vs. H' for Compound Weir Consisting of a V-Notch and a Trapezoidal

Rating data also show a third flow region corresponding to extreme low flows. Low flows are dominated by contribution of groundwater baseflow. Hydraulically they may not be fully turbulent, exhibiting parabolic (non log-linear) relationship for discharge-depth rating. Most ratings are also very unstable for low flows as channel debris and shifting live bed conditions highly influence the rating behavior. For example,

most low-water discharge measurements have different gage stage at zero flow (GZF) and consequently, do not define the same rating or adapt to logarithmic plotting (Kennedy, 1984). This condition renders it harder to represent in a general model, thus this study did not consider the mathematical representation of low flows. At present, the author believes that it is doubtful if any generalized mathematical model can be developed for the very lowest flow conditions.

5.2 Model for the Intermediate-Flow Region

The model for the intermediate-flow region was developed using a least square regression analysis. Only discharge and water depth values corresponding to the intermediate-flow region were included in the analysis. The upper limit of the intermediate-flow region was approximated from the rating data, as the point where a change in the rating slope occurs (i.e., rating break point) (See Figure 16).

Figure 16. Generalized Log-Linear Rating Behavior

The generalized relation based on relative discharge and depth was defined with a log-linear equation with zero intercept. For the forty-three stations in the study, the best fit slope was found to be 2.0 for the West-Central Florida study area. The mathematical model was described as:

$$\log Q' = 2 \log d' \quad (19)$$

Table 5 shows the statistics of the model.

Table 5. Statistics of the Regression Model for the Intermediate Flows Region

R^2	Adj R^2	RMSE	Coeff Var	F Value	Pr > F
0.95	0.95	0.1862	291.3	21319.3	<.0001
Variable	Coefficient	SE	t Value	Pr > t	VIF
d	2.0	0.01445	146.01	<.0001	1

Results from this model were compared to the USGS rating data. The accuracy of the prediction was measured in terms of the relative error. Predicted values were first calculated using values of Q_{10} and d_{10} specific for each station. The average relative error was less than 20% for 58% of the stations; 21% to 30% for 16% of the stations; 31% to 50% for 12% of the stations; and larger than 51% for 14% of the stations. Basin characteristics data and relative error for the specific model is shown in Appendix F.

A value of discharge and depth exceeded 10% of the time is required to generate the ratings in un-gauged stations. As in the Approach 3, known values of discharge as Q_{10} were related to drainage area, but a better correlation was found by relating values of depth (d_{10}) to Q_{10} . The correlation coefficient for d_{10} was improved from 0.62 to 0.86.

The corresponding regression equations for Q_{10} and d_{10} are:

$$Q_{10} = 0.0522A \quad (20)$$

$$d_{10} = 0.6505Q_{10}^{0.4053} \quad (21)$$

Where Q_{10} is in CMS, drainage area is in square miles and d_{10} is in meters. Figures 17 and 18 show data and regression equations for discharge and depth, respectively.

Discharge was then predicted using the model with Q_{10} and d_{10} estimated from the regression equations. The average relative error compared to the USGS data was less than 20% for 23% of the stations; 21% to 30% for 27% of the stations; 31% to 50% for 24% of the stations; and larger than 51% for the remaining 26%. These results are comparable to the ones obtained with the specific known values.

Figure 17. Data and Regression Equation for Q_{10}

Figure 18. Data and Regression Equation for d_{10}

5.3 Model for the High-Flow Region

The slopes in the high-flow region, although different from the slopes in the intermediate region, exhibit similar behaviors among them but in this case, with a very different intercept.

The model for this region was developed by error minimization using the least mean square procedure. Not all stations in the study area have data in the high-flow region, thus the analysis was performed for those stations where high flows were available, for a total of twenty-seven stations. Using the specific intercept for each station, the best fit slope was found to be 5.0 for the West-Central Florida study area. The mathematical model was described as:

$$\log Q' = 5 \log d' + b_{station} \quad (22)$$

Where $b_{station}$ is the specific intercept for each station.

The model was tested using the specific intercept for each station and results were compared to the USGS rating data. The average relative error was less than 20% for 33% of the stations; 21% to 30% for 7% of the stations; 31% to 50% for 4% of the stations; and larger than 51% for 56% of the stations. Basin characteristics data and relative error for the specific model is shown in Appendix G.

A value for the intercept is required to generate the rating in un-gauged stations. The intercept is related to the discharge where the high-flow region departs from the intermediate-flow region, believed to be the out-of-bank condition above which floodplain flows become hydraulically significant (shown as break point in Figure 16). Therefore, those values of discharge of departure (transition to out-of bank flow) (Q_{dep}) were identified from the rating data and were related to drainage area. The corresponding depth of departure (d_{dep}) was related to Q_{dep} . The resulting trend line showed a correlation, R^2 of 0.90 for Q_{dep} and 0.86 for d_{dep} .

The corresponding regression equations for discharge of departure (Q_{dep}) and depth of departure (d_{dep}) are:

$$Q_{dep} = 0.16A \quad (23)$$

$$d_{dep} = 0.479Q_{dep}^{0.428} \quad (24)$$

Where Q_{dep} is in CMS and drainage area is in square miles. Figures 19 and 20 shows data and regression equation for Q_{dep} and d_{dep} , respectively.

Data from the high-flow region were tested using a linear model with a fixed slope of 5.0 and an intercept calculated from Q_{dep} and corresponding d_{dep} . The results were very poor with most of the stations exhibiting relative errors exceeding, in some cases, 100%. Therefore, it is apparent that more work needs to be done on the general departure threshold.

Figure 19. Data and Regression Equation for Discharge of Departure (Q_{dep})

Figure 20. Data and Regression Equation for Depth of Departure (d_{dep})

6. MODEL VERIFICATION

To measure the success in predicting rating discharge for the intermediate region, the model was verified using data from thirty stations that had not been previously used in development. The stations in the verification data set were randomly selected within the study area. The range of discharge and drainage areas was similar to the stations in the calibration set. Table 6 gives the ranges of values for discharge, depth and drainage area for the verification data set.

Table 6. Ranges of Values for Hydraulic Parameters for Verification Data

Parameter		Units	Mean	Std Dev	Minimum	Maximum
Discharge	Q	CMS	31.5	54.7	0.0	393.9
Depth	d	m	2.00	1.47	0.00	5.89
Drainage Area	A	Sq. mi	214.39	507.49	1.46	1825.00

The model was tested using the Q_{10} and d_{10} calculated from the regression equations. Results from the model were compared to the USGS rating data and the accuracy was measured as the relative error. The average relative error when compared to the USGS data for the intermediate flow was less than 30% for 43% of the stations, 31% to 50% for 27% of the stations and larger than 51% for the remaining 30%. Thus, the error was comparable to the results obtained with the calibration data set. Basin characteristics data and relative error for the specific model is shown in Appendix H.

Because of the lack of accurate results in the high-flow region using the intercept values from the regression equations, the high-flow model was not validated using the verification data set.

7. MODEL VALIDATION

To evaluate the applicability of the proposed model in an area outside West Central Florida, the model was tested at forty stations located in the areas of North Florida, and South Georgia and Alabama (See Table 7 and Figure 21). These stations comprise the validation data set and were selected randomly, with drainage areas varying from 17 to 13600 square miles, with an average of 1830 square miles. The drainage area and Q_{10} values were taken from the station record, from the Water Resources Data of Florida, Georgia and Alabama, USGS (2004). The rating data corresponds to data actually in use by the USGS for 2005-2006.

Following the same approach as before, this validation was performed using two separate models for data in the intermediate and high flow regions. The limit between the intermediate and high-flow region was also approximated from the rating data, as the point where a change in the rating slope occurs.

As with the stations in West Central Florida, the model was tested using both, the specific values of Q_{10} and d_{10} , and general values obtained from a regression equation. For this purpose, a new relation was developed for the non-dimensional parameters. The regression equations for Q_{10} and d_{10} including the new stations in the validation set are:

$$Q_{10} = 0.0522A \quad (25)$$

$$d_{10} = 0.6505Q_{10}^{0.4053} \quad (26)$$

Table 7. Discharge and Depth for the 10% Discharge Exceedance and the Slope of the Corresponding Rating for Validation Data Set

Gage #	USGS Station Name	Slope ₁₀	Q ₁₀ CMS	d ₁₀ m
2369800	Blackwater River Near Bradley Al	1.12	106.55	4.67
2361500	Choctawhatchee River Near Bellwood Al	1.65	89.55	2.28
2378300	Magnolia River At Us 98 Near Foley, Alabama	2.80	1.13	0.49
2376500	Perdido River At Barrineau Park, Fl	1.28	40.52	1.52
2374250	Conecuh River At State Hwy 41 Near Brewton, Al	1.80	203.75	3.65
2373000	Sepulga River Near Mckenzie Al	2.02	47.89	1.25
2361000	Choctawhatchee River Near Newton, Al	1.24	54.98	1.80
2363000	Pea River Near Ariton Al	1.12	39.11	1.28
2372422	Conecuh River Bel Pt A Dam Nr River Falls, Al	0.84	99.19	1.22
2364500	Pea River Near Samson Al	1.63	106.55	3.68
2377570	Styx River Near Elsanor, Al	1.43	22.98	1.26
2374950	Big Escambia Cr At Sardine Br Nr Stanley Crossroad	1.06	16.97	0.62
2362240	Little Double Bridges Creek Nr Enterprise, Al	2.04	1.70	0.82
2323000	Suwannee River Near Bell, Florida	1.13	427.91	4.01
2319800	Suwannee River At Dowling Park, Florida	1.21	306.06	4.13
2319000	Withlacoochee River Near Pinetta, Fla	1.24	129.51	2.36
2322500	Santa Fe River Near Fort White, Fla	1.03	72.26	0.87
2321500	Santa Fe River At Worthington Springs, Fla	1.66	31.17	2.54
2330150	Ochlockonee River Nr Smith Creek, Fla	1.1	121.86	2.65
2330100	Telogia Creek Nr Bristol, Fla	1.64	12.24	1.74
2359000	Chipola River Nr Altha, Fla	0.94	78.21	2.03
2365500	Choctawhatchee River At Caryville, Fla	1.84	320.23	4.63
2368500	Shoal River Nr Mossy Head, Fla	1.42	12.36	0.90
2370500	Big Coldwater Creek Nr Milton, Fla	1.41	25.16	1.44
2376500	Perdido River At Barrineau Park, Fl	1.23	40.52	1.53
2322700	Ichetucknee R @ Hwy27 Nr Hildreth, Fl	1.11	10.03	0.47
2226500	Satilla River Near Waycross, Ga	1.34	81.90	3.23
2228000	Satilla River At Atkinson, Ga	1.33	170.03	3.41
2314500	Suwannee River At Us 441, At Fargo, Ga	1.52	74.25	3.44
2226000	Altamaha River At Doctortown, Ga	1.2	889.83	3.59
23177483	Withlacoochee River At Mcmillan Rd, Ga	2.1	34.57	2.87
2327500	Ochlockonee River Near Thomasville, Ga	2.1	35.99	2.84
2329342	Little Attapulcus Creek At Attapulcus, Ga	1.32	0.68	0.38
2353000	Flint River At Newton, Ga	1.42	368.40	3.33
2353265	Ichawaynochaway Creek At Ga 37, Near Morgan, Ga	1.39	12.92	1.34
2354410	Chickasawhatchee Creek Near Leary, Ga	3.2	8.08	0.66
2354800	Ichawaynochaway Creek Near Elmodel, Ga	1.56	55.83	1.65
2355662	Flint River At Riverview Plantation Nr Hopeful, Ga	1.35	402.41	3.92
2357000	Spring Creek Near Iron City, Ga	1.93	33.44	2.63
2316000	Alapaha River Near Alapaha, Ga	2.47	42.51	3.19

Figure 21. Location of USGS Stations in the Areas of North Florida, Georgia and Alabama

Where Q_{10} is in CMS, drainage area is in square miles and d_{10} is in meters. Figures 22 and 23 show data and regression equations for discharge and depth, respectively. As shown, when adding the stations in the validation data set, the correlation coefficient improved slightly for Q_{10} compared to the regression with just the West Central Florida stations. The regression for d_{10} shows a poorer correlation but still moderate.

Data for the intermediate flow region was initially tested using the same model developed for West Central Florida stations (Equation 19). The average relative error using values of Q_{10} and d_{10} specific for each station was less than 30% for 33% of the

stations and less than 50% for 68% of the stations. The average relative error using values of Q_{10} and d_{10} estimated from the regression equations was less than 30% for 23% of the stations and less than 50% for 63% of the stations. Drainage area data and relative error for the specific model is shown in Appendix I.

In an attempt to improve these results, a model for the intermediate-flow region specific to the data in the validation set was developed using a least square regression analysis. The generalized relation based on relative discharge and depth was defined with a log-linear equation with zero intercept. For the forty stations in the validation data set, the best fit slope was found to be 1.35. The mathematical model was described as:

$$\log Q' = 1.35 \log d' \quad (27)$$

This difference in the rating slope can be observed in the plot of relative discharge versus relative depth for the stations in the validation data set (Figure 24). When compared to the same plot for the stations in West Central Florida (Figure 4), most of the ratings in the validation set show a lower slope.

Figure 22. Data and Regression Equation for Q_{10} Including Validation Data Set

Figure 23. Data and Regression Equation for d_{10} Including Validation Data Set

Figure 24. Relative Discharge ($\text{Log } Q'$) Versus Relative Depth ($\text{Log } d'$) for Stations in North Florida, Alabama and Georgia

The lower rating slope can be explained by looking at the watershed characteristics. The stations in the validation data set have a much larger drainage area than the stations used in the calibration and verification data set. As indicated, the mean drainage area in the data validation set is 1830 square miles, that compared to 138 sq. miles in the calibration set and 214 sq. miles in the verification set, in average is much larger. Large drainage areas are associated with flatter average channel slope and consequently larger water depths for the mean discharge than the smaller sized watersheds. As a result, the ratings at the larger watersheds will exhibit higher values of depth for the mean discharge, resulting in flatter rating slopes. Figure 25 shows the relation of drainage area and channel slope and water depth, for some stations in Florida, Georgia and Alabama. In this figure, water depth is shown as d_{10} as a representative value for the streams.

Figure 25. Relation Between Drainage Area and Channel Slope and Water Depth (d_{10}) for Some Stations in Florida, Georgia and Alabama

The bankfull channel dimensions could also be a factor in the flatter slope. A study for regional channel characteristics in Florida streams (Metcalf, 2004) demonstrated that streams in Northwest Florida have much larger bankfull areas and discharge than other areas of Florida. The study attributes the difference to precipitation and geologic runoff factors in the Northern Florida area. Also, some reviewed studies on development of regional curves (Cinotto, 2003; Keaton, 2005; Moody, 2003; Kuck, 2000) show drainage area as the main factor for the variability in bankfull characteristics (ie. bankfull area). This supports the rationalization presented previously of larger drainage areas in the validation data set as the possible reason for the flatter slope.

When testing Equation 27, the average relative error using values of Q_{10} and d_{10} specific for each station was less than 30% for 58% of the stations and less than 50% for 78% of the stations. These results are much better than the ones obtained with Equation 19 and comparable with the results obtained for West Central Florida stations. The average relative error using values of Q_{10} and d_{10} estimated from the regression equations was less than 30% for 25% of the stations and less than 50% for 63% of the stations. These results are comparable to the ones obtained with Equation 19.

A similar approach was used for the high flow region. A model specific to the high flow data in the validation set was developed by the least square regression procedure. Using the specific intercept for each station, the best fit slope was found to be 2.9 for the stations in the validation set. The mathematical model was described as:

$$\log Q' = 2.9 \log d' + b_{station} \quad (28)$$

Where $b_{station}$ is the specific intercept for each station.

The model was tested using the specific intercept for each station and results were compared to the USGS rating data. The average relative error using values of Q_{10} and d_{10} specific for each station was less than 30% for 36% of the stations and less than 50% for 48% of the stations. Due to the poor results obtained using a general equation for the intercept for the high flow region in the calibration data set, no general model was developed for the validation data set. Drainage area data and relative error for the specific model is shown in Appendix J.

8. RESULTS AND DISCUSSION

The main purpose of this research was to develop a generalized equation for rating stream depth-discharge when there is an absence of a rating measurement data set. The equation will describe the depth-discharge rating by recognizing and individually describing the intermediate and high-flow regions. A secondary interest was to provide a simple equation which could be used in model calibration.

From the three explored approaches, the general model based on the depth-discharge values using the 10% exceedence flow rate and depth, provided the best overall results. It is important to mention that even though all three explored approaches require some normalization parameters, in the case of Approach 2 and 3, the estimation of the scaling factors, may introduce some potential errors. Nevertheless, even factoring in the error into the analysis, Approach 3 yielded the best results.

A qualitative assessment of results from Approach 3 is shown in Figure 26. The qualitative comparison shows that those stations that provide an apparent “good fit” match only partially the USGS rating data. The matching region corresponds to low and intermediate flows. It is clear from these results that this model does not adequately represent the high flow region. For some stations that upper limit of applicability is around the Q_{10} and for others is near the rating break point. However, some stations showed good performance for discharges much larger than Q_{10} and Q_{full} flows.

In order to quantitatively evaluate the accuracy of the proposed method, values of discharge were obtained using Approach 3 and compared to discharge values from the USGS rating curves. The Student's paired T-test was used as the statistical analysis to measure the differences between the discharge from the USGS rating curves and the discharge estimated by the model. The T-test is commonly used to compare the mean differences between two data sets based on the paired differences of the data. The test statistic assumes that the sampling distribution of the differences is approximately normally distributed and independent of the magnitude of the discharge (Johnson, 1995). The test was performed for each of the stations in the study area. Results are shown in Table 8.

Figure 26. Some Stations that Partially Matched the USGS Rating Data Using Approach

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Table 8. Results of T-test for 43 Stations in West-Central Florida

Station	T test	Station	T test	Station	T test
5	-0.77	22	-1.68	44	-3.21
6	-0.66	23	-1.39	48	-6.37
7	-2.85	24	-1.21	50	-0.52
8	-0.19	28	-3.01	51	8.06
9	-1.41	29	-2.63	52	11.42
10	-0.38	30	-2.39	53	-2.26
11	-1.98	31	-5.97	54	-3.10
12	-1.37	32	-8.55	57	-2.16
13	-4.64	34	-2.58	58	-1.71
15	-0.49	35	-3.81	63	-1.60
16	-1.49	37	-5.95	64	-1.77
17	3.06	38	-3.44	44	-3.21
18	-2.07	39	-2.73	48	-6.37
19	-1.98	41	-3.75	50	-0.52
20	0.47	42	-5.06	51	8.06
21	-1.07	43	-8.64		

Results from the T-test were provided using a 95% level of confidence. Good model estimation for this level should result in a value within the range of ± 1.96 for the highest sampling size and ± 2.23 for the lowest. Approximately 50% of the stations fall within this range, suggesting that the proposed model might provide a good estimation of the rating curve for better than half of the stations.

To further analyze these results, the relative percent error in discharge was examined. As mentioned earlier, the average relative error of the proposed model compared to the USGS data varies from 20% to 50% for 42% of the stations and 51% to 100% in 48% of the stations. For the flow range between the Q_{90} and the Q_{10} discharge, the average relative error is below 30% for 47% of the stations, and below 50% for 65% of the stations. Although good performance was seen for many stations for much larger

than Q_{10} flows, the higher flows errors indicated that a better definition of model parameters and range of applicability is warranted.

From the analysis of the three approaches it is recognized that the slopes in the intermediate-flow region vary within a specific range and that the high-flow regions exhibited log-linear behavior with considerably different slopes than the intermediate-flow regions. Thus, two different mathematical relationships are proposed for each of the flow regions. The model for the intermediate-flow region using specific values of Q_{10} and d_{10} provided good overall results with 74% of the stations exhibiting errors below 30%. When testing the model using values of Q_{10} and d_{10} as determined from the regression equations, the results are still reasonably good, with 60% of the stations with errors below 30%. Therefore, the regression equations for Q_{10} and d_{10} provide a fairly good estimation of these highly sensitive model parameters, with an average relative error of 26% for Q_{10} and 20% for d_{10} . Table 9 shows the comparison between the USGS data and model results for some of the stations in the study.

A qualitative assessment of results for the intermediate-flow region is shown in Figures 27A and B. These figures show a comparison using both the specific and general values of Q_{10} and d_{10} , for some of the stations in the study area. As indicated from the relative errors, when using the proposed model with Q_{10} and d_{10} values specific for each station, the matching region (i.e., the region exhibiting excellent performance) with the USGS data is much larger than when the values are estimated from the regression equations. This would be very useful if using the relationship for calibration purposes, where specific values of Q_{10} and d_{10} are known for a particular stream; in those cases, a much better performance of the model could be expected. This would also represent a

good relationship for the stage-discharge characteristics of the particular stream (perhaps even in un-gauged regions).

Table 9. Relative Percent Error for Some Stations in West-Central Florida for the Intermediate and High-Flow Region

Station 2300500							
<i>Intermediate-Flow Region</i>					<i>High-Flow Region</i>		
Q-USGS ¹	Q-Mod_Specific ²	RE ³	Q-Mod_General ⁴	RE	Q-USGS	Q-Model	RE
CMS	CMS	%	CMS	%	CMS	CMS	%
6.7	5.9	12.3	6.1	8.0	47.8	48.2	0.9
10.6	10.6	0.2	11.1	5.2	66.0	70.0	6.1
23.0	27.2	18.6	28.6	24.5	170.9	180.4	5.5
40.7	47.6	17.0	49.9	22.8	393.1	414.0	5.3
Station 2301300							
<i>Intermediate-Flow Region</i>					<i>High-Flow Region</i>		
Q-USGS	Q-Mod_Specific	RE	Q-Mod_General	RE	Q-USGS	Q-Model	RE
CMS	CMS	%	CMS	%	CMS	CMS	%
0.6	0.4	26.5	0.4	23.4	11.6	9.3	19.8
1.6	1.3	19.1	1.4	15.7	21.9	19.5	10.7
3.2	2.8	10.7	3.0	7.0	41.3	35.7	13.4
5.3	5.2	2.3	5.4	1.8	54.0	46.1	14.5
6.0	6.0	0.3	6.2	4.0			
Station 2297310							
<i>Intermediate-Flow Region</i>					<i>High-Flow Region</i>		
Q-USGS	Q-Mod_Specific	RE	Q-Mod_General	RE	Q-USGS	Q-Model	RE
CMS	CMS	%	CMS	%	CMS	CMS	%
0.3	0.3	24.2	0.4	9.6	37.2	30.3	18.5
1.9	1.6	16.8	2.3	20.4	89.1	66.6	25.3
5.3	4.8	8.9	6.9	31.8	121.7	88.3	27.5
12.1	12.1	0.2	17.5	44.3	270.0	181.7	32.7
23.2	24.8	7.0	35.9	54.8			

¹ Q-USGS = USGS Published rating relationship data (Water Resources Data of Florida, USGS, 1987-1998)

² Q-Mod_Specific = model results using Q_{10} and d_{10} values specific for the station

³ RE = relative error

⁴ Q-Mod_General = model results using Q_{10} and d_{10} generalized parameters for the study region

The model for the high-flow region using specific values of Q_{10} and d_{10} provided reasonably good overall results with 40% of the stations with errors below 30%. A

qualitative assessment of results for the high-flow region is shown in Figures 28A and B. Table 6 shows the results for some of the stations in the study.

As mentioned, when testing the model using values of Q_{dep} as determined from the regression equations, the errors were larger than 100% in most of the stations. The regression equation for Q_{dep} provides a poor estimation of the parameter, with an average relative error of 57%. The lack of accuracy in the prediction of the high-flow region model with a general intercept is mostly due to the lack of an equation that better describes the Q_{dep} parameter.

From testing the model with the verification data set, the average relative error when compared to the USGS data for the intermediate flow was less than 50% for 70% of the stations. Thus, the error was comparable to the results obtained with the calibration data set.

Testing the model in some stations at North Florida, and South Alabama and Georgia, show some reasonable relative errors but not as good as the results obtained for West Central Florida. Using a model with a different slope, developed for those particular stations improved the results significantly. The larger watershed size in this area could explain the different, lower slope of the ratings, considering that large sized watersheds will exhibit higher values of depth for the mean discharge, resulting in flatter rating slopes.

It is important to mention that when comparing a fixed USGS rating relationship to actual historical USGS physical measurements, the average relative error among the stations was found to be around 90%. Thus, results from the proposed models may still

be comparable to the accuracy of a well established rating when compared to a particular flow measurement.

Figure 27. Comparison of USGS Rating with Model Results, for the Intermediate-Flow Region, for Some Stations in the Study Area

Figure 27. (Continued)

Figure 28. Comparison of USGS Rating with Model Results, for the High-Flow Region, for Some Stations in the Study Area

Figure 28. (Continued)

9. CONCLUSIONS

This study provides a generalized mathematical expression that describes depth-discharge relationships for stream gauging stations in West-Central Florida, for the intermediate and high-flow regions. The study also provides the parameters required to estimate rating curves when there is limited or no measured data available.

Despite using stage-discharge by the conventional methods, this study used the channel depth instead of stage elevation to define the rating curve. This approach provided the advantage of being easier to correlate to a reference in un-gauged streams and it was contended to be more realistic in terms of the physical processes of the system.

For the intermediate-flow region, rating curves developed in mild-sloped streams of West-Central Florida, provided by USGS data plotted in log-log scale, exhibit linear behavior with similar slopes and approximate zero intercept. Also, the high-flow regions exhibited log-linear behavior with considerably different slopes than the intermediate-flow regions, and different intercepts. Thus two different mathematical relationships can be defined for each of the flow regions.

In this study, the difference in streamflow behavior between the two regions and within the same flow region was examined by presuming simple control at stream sections (e.g., behaving as weirs). The variation of the rating slopes within the range of 1.5 to 2.5 in the intermediate-flow region could be due to streamflow being controlled at a section that is through a relative degree of contraction (e.g., behaving either as

rectangular, trapezoidal or V-notch section with discharge coefficients between 3/2 and 5/2). For the high-flow region, steeper rating slopes are undoubtedly indicating a higher degree of contraction and non-uniform flow. The different frictional conditions and cross section characteristics of floodplain flows (e.g., with or without houses) also plays a role in the behavior.

A log-linear equation with zero intercept and a slope of 2.0 is proposed for the intermediate-flow region for the West-Central Florida study area as a general mathematical model. The model is defined using the 10% exceedence flow rate (Q_{10}) and corresponding depth (d_{10}). The Q_{10} was shown to be reasonably well correlated to the watershed drainage area and the d_{10} showed a reasonable good correlation to the Q_{10} , thus a regression equation was defined to obtain general values for those two parameters.

A log-linear equation with a slope of 5.0 and an intercept specific for each station is proposed for the high-flow region for the West-Central Florida study area. The model uses the same Q_{10} and d_{10} parameters defined for the intermediate-flow region. The intercept is related to the discharge where the high-flow region departs from the intermediate-flow region (Q_{dep}). General values for intercept were obtained by defining a regression equation of Q_{dep} as a function of drainage area.

The accuracy of the proposed two-region model was examined statistically. Results show that for the intermediate-flow region, the average relative error is below 50% for 86% of the stations when using values of Q_{10} and d_{10} specific for each station; and below 50% for 74% of the stations when using values of Q_{10} and d_{10} from the regression equations. For the high-flow region, the average relative error is below 50% for 44% of the stations when using values of the intercept specific for each station. When

using values of the intercept from the regression equations the errors are higher than 100%. Thus, this is not a good predictive approach. The accuracy in the prediction of the high-flow region model with a general intercept could be improved with an equation that better describes the Q_{dep} parameter. Other expressions may exist for this parameter but no insight yet exists as to how it could be better estimated in the absence of site specific data.

Results from verifying the intermediate flow region model in thirty stations that had not been previously used in developing the model, showed to be comparable to the ones obtained with the calibration data set.

The model was validated by testing in some stations at North Florida, and South Alabama and Georgia. Using the model with a slope developed specific for those particular stations showed the best results. A log-linear equation with zero intercept and a slope of 1.35 is proposed for the intermediate-flow region for those areas. The different, lower slope of the ratings in those areas may be due to the size of the watersheds.

It is interesting to note that the accuracy of the proposed models may be comparable to (or better than) the discrepancies between a fixed USGS rating relationship and periodic physical flow measurement. Therefore, the use of similar general rating relationships in West-Central Florida or elsewhere should prove to be a useful method to populate model data sets (subject to calibration through simple parameterization) when limited field data exist for model stream sections.

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APPENDICES

**Appendix A: Results from Weir Analysis in Channel Controlled by a
Horizontal_Uncontracted Section**

**Table 10. Results from Weir Analysis in Channel Controlled by a
Horizontal_Uncontracted Section**

C=	3.3			C=	3.5		
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.08	0.06	0.03	0.06	0.09	0.06	0.03
0.15	0.33	0.15	0.11	0.15	0.35	0.15	0.11
0.30	0.94	0.30	0.30	0.30	0.99	0.30	0.32
0.46	1.72	0.45	0.55	0.46	1.82	0.45	0.58
0.61	2.65	0.61	0.85	0.61	2.81	0.61	0.90
0.91	4.86	0.91	1.56	0.91	5.15	0.91	1.65
1.22	7.48	1.21	2.40	1.22	7.93	1.21	2.55
1.52	10.46	1.52	3.35	1.52	11.09	1.52	3.56
C=	4			C=	4.4		
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.10	0.06	0.03	0.06	0.11	0.06	0.04
0.15	0.40	0.15	0.13	0.15	0.44	0.15	0.14
0.30	1.13	0.30	0.36	0.30	1.25	0.30	0.40
0.46	2.08	0.45	0.67	0.46	2.29	0.45	0.73
0.61	3.21	0.61	1.03	0.61	3.53	0.61	1.13
0.91	5.89	0.91	1.89	0.91	6.48	0.91	2.08
1.22	9.07	1.21	2.91	1.22	9.98	1.21	3.20
1.52	12.67	1.52	4.07	1.52	13.94	1.52	4.47

**Appendix B: Results from Weir Analysis in Channel Controlled by a
Horizontal_Contracted Section**

**Table 11. Results from Weir Analysis in Channel Controlled by a
Horizontal_Contracted Section**

C= 3.3				C= 3.5			
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.03	0.06	0.01	0.06	0.00	0.06	0.01
0.15	0.13	0.15	0.04	0.15	0.00	0.15	0.04
0.30	0.36	0.30	0.11	0.30	0.01	0.30	0.12
0.46	0.64	0.45	0.20	0.46	0.01	0.45	0.22
0.61	0.95	0.61	0.31	0.61	0.02	0.61	0.32
0.91	1.65	0.91	0.53	0.91	0.03	0.91	0.56
1.22	2.39	1.21	0.77	1.22	0.03	1.21	0.81
1.52	3.14	1.52	1.01	1.52	0.04	1.52	1.07
C= 4				C= 4.4			
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.04	0.06	0.01	0.06	0.00	0.06	0.01
0.15	0.16	0.15	0.05	0.15	0.00	0.15	0.06
0.30	0.43	0.30	0.14	0.30	0.01	0.30	0.15
0.46	0.77	0.45	0.25	0.46	0.01	0.45	0.27
0.61	1.15	0.61	0.37	0.61	0.02	0.61	0.41
0.91	2.00	0.91	0.64	0.91	0.03	0.91	0.71
1.22	2.90	1.21	0.93	1.22	0.03	1.21	1.02
1.52	3.80	1.52	1.22	1.52	0.04	1.52	1.34

Appendix C: Results from Weir Analysis in Channel Controlled by a V-Notch Section

Table 12. Results from Weir Analysis in Channel Controlled by a V-Notch Section

C=	2			C=	2.5		
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.00	0.06	0.00	0.06	0.00	0.06	0.00
0.15	0.01	0.15	0.01	0.15	0.01	0.15	0.01
0.30	0.06	0.30	0.02	0.30	0.07	0.30	0.02
0.46	0.16	0.45	0.03	0.46	0.20	0.45	0.04
0.61	0.32	0.61	0.05	0.61	0.40	0.61	0.06
0.91	0.88	0.91	0.09	0.91	1.10	0.91	0.12
1.22	1.81	1.21	0.15	1.22	2.27	1.21	0.18
1.52	3.17	1.52	0.20	1.52	3.96	1.52	0.25
C=	3			C=	4.3		
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.00	0.06	0.00	0.06	0.00	0.06	0.00
0.15	0.02	0.15	0.01	0.15	0.02	0.15	0.01
0.30	0.09	0.30	0.03	0.30	0.12	0.30	0.04
0.46	0.23	0.45	0.05	0.46	0.34	0.45	0.07
0.61	0.48	0.61	0.08	0.61	0.69	0.61	0.11
0.91	1.33	0.91	0.14	0.91	1.90	0.91	0.20
1.22	2.72	1.21	0.22	1.22	3.90	1.21	0.31
1.52	4.75	1.52	0.30	1.52	6.81	1.52	0.44

**Appendix D: Results from Weir Analysis in Channel Controlled by a
Broad Crested Weir**

**Table 13. Results from Weir Analysis in Channel Controlled by a
Broad Crested Weir**

C= 2.3				C= 2.63			
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.06	0.06	0.02	0.06	0.07	0.06	0.02
0.15	0.23	0.15	0.07	0.15	0.26	0.15	0.08
0.30	0.64	0.30	0.21	0.30	0.73	0.30	0.24
0.46	1.16	0.45	0.38	0.46	1.33	0.45	0.44
0.61	1.77	0.61	0.59	0.61	2.02	0.61	0.68
0.91	3.18	0.91	1.09	0.91	3.64	0.91	1.24
1.22	4.80	1.21	1.67	1.22	5.49	1.21	1.91
1.52	6.56	1.52	2.34	1.52	7.50	1.52	2.67
C= 3				C= 3.3			
H	Q	H'	Q'	H	Q	H'	Q'
m	CMS			m	CMS		
0.06	0.08	0.06	0.02	0.06	0.08	0.06	0.03
0.15	0.30	0.15	0.10	0.15	0.33	0.15	0.11
0.30	0.83	0.30	0.27	0.30	0.92	0.30	0.30
0.46	1.51	0.45	0.50	0.46	1.67	0.45	0.55
0.61	2.31	0.61	0.77	0.61	2.54	0.61	0.85
0.91	4.15	0.91	1.42	0.91	4.57	0.91	1.56
1.22	6.26	1.21	2.18	1.22	6.88	1.21	2.40
1.52	8.55	1.52	3.05	1.52	9.41	1.52	3.35

Appendix E: Results from Weir Analysis in Channel Controlled by a Compound Weir consisting of a V-Notch and a Trapezoidal Weir

Table 14. Results from Weir Analysis in Channel Controlled by a Compound Weir consisting of a V-Notch and a Trapezoidal Weir

H	Q _v	Q _t	Q _{comb}	H _{total}	H'	Q'
m	CMS	CMS	CMS	m		
0.15	0.013	0.331		0.013	0.15	0.01
0.30	0.071	0.935		0.071	0.30	0.02
0.46	0.195	1.718		0.195	0.45	0.04
0.61	0.401	2.645		0.401	0.61	0.06
0.15			16.882	17.283	0.76	0.17
0.30			47.751	48.151	0.91	0.37
0.46			87.723	88.124	1.06	0.63
0.61			135.059	135.460	1.21	0.93

Appendix F: Basin Characteristics Data and Relative Error for Stations in Calibration Data Set for Intermediate-Flow Region

Table 15. Basin Characteristics Data and Relative Error for Stations in Calibration Data Set for Intermediate-Flow Region

Gage #	S10	Q10	d10	Ch Slope	Slope	Area	% Wetland	DTWT	RE
		CMS	m	%	m/m	mi ²	%	m	%
2295420	1.34	7.5	1.3	2.14	0.010876	125.2	10.25	4.34	52
2294898	1.73	15.5	1.8		0.0108763	479.6	23.89	5.83	16
2296750	1.74	76.5	2.8	1.3	0.0088	1372.9	19.88	3.55	25
2300500	1.72	11.0	1.9		0.00738	151.7	12.58	3.714	15
2300100	1.72	2.2	1.3		0.0060	30.9	12.59	3.88	12
2301000	2.1	8.5	1.8	4.96	0.01	136	5.1	4.765	2
2301500	1.67	20.5	1.9	3.45	0.0088	339.4	12.87	4.77	23
2294650	1.6	6.2	1.6	1.25	0.0120	404.7	26.03	5.20	10
2297155	1.6	2.1	0.8	5.5	0.0050	40.9	13.01	3.50	53
2296500	1.98	21.2	2.4	1.68	0.0061	326.5	19.63	3.51	4
2301300	1.9	6.3	1.5	4.17	0.0070	112.2	11.52	4.53	11
2297310	1.9	15.0	2.4	2.79	0.004779	217.3	17.71	3.50	8
2295637	1.61	41.1	2.6	1.38	0.00994	839.1	19.55	4.15	15
2303350	2.34	1.6	0.7	2.44	0.005	17.3	27.52	3.46	10
2303420	2.37	3.6	1.3	2.65	0.010444	128.7	30.54	3.68	20
2293987	2.45	9.0	1.3		0.014	170.7	31.14	3.68	21
2295013	2.36	2.2	0.9	4.96	0.007	46.3	25.21	4.135	17
2297220	2.25	1.9	1.1		0.004	47.9	19.27	3.24	29
2297100	2.19	7.8	1.7	4.06	0.004	120.9	10.96	3.37	2
2298830	2.71	19.4	2.0	2.14	0.00455	225.5	22.18	3.28	22
2299120	2.6	3.8	1.3		0.001	26.1	36.82	3.02	20
2299410	2.29	2.7	1.0	1.23	0.002	35.8	21.99	3.20	2
2299861	1.94	0.4	0.4		0.005	6	7.38	3.35	24
2299780	1.7	3.1	0.8		0.005	31.1	8.92	3.32	82
2299684	1.48	0.1	0.2		0.002	4.3	19.88	3.21	98
2300032	1.91	2.4	1.2		0.004	25.2	13.16	3.40	17
2300700	1.98	2.3	1.0	7.01	0.007	28.6	12.10	3.67	14
2301900	4.16	0.5	0.7	6.1	0.009	9.3	12.24	4.75	55
2302500	1.84	5.3	0.9	3.52	0.009011	98.6	17.79	3.23	17
2303000	1.89	14.9	1.6	3.87	0.005	227.2	16.82	4.09	29
2303205	2.22	1.2	0.5		0.009011	21.6	13.4	4.869	3
2303330	8.08	17.2	3.2		0.01206	387.9	18.05	3.87	34
2303800	5.1	6.6	1.3	2.1	0.010081	167.8	32.60	5.00	56

Appendix F: (Continued)

Table 15. (Continued)

Gage #	S10	Q10 CMS	d10 m	Ch Slope %	Slope m/m	Area mi ²	% Wetland %	DTWT m	RE %
2301750	2.74	0.7	0.4	5.2	0.011	14.2	8.35	3.80	41
2268390	2.7	1.9	0.9		0.025	53.1	18.95	6.79	4
2269520	1.91	3.7	1.1		0.013	118.3	32.33	4.13	14
2270000	2.54	1.5	1.0		0.014	39	18.90	6.17	4
2271500	2.34	4.8	1.1	3.81	0.01275	113.2	26.96	5.37	16
2307200	2.74	0.3	0.4	1.62	0.003	5.2	33.14	3.51	38
2307359	2.5	1.4	1.0	2.81	0.00545	33	34.68	3.31	32
2310000	2.1	4.9	1.7	3.54	0.002821	69.6	29.61	3.43	4
2310280	2.69	0.5	0.4	2.3	0.015	148.8	13.32	3.82	35
2310300	3.66	2.0	1.0	2.7	0.01342	181.4	17.53	3.82	48

**Appendix G: Basin Characteristics Data and Relative Error for Stations in
Calibration Data Set for High-Flow Region**

**Table 16. Basin Characteristics Data and Relative Error for Stations in Calibration
Data Set for High-Flow Region**

Gage #	S10	b	Q10	d10	Ch Slope	Slope	Area	Wetland	DTWT	RE
	%		CMS	m	%	m/m	mi ²	%	m	%
2295420	4.42	-1.54	263	4.13	2.14	0.0108	125.2	10.25	4.34	145
2294898	3.03	0.02	546	6		0.0108	479.6	23.89	5.83	2
2296750	3.95	-0.29	2700	9.24	1.3	0.0088	1372.9	19.88	3.55	8
2300500	4.95	-1.03	389	6.1		0.0073	151.7	12.58	3.71	5
2300100	4.77	-0.34	77	4.3		0.0060	30.9	12.59	3.88	0.5
2301000	5.14	-0.67	299	6	4.96	0.01	136	5.1	4.76	6.2
2297155	5.73	-2.83	74	2.66	5.5	0.0050	40.9	13.01	3.50	70
2296500	4.54	-0.66	747	7.76	1.68	0.0061	326.5	19.63	3.51	47
2301300	5.37	-0.42	224	4.84	4.17	0.0070	112.2	11.52	4.53	13
2297310	5.56	-0.62	530	7.9	2.79	0.0047	217.3	17.71	3.50	27
2295637	3.83	-0.36	1450	8.45	1.38	0.0099	839.1	19.55	4.15	129
2303350	3.83	-0.35	55	2.45	2.44	0.005	17.3	27.52	3.46	223
2297100	7.40	-1.91	275	5.54	4.06	0.004	120.9	10.96	3.37	98
2298830	4.88	0.00	686	6.7	2.14	0.0045	225.5	22.18	3.28	14
2299410	7.50	-1.37	95	3.13	1.23	0.002	35.8	21.99	3.20	87
2299684	4.75	-2.44	4.2	0.55		0.002	4.3	19.88	3.21	14
2300032	4.65	-1.43	85	4		0.004	25.2	13.16	3.40	71
2300700	5.83	-1.87	82	3.16	7.01	0.007	28.6	12.10	3.67	64
2302500	4.01	-0.81	187	2.89	3.52	0.0090	98.6	17.79	3.23	218
2303000	5.52	-1.46	525	5.2	3.87	0.005	227.2	16.82	4.09	4
2303330	4.80	0.08	606	10.53		0.01206	387.9	18.05	3.87	21
2271500	3.80	-0.06	171	3.55	3.81	0.0127	113.2	26.96	5.37	56
2307359	6.95	-0.36	50	3.17	2.81	0.0054	33	34.68	3.31	76

**Appendix H: Basin Characteristics Data and Relative Error for Stations in
Verification Data Set for Intermediate-Flow Region**

**Table 17. Basin Characteristics Data and Relative Error for Stations in Verification
Data Set for Intermediate-Flow Region**

ID	station	A mi ²	RE %
2	2299950	67	32
3	2294491	145	44
4	2294217	59.5	12
37	2300530	7.3	26
44	2303300	57.7	24
49	2267000	46	57
54	2270500	388.5	68
58	2307323	229	108
65	2236350	41.8	40
66	2310800	107.6	45
67	2310947	352.8	47
68	2311500	419.6	48
69	2312000	572.6	24
70	2312180	88	85
72	2312500	805.9	32
73	2262900	84	36
74	2266300	84.6	57
75	2298760	20	15
76	2300032	25.8	19
77	2300500	149	24
78	2306774	17.8	15
79	2313000	1825	79
80	2300018	50.6	25
81	2301738	2.6	113
83	2300300	38.4	32
84	2305851	2.59	29
85	2301740	6.5	24
86	2301745	2	78
87	2301793	1.46	58

**Appendix I: Drainage Area and Relative Error for Stations in Validation Data Set
for Intermediate-Flow Region**

**Table 18. Drainage Area and Relative Error for Stations in Validation Data Set for
Intermediate-Flow Region**

Station	Area mi ²	RE %
2369800	1182	24
2361500	1280	15
2378300	16.6	40
2376500	394	3
2374250	2661	17
2373000	470	9
2361000	686	7
2363000	498	23
2372422	1273	102
2364500	1182	11
2377570	192	4
2374950	193	21
2362240	21.4	45
2323000	9390	11
2319800	7190	6
2319000	2120	8
2322500	1017	15
2321500	575	57
2330150	2080	54
2330100	126	49
2359000	781	26
2365500	3499	41
2368500	123	4
2370500	237	51
2376500	394	5
2322700	213	344
2226500	1200	55
2228000	2790	49
2314500	1260	41
2226000	13600	47
23177483	502	14
2327500	550	33
2329342	16.9	3

Appendix I: (Continued)

Table 18. (ContinueD)

Station	Area mi ²	RE %
2353000	5740	4
2353265	303	6
2354410	157	106
2354800	1000	17
2355662	7080	3
2357000	485	31
2316000	663	270

**Appendix J: Drainage Area and Relative Error for Stations in Validation Data Set
for High-Flow Region**

**Table 19. Drainage Area and Relative Error for Stations in Validation Data Set for
High-Flow Region**

Station	Area mi ²	RE %
2361500	1280	9
2378300	16.6	85
2376500	394	2
2374250	2661	73
2373000	470	205
2361000	686	29
2363000	498	82
2377570	192	8
2374950	193	411
2362240	21.4	54
2323000	9390	42
2319800	7190	6
2319000	2120	88
2322500	1017	451
2330100	126	26
2359000	781	41
2365500	3499	3
2368500	123	30
2370500	237	47
2376500	394	3
23177483	502	65
2327500	550	75
2354410	157	68
2357000	485	70
2316000	663	76

ABOUT THE AUTHOR

Auristela Mueses-Pérez was born on October 10, 1967 in Dominican Republic. She attended San Judas High School, finishing as the best GPA in 1984. In 1987 she graduated Magna Cum Laude with her Bachelor in Civil Engineering from Instituto Tecnológico Santo Domingo. In 1989 she moved to Puerto Rico to pursue her Master of Science in Water Resources Engineering, at University of Puerto Rico, Mayaguez. She completed her degree in 1991. In 1992 she joins Polytechnic University of Puerto Rico as an Assistant Professor, and was promoted to Associate Professor in 1999. In 2003, she began Ph.D. coursework in the Mayaguez Campus, and after a year she decides to continue her Ph.D. in Water Resources at University of South Florida. She completed her work in the field of non-dimensional rating curves in the summer of 2006. She already took a position as a faculty member at Polytech University in Orlando.