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Bankfull Hydraulic Geometry Relationships for Rivers and Streams of the Western and Southwest Regions of Paraná State, Brazil

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Abstract

This study presents regional hydraulic geometry relationships for rivers and streams in the western and southwestern regions of the state of Paraná, Brazil. Regional hydraulic geometry relates the area of the river basin to the dimensions of the river channel (width, depth, channel capacity) and the flow measured at bankfull stage by potential functions. Both regions integrate a homogeneous area in the basaltic plateau of the Paraná sedimentary river basin. The climate is humid sub-tropical and the average rainfall is 1,830 mm annually. The nesting of the rivers in the study area does not allow the development of alluvial plains. For this reason, sandy deposits deposited by floods were used as a reference in defining bankfull stages. The data were collected by 46 fluviometric stations and reference sections, whose drainage areas ranged from 0.44 to 17,400 km^2. The coefficients of determination (R^2) of the equations reached values between 0.911 and 0.966 and were valid for the studied regions and for alluvial stretches in rural areas.

Keywords: Fluvial geomorphology; Bankfull stage; Basaltic plateau of Paraná; Paraná River.

1. Introduction

The concept of hydraulic geometry in river basins proposed by Leopold and Maddock (1953) describes spatial variations of channel dimensions (width, mean depth) and flow speed in response to the gradual increase of flows towards downstream. This concept is based on the assumption that channel dimensions vary in response to the geomorphological activity of the annual mean flow. The relationships are expressed by potential functions. They have as dependent variables width, depth and flow speed and as the independent variable the average annual flow. Detailed information on the theoretical and methodological aspects of hydraulic geometry can be found in the works of Knighton (1975), Park (1977), Thornes (1977),

Ferguson (1986) and others. Among the studies developed on this subject in Brazil, there are the works of Christofoletti (1976, 1981), Latrubesse and Aquino (1998), Aquino et al. (2005), Grison and Kobiyama (2011a, b) and Grison et al. (2009, 2014). Later, Leopold (1964) used bankfull flows instead of average annual flows to predict the physical dimensions of channels. The definition of bankfull flow and the criteria for identifying the level of this flow in field are discussed below. Because the use of bankfull flow as an independent variable limits the development of hydraulic geometry equations only in basins with a considerable number of fluviometric stations, Dunne and Leopold (1978) adopted basin area instead of bankfull stage. In order to increase the precision of equations, data collection stations are spatially organized according to homogeneous areas based on regionalization methods that take into account hydrological and physiographic (CASTRO and JACKSON, 2001; JOHNSON and FECKO, 2008) and ecoregional characteristics (CASTRO and JACKSON, 2001; SPLINTER et al., 2010). Thus, the equations developed using data organized by one of such regionalization methods are valid only for the region under study.

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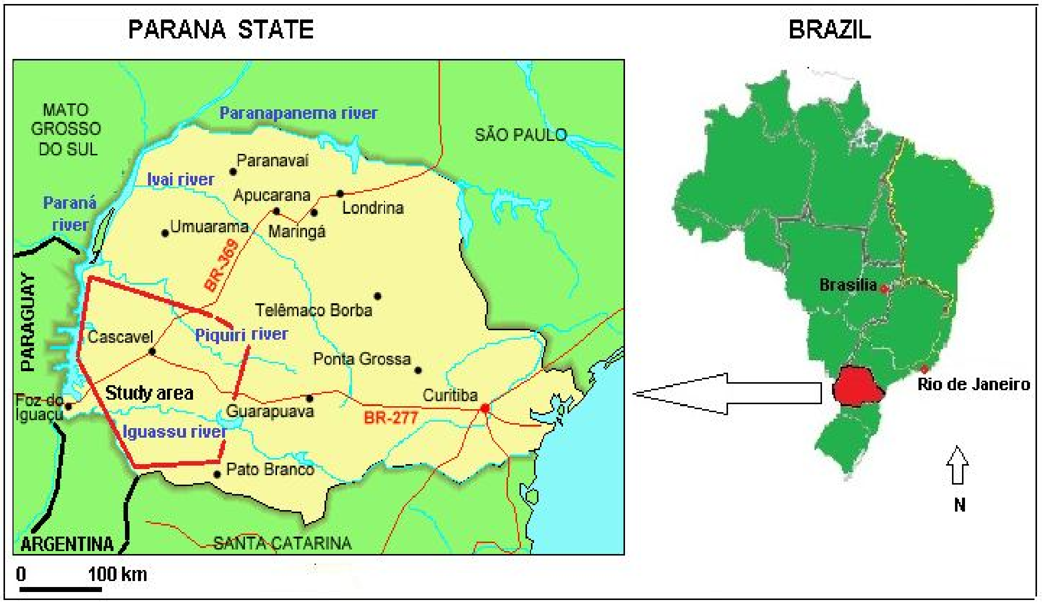
They are named regional hydraulic geometry or regional curves. After the pioneering work of Dunne and Leopold (1978), numerous researchers have developed the regional hydraulic geometry relationships for different regions of the United States of America (MOODY and ODEM, 1999; HARMAN et al., 1999; WHITE, 2001; CASTRO and JACKSON, 2001; McCANDLESS, 2003; SWEET and GERATZ, 2003; CINNOTO, 2003; EMMERT, 2004; MESSINGER and WILEY, 2004; SHERWOOD and HUITGER, 2005; KEATON et al., 2005; KRSTOLIC and CHAPLIN, 2007; MULVIHILL et al., 2009; AGOURIDIS et al., 2011; MODRICK and GEORGAKAKOS,2014; among others).

The practical usefulness of regional hydraulic geometry equations is to estimate the flow and channel dimensions at bankfull stage based on the value of basin area. The information obtained can guide technicians in projects addressing the physical and ecological restoration of channels, subsidize evaluation studies of degradation conditions in fluvial environments (ROSGEN, 1998) and assist in projects of dimensioning of bridges and gullies (MULVIHILL et al., 2009). The channel dimensions estimated by the equations can be used as input variables in hydrological models (AMES et al., 2009).

2. **Objective and Study Area**

The objective of this study is to develop regional hydraulic geometry relationships for the west and southwest regions of the state of Paraná (Figure 1). The study area is located in a homogeneous region with common physiographic characteristics (geological, geomorphological and climatic). The combination of these factors produces a certain relationship between rainfalls and surface runoff which characterizes each physiographic region (FISRWG, 1998).

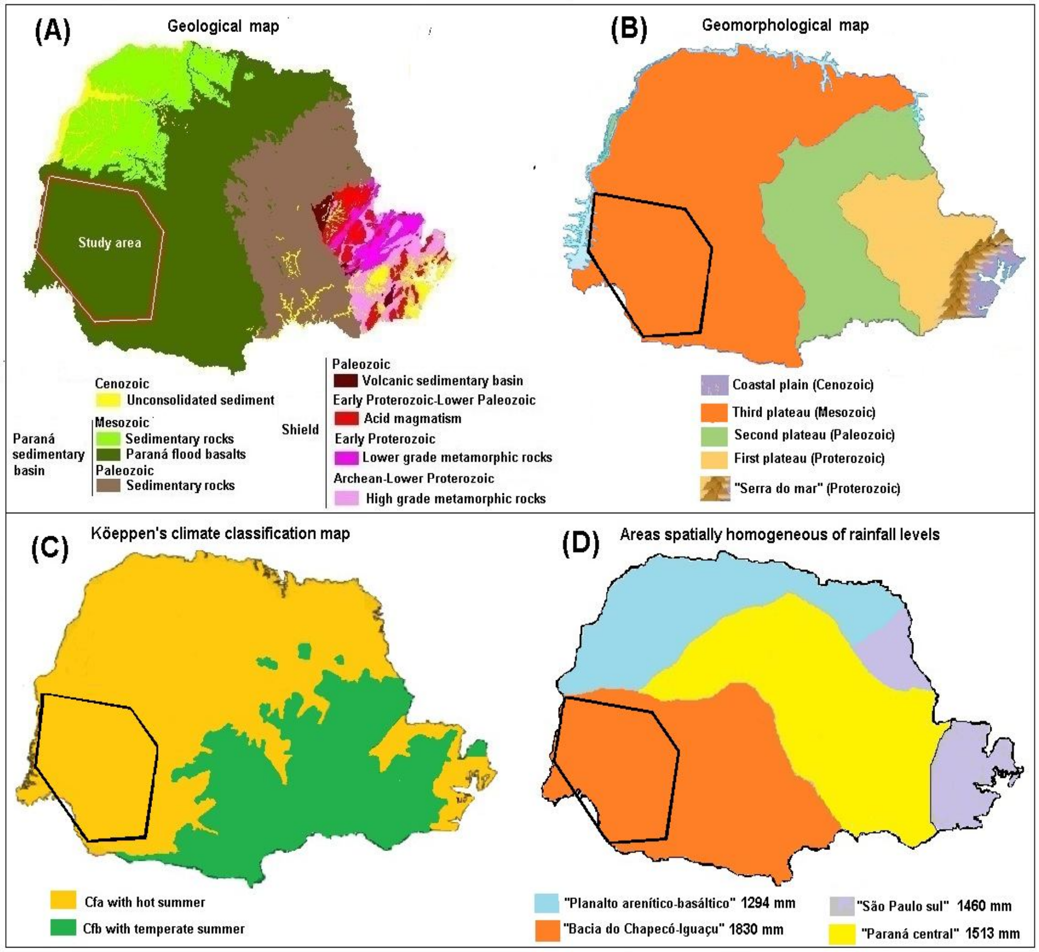
Figure 1: Delimitation of the study area in the west and southwest regions of the state of Paraná.



In the study area, there are the basaltic rocks of the Serra Geral Formation formed by thick flow sequences (Figure 2A) (RENNE et al., 1992; NARDY et al., 2002). In geomorphological terms, the study area forms part of the arenitic-basaltic plateau called by Maack (1968) the Third Plateau or Guarapuava Plateau (Figure 2B). This plateau is composed by basaltic rocks in the North, South and West parts and by sandstones from the Caiuá Formation (Upper Cretaceous) in its Northwest section (Figure 2A). The altitude of the Third Plateau varies from 225 m in the west extreme to 1,150 m at its border with the second plateau in the center of the state (SANTOS et al., 2006). The evolution of Paraná plateaus is related to the epirogenic rise of the South American Platform which occurred from the Upper Cretaceous to the Paleogene-Neogene division (FRANCO-MAGALHÃES et al., 2010). It raised the entire region to altitudes above 1,000 m at the central-south region of the state of Paraná, subjecting the study area to a continuous dissection process.

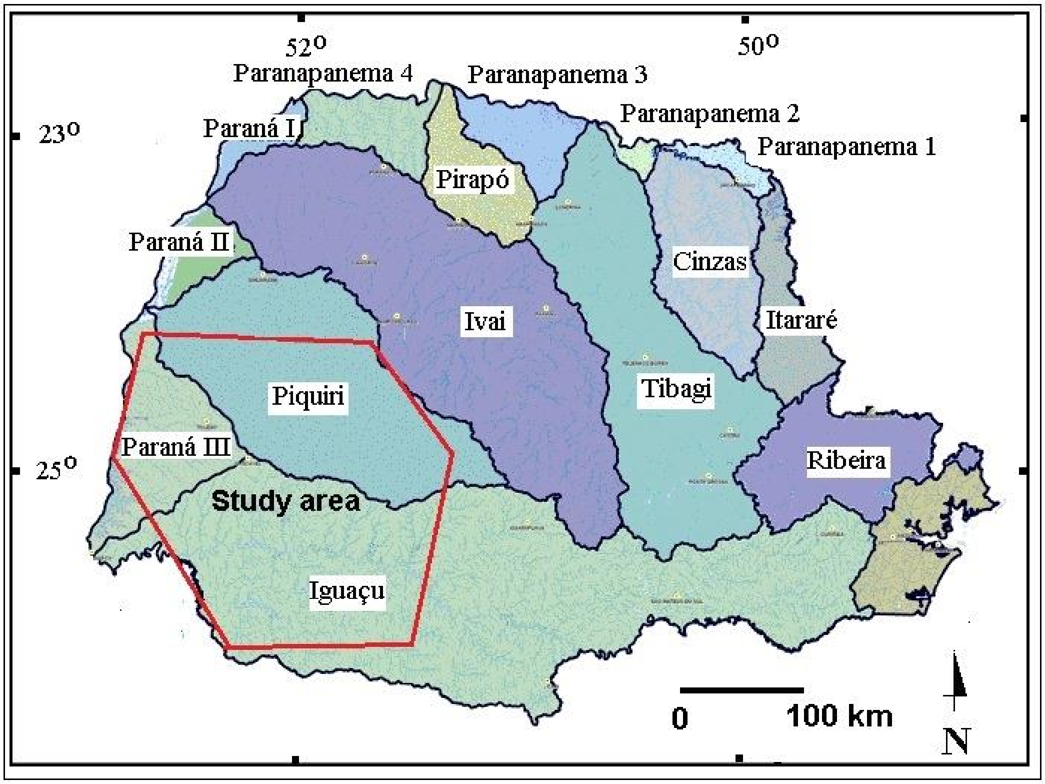
The climate in the study area is subtropical humid, mesothermic (Cfa, according to the Köppen classification) (Figure 2C), with an average temperature above 22ºC in the summer and below 18ºC in the winter, with no defined dry season, hot summers and less frequent frosts (IAPAR, 2000). Taking into account rainfall levels, Silva et al. (2009) divided the state into four spatially homogeneous areas. The western and southeastern regions of the state are located in a homogeneous area called Chapecó-Iguaçu Plateau, characterized by an average annual rainfall of 1,830 mm (Figure 2D).

Figure 2: Location of the study area in the west and southwest regions of the state of Paraná in geological (MINEROPAR, 2001) (A), geomorphological (based on MAACK, 1968) (B), climatic (IAPAR, 2000) (C) and homogeneous areas of rainfall level maps (SILVA et al., 2009) (D).



In hydrographic terms, the study area covers the river courses of the Paraná III basin, the Piquiri basin (except for the region around the mouth and the tributaries of the right margin in the lower and middle stretches) and the lower third of the Iguaçu River basin (Figure 3). The rivers mentioned are tributaries of the left bank of the Paraná River.

Figure 3: Delimitation of the study area within the water basins of Piquiri, Iguaçu and Paraná III (Map source: Instituto das Águas do Paraná).



3. Materials and Methods

3.1. Defining bankfull stages

For the determination of regional hydraulic geometry relationships, it is essential to define bankfull stages and their respective discharges. The discharge of bankfull is defined as the net discharge that fills the channel at the floodplain level (WOLMAN and LEOPOLD, 1957). This plain is defined as a flat surface adjacent to the fluvial channel modeled by the erosive or depositional action of flood flows, and flooded at least once every two years. Williams (1978), in turn, defines bankfull discharge as the flow that fills the channel until it reaches the top of the bank. The bankfull stage demarcates the limits of action of flows that model the channel and limits that demarcate the floodplain.To determine the bankfull stage, according to the definition of Wolman and Leopold (1957), an identification of the alluvial plain is necessary. In many cases, as in rivers with notched thalwegs or steep and confined valleys in sloping terrains, the alluvial plain is poorly developed or inexistent. Williams (1978) listed the various criteria proposed by numerous researchers to identify a surface equivalent to the alluvial plain in case it is not well developed. In the Paraná basaltic plateau, most of the drainage network is embedded at the valley bottom, with a narrow or non-existent alluvial plain. For this reason, Fernandez and Bortoluzzi (2008) and Fernandez (2010) adopted sandy deposits formed by floods as a reference to estimate bankfull stages at fluviometric stations with drainage areas greater than 1,000 km^2. This criterion was proposed by Nunnally (1967) and Leopold and Skibitzke (1967). Figures 4 and 5 show the use of such criteria exemplified by fluviometric stations with undeveloped and non-existent alluvial plains, respectively.

Figure 4: Identification of bankfull stages (Bs) at the Balsa do Cantu station showing a narrow alluvial plain (Source of river cross-section data: Instituto das Águas do Paraná).

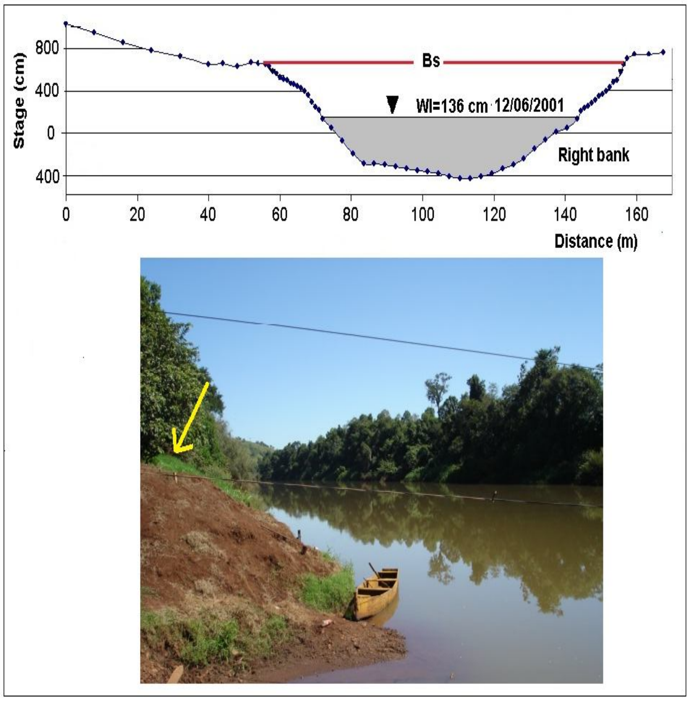
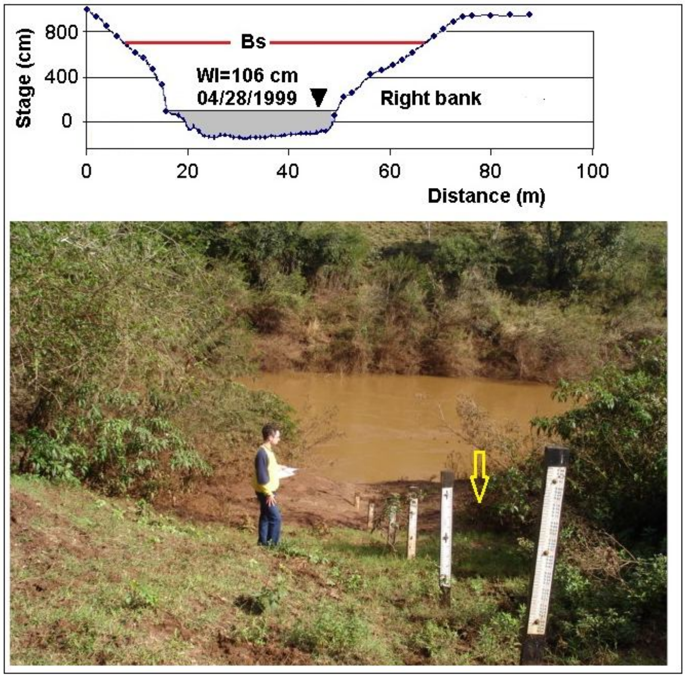


Figure 5: Identification of bankfull stage (Bs) in notched rivers without an alluvial plain, such as at the São Sebastião station (Source of river cross-section data: Instituto das Águas do Paraná).



3.2. Data collection and analysis

Hydraulic geometry variables such as discharge, width, depth and cross-sectional area were collected at two types of stations: fluviometric stations and reference sections. Fluviometric stations, installed in basins with an area greater than 300 km^2, are operated by the National Water Agency (ANA), Instituto das Águas do Paraná (former Suderhsa) and Itaipu Binacional. The reference sections refer to fluvial segments with beds and margins formed by alluvial sediments located in rural areas of basins with an area smaller than 200 km^2 without a fluviometric station. The concept of reference sections was introduced by Rosgen (1998) to designate a fluvial segment with little or no anthropic changes, whose original morphological, hydrological and ecological characteristics were preserved with minor modifications. At the 18 selected hydrometric stations (Figure 6 and Table 1), the bankfull stage was defined based on a field identification of the upper level of sandy deposits. The mean elevation of this surface was obtained by a conventional topographic survey (HARRELSON et al., 1994) based on the reference benchmarks of the stations. The level of bankfull stages at each station (Table 2), therefore, is based on the zero of the scale of fluviometric rulers. The flow corresponding to bankfull stages at each station was obtained by key curve equations (Table 2). The data needed to determine key curves as well as cross-sectional topographic profiles at the stations are provided by the National Water Agency (ANA) on its website at http://hidroweb.ana.gov.br. Channel width, depth and cross-sectional area at bankfull stages were obtained based on river cross-section after tracing bankfull stages (See Figure 4).

Figure 6: Location of fluviometric stations in the Piquiri, Paraná III and Iguaçu river basins (Source: Instituto das Águas do Paraná).

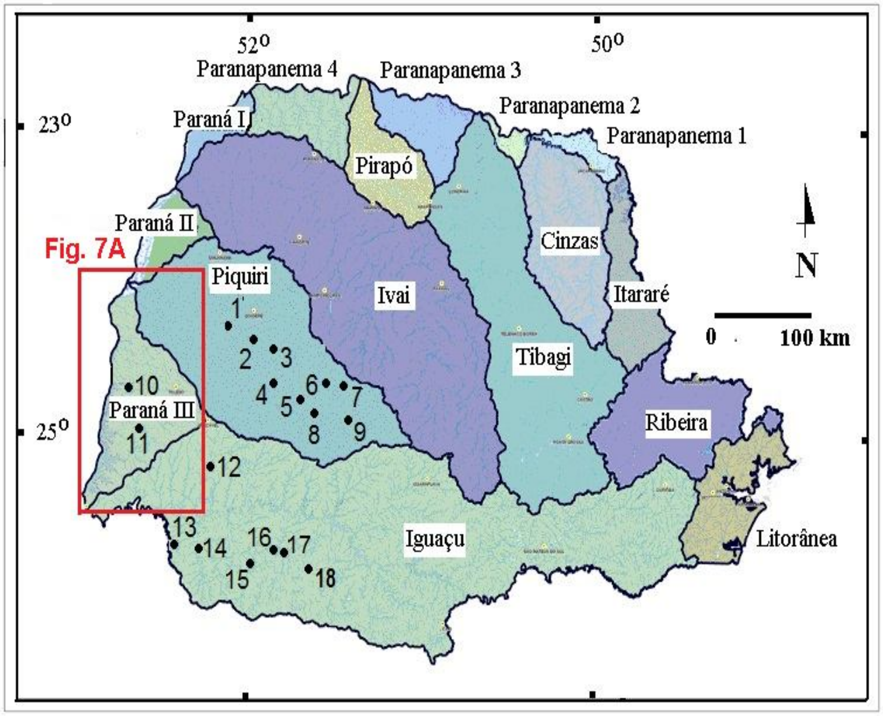


Table 1: Data from fluviometric stations in the Piquiri, Paraná III and Iguaçu river basins (Source: Instituto das Águas do Paraná).

Number of Stations	Station Name/ANA Code	Geographic Coordinates	River	Municipality	Drainage area (km^2)
1	Formosa/64820000	24º 13’ 40” S 53º 20’ 05’ W	Piquiri	Alto Piquiri	17,400
2	Novo Porto II/ 64799500	24º 22’41” S 53º 09’ 45” W	Piquiri	Nova Aurora	12,100
3	Ponte do Piquiri/ 64795000	24º 33’31” S 53º 07’ 45”W	Piquiri	Corbélia	11,200
4	Ponte do Goio-Bang/ 64785000	24º 33’ 20” S 52º 54’28” W	Tricolor	Campina da Lagoa	1,340
5	Foz do Cantu/ 64776100	24º 45’ 07” S 52º 52’36” W	Piquiri	Campina da Lagoa	7,650
6	Balsa do Cantu/ 64775000	24º 44’55” S 52º 42’10” W	Cantu	Altamira do Paraná	2,520
7	Leôncio Primo/ 64773000	24º 43’ 37“ S 52º 18’ 34” W	Cantu	Palmital	757
8	Porto Guarani/ 64771500	24º 51’58” S 52º 45’46” W	Piquiri	Altamira do Paraná	4,160
9	Guampará/ 64764000	24º 58’ 59”S 52º 16’ 59”W	Piquiri	Palmital	1,690
10	São Francisco Verdadeiro/ 64875500	24º 44’ 36”S 54º 05’ 48”W.	S. Francisco Verdadeiro	Marechal C. Rondon	1,406
11	São Francisco Falso/ 64892500	24º 57’ 36”S 54º 10’ 30”W	S. Francisco Falso	Diamante do Oeste	568
12	São Sebastião/ 65979000	25º 27’37” S 53º 31’43” W	Andrada	Santa Lúcia	1,310
13	Muniz/ 65990550	25º 44’83” S 53º 50’49” W	Santo Antônio	Planalto	969
14	Ponte do Capanema/ 65981500	25º 46’05” S 53º 36’42” W	Capanema	Planalto	1,730
15	ETA F. Beltrão/ 65950200	24º 04’ 54”S 53º 04’ 28”W	Marrecas	Francisco Beltrão	336
16	Balsa do Santana/ 65955000	25º 54’ 54” S 52º 50’59” W	Santana	Itapejara d’Oeste	1,720
17	Águas do Verê/ 65960000	25º 46’37” S 52º 55’58” W	Chopim	Verê	6,690
18	Porto Palmeirinha/ 65927000	26º 01’46” S 52º 37’42” W	Chopim	Coronel Vivida	3,390

In smaller basins without hydrometric stations, 28 reference sections (Figure 7 and Table 3) were chosen, at which data of hydraulic geometry variables were collected. The basin area upstream from the reference sections was calculated in topographic charts, scale 1:50,000, using the Global Mapper software. In each section, the bankfull stage was identified in field, adopting the same criterion as used for fluviometric stations, that is, the upper limit of sandy deposits. Afterwards, a cross-sectional topographic profile was made using conventional topography techniques (HARRELSON et al., 1994). For the profiles, morphological data of channels were obtained to estimate discharge and slope (DOLL et al., 2003).

In reference sections, the flow corresponding to the bankfull stage (Qbkf) was estimated using the Manning equation (CHOW, 1959):

$$Qbkf = \frac{1}{n} A.R^{2/3} S^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where A is the cross-sectional area (m^2), R is the hydraulic radius (m), both measured at bankfull stage, S is the slope of water (m/m) and n is Manning's roughness coefficient. The cross-sectional area (A) was obtained based on the raised cross-section up to the bankfull stage. The hydraulic radius (R) was calculated by:

$$R = \frac{A}{WP} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where WP = wet perimeter of the channel at bankfull stage. This variable was measured indirectly based on the transversal profile:

$$WP = W + 2.D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where W and D are width and depth of the channel at bankfull stage.The slope of the river bed (S) was obtained by topographic survey along the channel (HARRELSON et al., 1994) at a distance equivalent to 20 times the channel width at bankfull stage (LEOPOLD, 1994). The roughness coefficient (n) was estimated using the method of Cowan (1956).

$$n = (N0 + N1 + N2 + N3 + N4).m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where: N0 is tabulated values for the type of material at the margin, N1 is the degree of unevenness of the river bed, N2 is cross-section variations, N3 is the obstruction effect, N4 is the vegetation type and **m** is the degree of meandering of the channel. The values tabulated for each variable presented above are found in specific texts on river hydraulics (e.g., JARRETT, 1985; BAPTISTA et al., 2001).

Table 2: Equations of key curves for fluviometric stations, where C = river stage (cm) and Q = discharge (m^3/s). The bankfull stage (BS) is referenced using the zero mark of the stations' rulers as an initial mark.

Number of stations	Station name and period analyzed	Rating curve equation and R^2	Bankfull stage BS (cm)
1	Formosa - 1968-2015	$Q=0.0037.C^2+1.8412.C-246.78$ $R^2=0.996$	645
2	Novo Porto 2 - 1979-2015	$Q=0.0012.C^2+6.2654.C-1{,}542.2$ $R^2=0.993$	564
3	Ponte do Piquiri - 1973-2015	$Q=0.0015.C^2+4.1731.C-510.86$ $R^2=0.999$	500
4	Ponte do Goio-Bang - 1969-2015	$Q=0.0008.C^2+0.2995.C+1.7837$ $R^2=0.979$	213
5	Foz do Cantu - 1988-2015	$Q=0.0073.C^2-0.3396.C+79.699$ $R^2=0.998$	489
6	Balsa do Cantu - 1969-2015	$Q=0.0015.C^2+0.9249.C-238.75$ $R^2=0.994$	645
7	Leôncio Primo - 1980-2015	$Q=0.0004.C^2+1.0739.C-205.46$ $R^2=0.997$	450
8	Porto Guarani - 1978-2015	$Q=0.0011.C^2+1.2243.C-227.62$ $R^2=0.998$	631
9	Guampará - 1986-2015	$Q=-0.0001.C^2+2.1931.C-648.77$ $R^2=0.997$	476
10	São Francisco Verdadeiro - 1990-2001	$Q=0.006.C^2+5.4197.C-790.17$ $R^2=0.975$	175
11	São Francisco Falso - 1990-2008	$Q=0.0001.C^2+0.346.C-6.4903$ $R^2=0.999$	369
12	São Sebastião - 1978-2015	$Q=0.0006.C^2+0.2526.C-6.2746$ $R^2=0.999$	704
13	Muniz - 1987-2015	$Q=0.0007.C^2+0.1206.C-19.765$ $R^2=0.999$	380
14	Ponte do Capanema - 1977-2005	$Q= -0.000003.C^2+0.5062.C-100.3$ $R^2=0.998$	996
15	ETA Francisco Beltrão - 2003-2015	$Q=0.0006C^2-0.1475.C+25.68$ $R^2=0.999$	442
16	Águas do Verê - 1958-2015	$Q=0.0085.C^2+2.8422.C-369.28$ $R^2=0.998$	318
17	Balsa do Santana - 1958-2001	$Q=0.0031.C^2+1.1216.C-104.2$ $R^2=0.998$	272
18	Porto Palmeirinha - 1956-2015	$Q=0.0002.C^2+2.6149.C-182.24$ $R^2=0.999$	322

Figure 7: Location of the 28 reference sections chosen for the Piquiri and Paraná III river basins. The location of Figure 7A is shown in Figure 6.

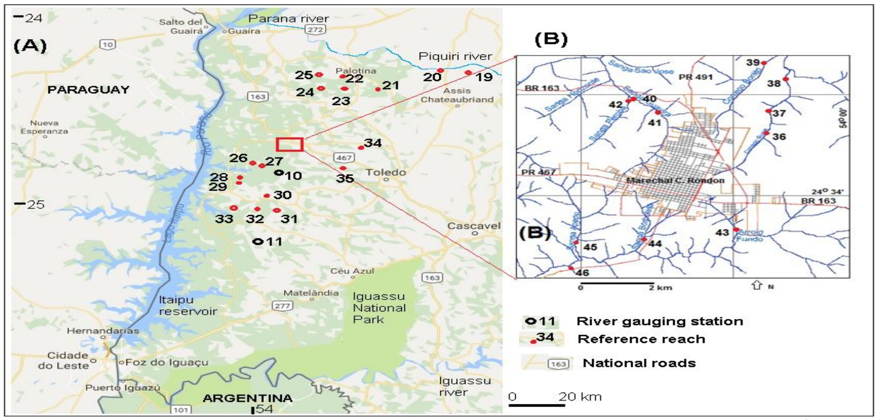


Table 3: Information on selected reference sections in the Piquiri and Paraná III river basins.

Number of section	Geographic Coordinates	Stream	Municipality	Drainage area (km^2)
19	24º 16’ 15”S and 53º 27’ 06”W	Araras	Formosa do Oeste	49.8
20	24º 15’ 07”S and 53º 32’ 38”W	Baiano	Assis Chateaubriand	69.78
21	24º 21’ 16”S and 53º 44’ 15”W	Aurora	Palotina	30.5
22	24º 13’ 02” S and 53º 49’ 25”W	Água Branca	Palotina	5.24
23	24º 10’ 55”S and 53º 49’ 20” W	Jequitiba	Palotina	2.54
24	24º 18’ 0 “ S and 53º 51’ 04” W	Santa Fé	Palotina	28.9
25	24º 18’ 28”S and 53º 54’ 22”W	Quati	Palotina	6.6
26	24º 38’ 33”S and 54º 11’ 16” W	Arroio Fundo	Pato Bragado	187.2
27	24º 38’ 35” S and 54º 11’ 18” W	São João	Pato Bragado	5.52
28	24º 45’ 19” S and 54º 12’ 10” W	Golondrina	Santa Helena	2.16
29	24º 46’ 37” S and 54º 12’ 31” W	Volta Seca	Santa Helena	0.44
30	24º 48’ 20” S and 54º 08’ 57” W	Barra Funda	São José das Palmeiras	3.58
31	24º 50’ 47” S and 54º 13’ 29”W	Sanga Nova	Santa Helena	1.63
32	24º 49’ 26”S and 54º 06’ 58”W	Abelha	São José das Palmeiras	3.22
33	24º 49’ 42”S and 54º 16’ 16” W	Ponte Queimada	Santa Helena	24.24
34	24º 35’ 06” S and 53º 48’ 45” W	Guaçu	Toledo	204.33
35	24º 39’ 32” S and 53º 57’ 12” W	Marreco	Toledo	124.0
36	24º 31’ 50” S and 54º 01’ 36”W	Guará	Marechal C. Rondon	7.44

37	24º 31’ 19” S and 54º 01’ 22”W	Guará	Marechal C. Rondon	9.70
38	24º 30’ 59” S and 54º 01’ 18”W	Guará	Marechal C. Rondon	13.63
39	24º 31’ 24” S and 54º 02’ 25”W	Bonito	Marechal C. Rondon	6.74
40	24º 31” 48” S and 54º 03’ 45”W	Guavirá	Marechal C. Rondon	8.9
41	24º 31” 17” S and 54º 04’ 23”W	Guavirá	Marechal C. Rondon	10.7
42	24º 31’ 21” S and 54º 04’ 26”W	Peroba	Marechal C. Rondon	5.35
43	24º 34’ 54” S and 54º 02’ 12”W	Matilde-cuê	Marechal C. Rondon	4.63
44	24º 35’ 12” S and 54º 04’ 04”W	Borboleta	Marechal C. Rondon	4.96
45	24º 35’ 23” S and 54º 05’ 21”W	Apepu	Marechal C. Rondon	7.62
46	24º 36’ 54” S and 54º 06’ 26 W	Concórdia	Marechal C. Rondon	2.17

The mathematical relationships among hydraulic geometry variables are expressed by linear equations with the adjustment of a power function expressed by the equation:

$$Y = a.X^{b} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where: Y is dependent variables (discharge, width, depth and channel capacity) measured at the bankfull stage, and X is the independent variable (area of the river basin above the section under study).

The reliability of equations was analyzed using the coefficient of determination (R^2) and the standard estimation error (SEE). The R^2 value is the percentage of variation of the dependent variable explained by the independent variable. This coefficient ranges from 0 to 1. A value of $R^2 = 0.675$ indicates that the independent variable explains 67.5% of variation of the dependent variable. On the other hand, the standard estimation error (SEE) is the measurement of proximity of the values estimated by the equation with real values measured in field. The lower the standard error the more reliable the predictions.

4. Results and Discussion

4.1. Development of Regional Hydraulic Geometry Equations

Based on the data collected by the hydrometric stations and reference sections, the regional hydraulic geometry relationships for rivers and streams of the western and southwestern regions of Paraná (Figures 8 and 9) were determined. The equations have high coefficients of determination (R^2). This evidences strong associations between drainage area and bankfull discharge (0.966), drainage area and bankfull width (0.934), drainage area and bankfull depth (0.911) and drainage area and cross-sectional area (0.956). The high R^2 values evidence the upper limit of sandy deposits as a reliable reference for the identification of bankfull stages in rivers that drain the basaltic plateau of the Paraná basin. On the other hand, SEE values show that, among the developed equations, the drainage area (DA) is the best predictor variable to estimate channel depth.

Table 4: Regional regression equations for estimating bankfull discharge (Bbkf), bankfull width (Wbkf), bankfull depth (Dbkf) and bankfull cross-sectional area (Abkf) in function of drainage area (DA, km²) for rivers and streams in the western and southwest regions of Paraná state, Brazil.

Dependent variable	Equations	Coefficient of determination (R^2)	Standard estimate error (SEE) (%)
Bankfull discharge (m^3/s)	Q_{bkf}=0.549 $DA^{0.851}$	0.962	22.0
Bankfull width (m)	W_{bkf}=1.321 $DA^{0.499}$	0.931	17.6
Bankfull mean depth (m)	D_{bkf}=0.470 $DA^{0.290}$	0.894	13.0
Bankfull cross-sectional area (m^2)	A_{bkf}= 0.608 $DA^{0.800}$	0.957	21.8

The combination of data from fluviometric stations and reference sections was positive judging by the high R^2 values of the equations. Both in stations and reference sections, channel dimensions were measured based on transversal profiles, and the flow was estimated by two different indirect methods: key curve method at fluviometric stations and Manning method at reference sections. The size spectrum of the basins analyzed in this study ranged from 0.44 to 17,400 km² and covers areas occupied by agriculture. The predominant economic activity in the municipalities that integrate the Piquiri and Paraná III river basins (Western region) is grain production using modern agriculture (soybean, corn). In the lower section of the Iguaçu river basin (Southwest region), family agriculture predominates (farming and livestock) (LLANILLO et al., 2006). Therefore, the fluviometric stations and the reference sections are in an environmental reality characterized by an almost complete removal of the original vegetation (semi-deciduous seasonal forest) (LEITE and KLEIN, 1990).

This type of forest was the most devastated in the state, remaining only 6.07% of the original area, of which a large part is concentrated inside the Iguaçu National Park (see Figure 7). This significant reduction of the original forest cover is a consequence of the transformation of the region into agricultural areas favored by the excellent edaphic characteristics of the soils (ACCIOLY, 2013). All fluviometric stations and reference sections are located along alluvial stretches. We avoided the installation of reference sections in streams with rocky beds and banks. The adjustment of hydraulic geometry in rocky channels is still little known. However, some studies indicate that such adjustment is similar to adjustments of alluvial channels. The difference is the slow response of rocky beds to the erosive action of flows due to the resistance offered by rocky materials (LIMA, 2010). Due to uncertainties in the definition of the bankfull stage in rocky channels, this type of channel was not included in this research.

4.2. Potential Use and Limitations of Equations

Regional hydraulic geometry equations are valuable for researchers and technicians involved in riverland recovery projects. The equations can be used to estimate, in a preliminary way, the flow and the dimensions of fluvial channels at bankfull stages within the limits of a physiographic region for which the relationships are valid. However, regional curves do not eliminate the need for data collection in field to determine the actual flow, width, depth and capacity of channels along a given stretch (WHITE, 2001). Due to the geographical distribution of hydrometric stations and reference sections used to adjust the curves, the equations should be applied only to the West and Southwest regions of Paraná state and only along alluvial stretches located in rural areas. The abundance of rocky stretches in the rivers that drain the basaltic plateau of Paraná (LIMA, 2012) limits a wide use of the equations for the studied basins.

5. Conclusion

This study presented regional hydraulic geometry relationships for rivers and streams in the western and southwestern regions of the state of Paraná, Brazil. Both regions are within a homogeneous region according to the physiographic characteristics defined by the following conditions: geological (basaltic rocks), geomorphologic (plateau relief) and climatic (subtropical climate, Cfa, with an annual rainfall of 1,850 mm). Regional hydraulic geometry equations were obtained using data collected at specific locations with drainage areas ranging from 0.44 to 17,400 km². The high coefficients of determination (R^2) indicate that the prediction of discharge and channel dimensions at bankfull stages, based on the value of drainage area, can be reliable.

However, the measurement of the morphological variables of channels in field may be necessary depending on the research objectives and on the nature of projects. The high R^2 values of the equations indicate that the upper limit of sandy deposits is a safe criterion to identify bankfull stages in rivers in the basaltic plateau of the Paraná river basin. Regarding the application of the equations, they should be restricted to the West and Southwest regions of Paraná state and alluvial stretches of rural areas.

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