Geospatial methods for morphometric characterization of the Caxiuanã river basin, Amazon, Brazil

Métodos geoespaciais para caracterização morfométrica da bacia do rio Caxiuanã, Amazônia, Brasil

Milena Marília Nogueira de Andrade[I] | Amílcar Carvalho Mendes[II]

[I]Universidade Federal Rural da Amazônia. Belém, Pará, Brasil

[II]Museu Paraense Emílio Goeldi/MCTIC. Belém, Pará, Brasil

Abstract: The aim of this article is to present a morphometric characterization of the Caxiuanã river basin (Pará, Brazil) located in the Caxiuanã National Forest, Melgaço municipality. As a conservation unit, and an isolated area with important natural resources, the use of remote sensing technologies such as radar images and Landsat can provide information about this watershed. Aspects such as drainage network characterization, basin geometry, and relief characteristics were measured through 22 morphometric parameters. This analysis was performed using geoprocessing techniques with ArcHydro and SurfaceAnalysis tools in the ArcGis program. A semi-automatic delimitation of the river basin was carried out from a fusion of radar and optical sensors. The results indicate that the drainage basin of the Caxiuanã River has a developmental dendritic pattern on the sedimentary rocks of the Alter-do-Chão geological formation and alluvial deposits. The basin has an elongated shape which indicates the concentration of the water volume at different points and a low factor form representing low tendency to floods. Morphometric parameters are used for quantitative environmental and physical characterization.

Keywords: Hydrology. Geoprocessing. Shuttle Radar Topography Mission (SRTM).

Resumo: O objetivo deste artigo é apresentar a caracterização morfométrica da bacia hidrográfica do rio Caxiuanã, localizado na Floresta Nacional de Caxiuanã, no município de Melgaço, Pará. Por ser uma unidade de conservação e uma área isolada com recursos naturais importantes, tecnologias de sensores remoto, tais como imagens de satélite Landsat e de radar, podem prover informações a respeito desta bacia hidrográfica. Aspectos como a caracterização da rede de drenagem, a geometria da bacia e as características do relevo foram mensurados através de 22 parâmetros morfométricos. Esta análise foi obtida com técnicas de geoprocessamento por meio das ferramentas do ArcHydro e do SurfaceAnalysis no programa ArcGis. Foi realizada uma delimitação semiautomática da bacia hidrográfica a partir de fusão de sensores de radar e óptico. Os resultados indicaram que a bacia de drenagem do rio Caxiuanã possui um padrão dendrítico de desenvolvimento, instalado em rochas sedimentares da formação geológica Alter-do-Chão e em depósitos aluvionares. A bacia possui forma alongada, o que indica a concentração do volume de água em diferentes pontos; o baixo valor do fator forma indica uma bacia não suscetível a enchentes. Os parâmetros morfométricos foram utilizados para a caracterização quantitativa ambiental e física.

Palavras-chave: Hidrologia. Geoprocessamento. *Shuttle Radar Topography Mission* (SRTM).

INTRODUCTION

The Caxiuanã river basin is part of the Caxiuanã National Forest (CNF) which is a conservation unit stated by law to environmental protection and natural resources conservation (Lisboa, 1997; ICMBio, 2012). The management plan for the CNF indicate among other specific goals to protect the river basins (ICMBio, 2012). The previous knowledge about the local hydrography describes the developed drainage over sedimentary rocks, the water temperature, the physical-chemical water aspects and the location of the rivers sources which are loaded during the high precipitation period (Berredo et al., 2012).

There so to complement the hydrological and morphological information, morphometric aspects can provide a detailed basin description. It has been used in conservation areas to describe relief and drainage patterns and subside environmental management (Felippe et al., 2012; Marques Neto et al., 2008). Worldwide this type of studies uses geospatial techniques for drainage basin analysis (Rai et al., 2017; Franco & Dal Santo, 2015; Biswass et al., 2014; Das et al., 2012; Santos & Sobreira, 2008).

The great lack of studies related to the morphometry of fluvial systems in the northern region of Brazil is due to the deficiency of a cartographic base on a spatial scale suitable for the derivation of the morphometric data, which can be supplied in part with the use of remote sensing images. Remote sensing techniques and Geographical Information System are particularly interesting to be used in conservation unit areas, especially those difficult to access. The parameters of linear, aerial and relief of a basin can be automatic measured (Rai et al., 2017). Images of optical sensors, such as Landsat images, acquire physical-chemical information for visual interpretation and accuracy, whereas radars provide information on topographic and the geometric properties of the study area (Lewis et al., 1998). Additionally, the multi-sensor fusion provide a spectral combination helpful in areas with frequent cloud cover (Pohl & Genderen, 1998), as is the case of the Amazon region.

The study of hydrographic basins is of great importance in the planning of the use of natural resources and environmental diagnostics, precisely because it is the fundamental unit of environmental analysis. Among the several ways of studying the hydrographic basins is the analysis of the morphometric parameters, constitutes one of the first and most common procedures performed in hydrological or environmental analyzes and aims to elucidate the various issues related to the understanding of local and regional environmental dynamics (Teodoro et al., 2007). The relief and the drainage provides information for environmental assessment.

The geomorphology can be interpreted using slope and hypsometric data and geospatial techniques. The range of elevation make possible to interpreted different types of landforms and give base to interpretation of different environments (Kaliraj et al., 2015). Also, the hydrological process all over the earth is an important modifying agent for morphology. Therefore as the basin assumes a range of qualitative aspects it reflects on the relief and can be measured by quantitative characteristics (Goerl et al., 2012).

The most active morphogenetic processes of landscape sculpture are attributed to the stream, which adjust to the climatic, lithological characteristics, differences in the slope and geomorphological evolution of the region (Christofoletti, 1980). Morphometry refers to the quantitative aspects of relief. Among the most used variables for geomorphological, geological, pedological, hidrology and integrated environmental studies, as well as the evaluation of the fragility and vulnerability of the environments are: hypsometry, relief height, slope, drainage density, river frequency. Therefore, a physical evaluation of the environment require accurate information about morphology and morphometry (Rai et al., 2017).

The drainage quantification of a basin provides a description of the hydrological characteristics of a watershed (Strahler, 1964). The influence of drainage morphometry is vital to understanding topographical and landform

development and the geological and geomorphic history of a drainage basin (Rai *et al.*, 2017; Strahler, 1964). Also, systematic study of drainage morphometry can be used to identify indicators of structural influence on drainage development and neotectonic activity (Mantelli & Rossetti, 2009) or to assess vegetation species richness in lakes according to morphometric parameters (Pinheiro, 2015; Ferreira, L. S. *et al.*, 2015). According to Christofoletti (1980) morphometric analysis of river basins provide bases for landscape research. Therefore, the aim of this article it to describe and analyze the morphometry of the Caxiuanã river basin using geospatial methods, quantifying the morphometric parameters, relating them to the geological and geomorphological aspects, culminating with

the presentation of a Digital Elevation Model (DEM) for this basin. The respective characterization will generate information associated to the relief, highlighting the topographic parameters that most influence the structure of the drainage network of its tributaries.

MATERIAL AND METHODS

STUDY AREA
The study area corresponds to the north area of the CNF located at Pará State in the Melgaço municipality frontier with Portel, Gurupá and Porto de Moz. It is positioned approximately 328 km from Belém, the capital state, and the access is mainly fluvial (Figure 1).
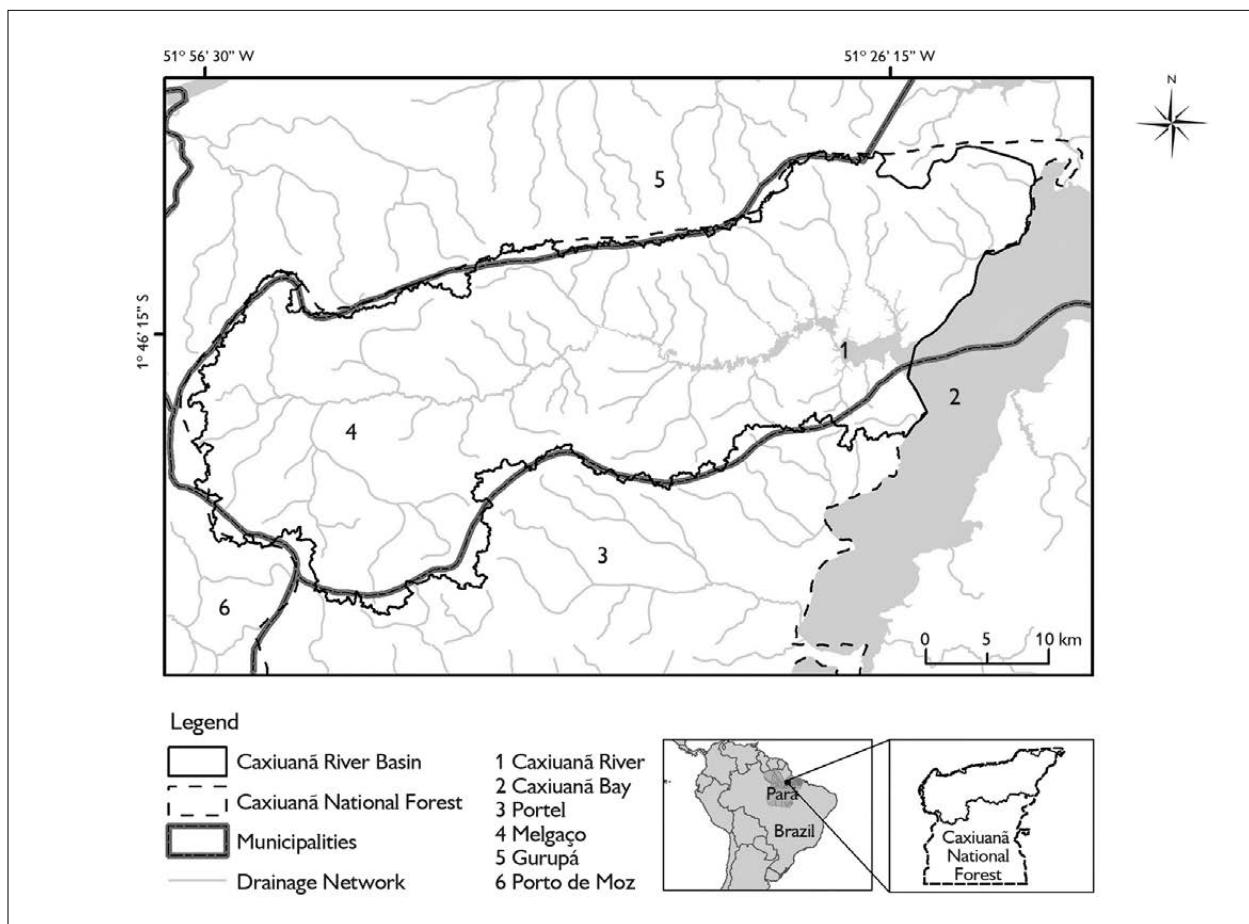

Figure 1. Location of the Caxiuanã basin in CNF. Adapted from ICMBio (2012) and IBGE (2015).

Soils of the study area are mainly yellow latosols with thick and unfertile characteristics (Rodrigues *et al*., 2011; Piccinin & Ruivo, 2012). The vegetation is dryland dense ombrophilous forest of the lower lands and alluvial dense ombrophilous forest. The latter is locally known and differentiated as *igapó* (forest from floodplains periodically flooded by black water rivers) and *várzea* (forest from floodplains periodically flooded by white water rivers) (Ferreira, L. V. *et al*., 2005; Behling & Costa, 2000). According the climatic Köppen classification is an "Am" tropical zone with a monsoon, having an annual rainfall of between 2,500 and 3,000 mm, and an average temperature of 25.7 ± 0.8 °C (Alvares *et al*., 2014; Oliveira *et al*., 2008).

The Caxiuanã River is the most prominent drainage running into Caxiuanã Bay. The bay has an 11-km-wide mouth and is a wide stretch of the Anapu River (ICMBio, 2012). Geological units of the area include the Alter-do-Chão Formation, composed of sedimentary rocks such as sandstones and mudstones formed during the Cretaceous period (João, 2013). Along the main rivers alluvial deposits represent the Holocene in the study area (CPRM, 2010). The sediments are clay and sand deposited on fluvial-lacustrine alluvial plains (Latrubesse, 2008).

The relief of these rock formations form geomorphological domains of low plateaus from the central-east amazon and amazon plains. The extensive tabular aspect sustained by maturate lateritic profiles is compounded by an aluminum-iron crust that decreases the intensity of erosional processes and, the amazon plain corresponds to a lower accumulation area (Teixeira & Dantas, 2013).

METHODS

The methods include a spatial analysis of hydrological and surface parameters using Shuttle Radar Topography Mission (SRTM) and Landsat images, image fusion from a series of geoprocessing tools in Arcgis 10.3 and fieldwork (Figure 2).
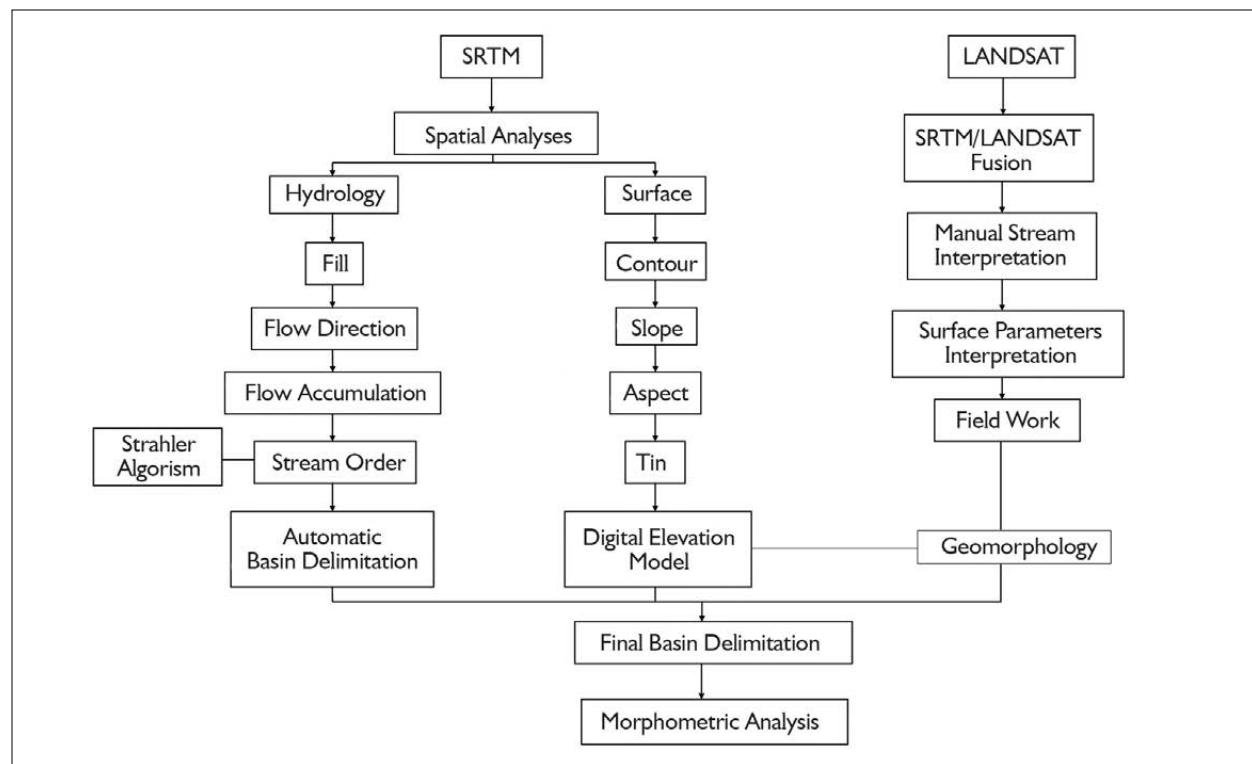

Figure 2. Flowchart of the methodology used to process the Landsat and SRTM images.

The initial step was to extract the drainage network and the hypsometric contours for relief parameters using SRTM with a spatial resolution of 1 arc-second for global coverage (~30 meters) available at U.S. Geological Survey and with word wild distribution (Valeriano & Carvalho Júnior, 2003). To reach the automatic basin delimitation it was necessary to correct some errors from the SRTM filling common discontinuous pixel information in Amazon low areas (Valeriano & Rossetti, 2008).

Drainage extraction from SRTM Digital Elevation Model (DEM) assumes that water will flow from higher to lower elevations but it needs a systematic and organized method to get accurate results (Magesh & Chandrasekar, 2014). The direction of flow and the accumulated flow into each cell indicates where the channel areas established. Therefore the program indicate the local of main channels. The output of this method is a basis for creating stream order vectors that correspond to river hierarchy according to Strahler (1964) order numbers. The automatic basin delimitation follows the identification of the flow until the stream order and basin determination (Biswass et al., 2014).

After the basin delimitation it was possible calculate twenty two morphometric parameters organized according to basin geometry, drainage network, drainage texture analysis and relief characteristics (Pareta & Pareta, 2012). Seven parameters of basin geometry, five from drainage network, and two for drainage texture analysis according to its own formulas (Table 1).

The surface spatial analysis initiated using a 10 m contour curve interval. The hypsometric curve features were the basis for generating slope, aspect, and a Triangular Irregular Network (TIN) model for the Digital Elevation Model (DEM) (Valeriano & Rossetti, 2008). Although, for downscaling the basin delimitation to the study area, it was necessary to integrate pan-sharpening using an SRTM panchromatic image with a Landsat GeoCover 2000 mosaic. This Landsat GeoCover 2000 mosaic was in a geotiff format, ETM sensor and 2001

latest acquisition date, Datum WGS84, zone 22S. For the study area the orbits/points were 225/61.

The data fusion increased the quality of remote information to analyze, compare and correct eventual errors of the automatic stream surface parameters. The geomorphology was generate according Dantas & Teixeira (2013) relief units delimitation for Pará state, based on slope and topographic amplitude. The parameters of Ross (1992) were used to identify features of relief patterns, top and valley geometry.

To verify the automatic and manual results a fieldwork occurred in March 2017 when GPS control points were collected around the study area. Using relief and hydrological aspects after multi-sensor fusion it was possible to manually delimit the south and east limit of the Caxiuanã basin.

RESULTS AND DISCUSSION

The calculation of morphometric parameters for drainage and relief the Caxiuanã basin are expressed in 22 parameters (Table 1). The total basin area is 1,157 km², with 270 km of perimeter and 58 km of basin length.

Although sufficient data on local topographic conditions are not yet available, this river can be classified as being of lowland, where it becomes evident the existence of meanders mainly in its medium and low course. The density of the drainage is 1.18 km/km², which indicates low density (Strahler, 1960 apud Christofoletti, 1980). This result is associated with landform features, climate, vegetation, soil and rock characteristics (Kelson & Wells, 1989). The stream frequency of the whole basin is 0.60 stream number/km², and low values indicate a permeable sub-surface material and low relief (Reddy et al., 2004).

The compactness coefficient is 2.2 which indicates a low tendency to flood. This coefficient represents the ratio of the perimeter of the watershed to the circumference of the circular area, which equals the area of the watershed (Villela & Mattos, 1975). Floods tend to occur as the value approximates 1 (Cardoso et al., 2006).

Table 1. Morphometric parameters calculated for 22 parameters in the Caxiuanã River basin.

Morphometric parameters	Formula	Results	Units	Reference
Basin Geometry				
Basin area (A)	A	1,157	km²	Strahler (1957); Schumm (1956)
Basin length (Lb) Kms	Calculated from DEM data in GIS	58	km	Schumm (1956)
Basin perimeter	P	270	km	Schumm (1956)
Compactness coefficient (Cc)	$Cc = 0.28* P/\sqrt{A}$	2.2	Dimensionless	Villela & Mattos (1975)
Form factor (Ff)	$Ff = A/(Lb^2)$	0.34	Dimensionless	Horton (1945)
Elongation ratio (Er)	$Re = 2/Lb * (A / \pi) 0.5$	0.66	Dimensionless	Schumm (1956)
Sinuosity index (Si)	$Si = L/Lt$	1.2	Dimensionless	Schumm (2003)
Drainage network				
Stream order	Hierarchical rank	1 to 6	Dimensionless	Strahler (1964)
Stream number (Nu)	$Nu = N1 + N2 ...Nn$	696	Number	Horton (1945)
Stream length (Lu) km	$Lu = L1 + L2 + ...Ln$	1367	km	Das *et al*. (2012)
Mean Stream Length (Lsm)	$Lsm = Lu/Nu$	1.9	km	Strahler (1964)
Principal river lenght (L)	Calculated from DEM data in GIS	60	km	Strahler (1964)
Drainage texture analysis				
Drainage density (Dd)	$Dd = Lu/A$	1.18	km/km²	Christofoletti (1980); Beltrame (1994)
Stream frequency (Fs)	$Fs = Nu/A$	0.60	Stream number/km²	Horton (1945)
Relief characteristics				
Maximum height of the basin (*Z*) m	Calculated from DEM data in GIS	70	m	Pareta & Pareta (2012)
Height of basin mouth (z) m	Calculated from DEM data in GIS	10	m	Christofoletti (1980)
Contour interval (m)	Calculated from DEM data in GIS	10	m	Christofoletti (1980)
Total basin relief (R)	R=H-h (height of the mouth)	60	m	Strahler (1952)
Relief ratio (Rhl)	$Rhl = H / Lb$	1	Dimensionless	Schumm (1956)
Ruggedness number (Rn)	$Rn = H*Dd$	70	Dimensionless	Strahler (1964)
Gradient ratio (Rg)	$Rg = (Z - z) / Lb$	1	m/km	Sreedevi *et al*. (2005)
Slope analysis	Slope degree = Arctan (Rise/Run)	0°-3°	Grade	Christofoletti (1980)

The form factor according to Horton (1945) is the calculation of the ratio of the area of the basin and the square of the basin length. For the Caxiuanã basin it is 0.34 which corresponds to an elongated basin with a low probability of floods. Also, the elongation rate for the study area is 0.66, corresponding to an elongated basin. The latter was calculated as the ratio of the diameter of a circle of the same area as the basin to the maximum basin length (Schumm, 1956).

According Christofoletti (1980), when the canal, due to fluvial dynamics, presents curved lineage, with sinuosity indexes between 1.1 and 1.5, can be considered as sinuous. Practically, this category appears as transitional between that of the straight channels and that of the meanders, and as the curves become regular, frequent and of similar amplitude, the pattern distances itself from the rectilinear and approaches the meandric. The sinuosity index 1.2 indicates a river pattern of low sinuosity, as slightly meandering. That is an intermediary value from strait to sinuous river evolution. However Schumm (2003) argues that the division between meandering and straight channels is arbitrary, but the sinuosity index over 1.2 indicates tendency to meander of channel pattern.

As for the global flow of its waters, the basin of the Caxiuanã River can be classified as endorreic, since the fluvial flow is directed towards the Caxiuanã Bay. The drainage network analysis results in stream order classification up to sixth order (Figure 3A). The Caxiuanã River corresponds to the highest (sixth order) at middle and lower basin area, an up to fifth order at high basin source area.

The rivers in third and fourth order are mainly connects to the Caxiunã River and corresponds to flooded areas colonized by *igapó* vegetation (Figura 4A). These rivers have an average of 150m width and are permanent drainage with black water characteristics. The principal rivers are *igarapé* Curuá, Caxiunã, Puraquequara, Tijucaquara, Sapucuzinho, Ararua and Umarizal (Moraes, 2006).

In the study area there are several micro channels interconnections that in the map scale representation does not appear. According to Bridge (2003, p. 3) "objective definition of stream segments is difficult because identification of stream segments of the smallest order of magnitude is very much dependent on the map scale and on the discharge condition of the streams, when the map was constructed". So, all this interconnections creates a plain surface at the border of floodplain that are susceptible to flooding during rainy season. Besides that, the soil at the study area has an low capacity of infiltration and precipitation has an average of 2,452.9 mm annually (Piccinin & Ruivo, 2012; Barbosa *et al.*, 2015).

The expressive drainage of first and second order network do not always present a permanent drainage in the actual valley (Prost, 2012). Mainly of this both drainage order were extract by automatic relief runoff pattern. Therefore the water flux tend to drain in this direction in case of rainfall.

The geomorphological map displays the relief units: floodplain, dissected low plateau and low plateau (Figure 3B). The fist are low area delimitated by low topography contour lines and low slope (0°-1°). The floodplain comprises an area influenced by the penetration of the hydrographic network in the holocene sediments, where there is a gradual increase in the width of the alluvial plain, which comprises the fluvial valley strip composed of alluvial sediments bordering the water courses and seasonally flooded in the period floods. This is the area with lower altitudes, 10-30 m, and with soft slopes (< 3°). However at the border of floodplain areas is possible to observe values up to 3° corresponding to the marginal alluvial dikes. The dissected low plateaus have low slope (0°-2°) and topographic amplitude varying from 30 up to 50 m. The low plateaus have a topographic amplitude over 51 m.

The northeast drainage that flow direct to Caxiuanã bay have the *várzea* environment and should be grouped in a different sub basin (Figure 4B). The *várzea* are flooded periodically by white and muddy waters and the vegetation grow over a clay soil (Ferreira, L. V. *et al.*, 2012).

There are 696 streams with a total stream length of 1,367 km and a mean stream length of 1.9 km. However the first and second order sum of the length are 1,029 km and permanent rivers from third, fourth and five order are 278 in total.
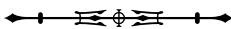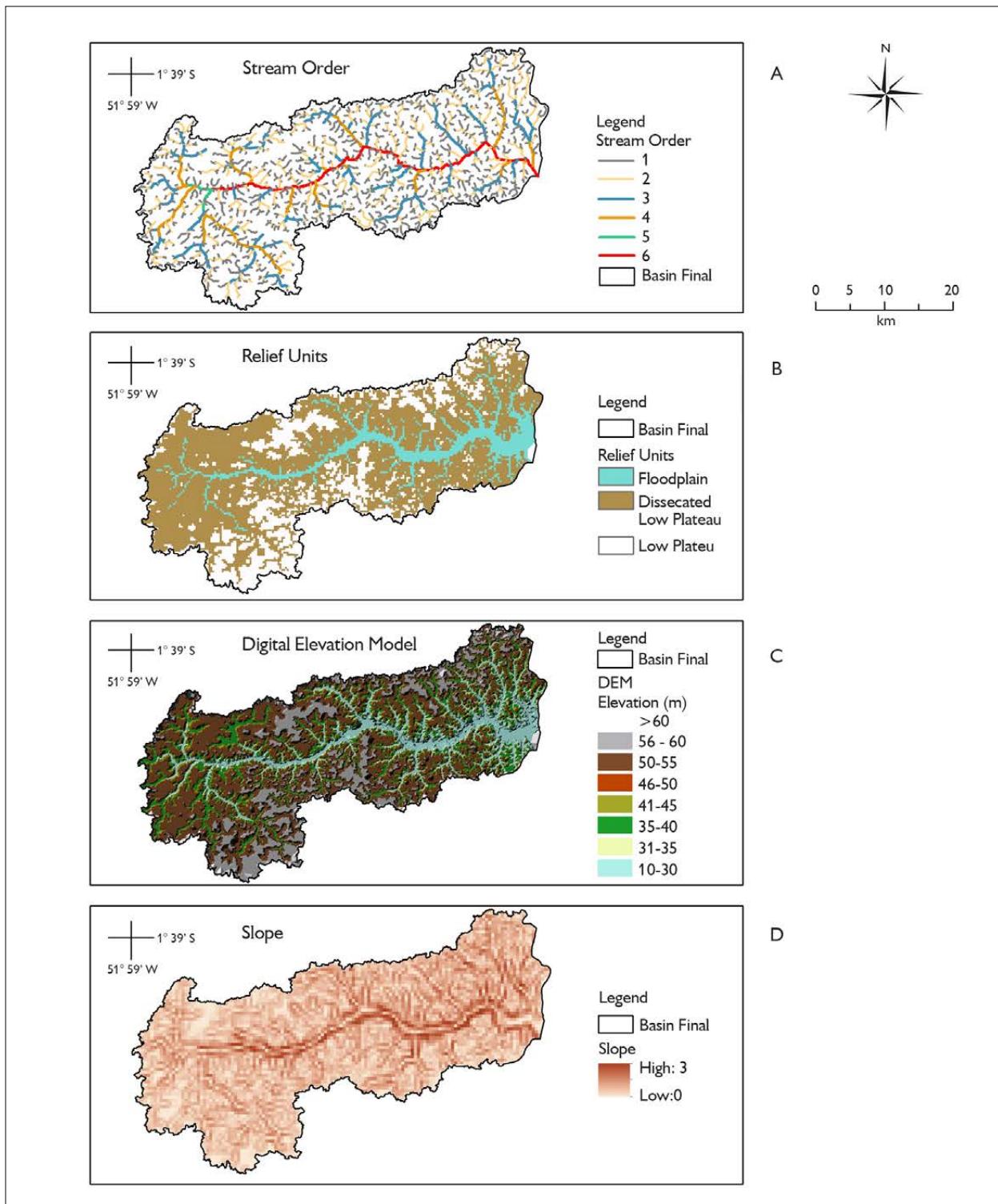
Figure 3. Maps of the Caxiuanã river basin related to stream order (A), relief units (B) elevation (C), and slope (D). Maps: Milena Andrade.

The stream length designates the total length of the stream network of each of the consecutive orders in a basin; it relates to a measure of the hydrological characteristics of the bedrock and the drainage extent (Horton, 1945). The length of stream segments is maximum for first order and decreases as the order increases. The principal river is the Caxiuanã which has a length of 60 km.

The drainage texture analysis indicates a dendritic to sub-dendritic pattern that is mainly developed over the sedimentary rocks of the Alter-do-Chão Formation and alluvial deposits.

It should be noted that river diversions are common and are caused by changes in local valleys gradients associated for example, with tectonism, deposition and erosion processes (Schumm *et al.*, 2000). According to Miall (1996) many rivers flow either parallel or transverse to the structural grain of the landscape. In this context, it is possible to observe specific stretches displaying a rectangular pattern under tectonic orientation NW-SE, as a secondary pattern. According to Costa *et al.* (1996) this orientation together with E-W and NE-SW are the main tectonic and geomorphological aspect of Amazon basin expressed in the drainage pattern network. Also the formation of Caxiuanã bay is related to middle/late Holocene period during a fault reactivation along NNW-SSE orientated strike slip zone which ultimately led to the enlargement of the river paleovalley (Rossetti & Valeriano, 2007).
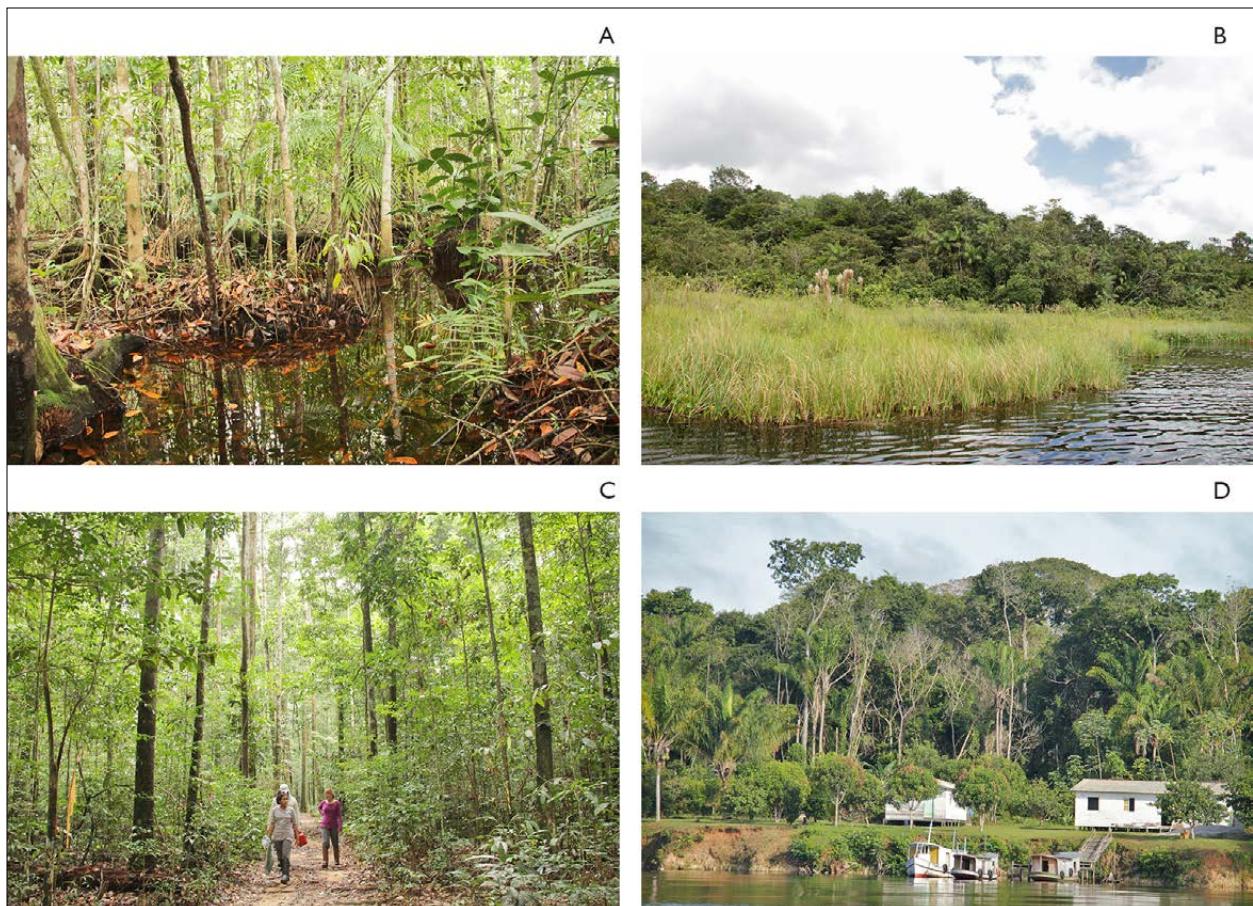
Figure 4. Environmental aspects of the study area: A) flooded plain areas colonized by *igapó* vegetation in rivers of low order; B) aquatic vegetation in *várzea* area at Caxiuanã bay; C) inland landscape; D) scarp border with 3° of slope at Caxiuanã river margin. Photos: Milena Andrade.

The relief characterization includes 70 m for the maximum height of the basin and 10 m for the lowest value, which corresponds to the elevation at the basin mouth (Figure 3C). The total basin relief is 60 m. Higher values corresponds to inland landscape and according to Prost (2012) are described as low plateaus (Figure 4C).

The relief ratio for the study area is 1. It is the difference in elevation between the highest point and lowest point of a watershed and the longest dimension of the basin parallel to the principal drainage line according to Strahler (1952). The gradient ratio is 1 and the slope varies between 1° and 3°; higher slopes are at the border of inland areas (Figures 3D and 4D). The Caxiuanã basin ruggedness number is 70. This number is the product of the basin relief and the drainage density and usefully combines slope steepness with its length (Strahler, 1964).

CONCLUSIONS

The proposal to subsidize the obtaining of morphometric data through remote sensing products (such as LANDSAT and SRTM images) and geoprocessing software demonstrate the feasibility and practicality of the use of geotechnologies in the automatic obtaining of such data and values for a later qualitative, analytical and comparative analysis.

The multi-sensor fusion approach facilitates analysis of the basin delimitation and the confirmation of different morphometric parameters based on the stream. The 22 morphometric parameters of the Caxiuanã basin reveal that lower order streams dominate this region. The sixth order river corresponds to the Caxiuanã that runs into Caxiuanã Bay, characterizing an endorheic basin. The elongation form, the form factor and low compactness coefficient calculation indicate a low tendency to flood. Although, the area does have low influence of dynamic tide and water level variation.

The drainage density was considered low, indicating a low relation between the length of and the area of the basin, which indicates an efficient flow of water and good infiltration into the water table, that is, a lower propensity to flood.

The Caxiuanã river basin has indication of structural control due the abrupt 90° curves along the river that indicate previous tectonic movement. And the Caxiuanã River has a pattern of low meandering stream according to sinuosity index what indicate and intermediary pattern between straight and meandering. The relief is higher to the north and southeast in the basin area and the slope is mainly low. It was possible to differentiate the floodplain areas from low plateaus according to the topography and slope.

ACKNOWLEDGMENTS

REFERENCES

ALVARES, C. A., J. L. STAPE, P. C. SENTELHAS, J. L. M. GONÇALVES & G. SPAROVEK, 2014. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift** 22(6): 711-728. DOI: https://doi.org/10.1127/0941-2948/2013/0507.

BARBOSA, P. H. D., A. C. L. COSTA, A. C. CUNHA & J. A. SILVA JUNIOR, 2015. Variabilidade de elementos meteorológicos e de conforto térmico em diferentes ambientes na Amazônia brasileira. **Revista Brasileira de Climatologia** 11(17): 98-118. DOI: http://dx.doi.org/10.5380/abclima.v17i0.43048.

BEHLING, H. & M. L. COSTA, 2000. Holocene environmental changes from the Rio Curuá record in the Caxiuanã Region, Eastern Amazon Basin. **Quartenary Research** 53(3): 369-377. DOI: https://doi.org/10.1006/qres.1999.2117.

BELTRAME, A. V., 1994. **Diagnóstico do meio físico de bacias hidrográficas**: modelo e aplicação. EdUFSC, Florianópolis.

BERREDO, J. F., D. M. B. MELO, M. M. RIBEIRO, A. C. MIGIYAMA & M. E. SALES, 2012. Hidrografia da Floresta Nacional de Caxiuanã. In: INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE (Ed.): **Plano de Manejo da Floresta Nacional de Caxiuanã**: 128-132. ICMBio, Brasília.

BISWASS, A., D. D. MAJUMDAR & S. BANERJEE, 2014. Morphometry governs the dynamics of a drainage basin: analysis and implications. **Geography Journal** 2014: Article ID 927176. DOI: http://dx.doi.org/10.1155/2014/927176.

BRIDGE, J. S., 2003. **Rivers and floodplain**: forms, processes and sedimentar records. Blackwell Publishing, Cornwall.

CARDOSO, C. A., H. C. T. DIAS, C. P. B. SOARES & M. S. VENÂNCIO, 2006. Caracterização morfométrica da bacia hidrográfica do rio Debossan, Nova Friburgo, RJ. **Revista Árvore** 30(2): 241-248. DOI: http://dx.doi.org/10.1590/S0100-67622006000200011.

CHRISTOFOLETTI, A., 1980. **Geomorfologia**. Blucher, São Paulo.

COMPANHIA DE PESQUISA E RECURSOS MINERAIS (CPRM), 2010. **Mapa geológico do estado do Pará**. Disponível: http://www.cprm.gov.br/publique/Geologia/Geologia-Basica/Cartografia-Geologica-Regional-624.html. Acesso em: 1 maio 2016.

COSTA, J. B. S., R. L. BERMEGUY, Y. HASUI, M. S. BORGES, C. R. P. FERREIRA JR., P. E. L. BEZERRA, M. L. COSTA & J. M. G. FERNANDES, 1996. Neotectônica da região amazônica-aspectos tectônicos, geomorfológicos e deposicionais. **Geonomos** 4(2): 23-44.

DANTAS, M. & S. TEIXEIRA, 2013. Origem das paisagens. In: X. S. J. JOÃO, S. G. TEIXEIRA & D. D. F. FONSECA (Org.): **Geodiversidade do estado do Pará**: 23-52. CPRM, Belém.

DAS, A., M. MONDAL, B. DAS & A. R. GHOSH, 2012. Analysis of drainage morphometry and watershed prioritization in Bandu Watershed, Purulia, West Bengal through remote sensing and GIS technology – a case study. **International Journal of Geomatics and Geosciences** 2(4): 995-1013.

FELIPPE, M. F., C. A. SILVA, A. H. SOUZA & A. P. M. JUNIOR, 2012. Caracterização morfométrica dos compartimentos do relevo do Parque Nacional da Serra do Cipó, Serra do Espinhaço Meridional – Minas Gerais. **Revista Espinhaço** 1(1): 3-14.

FERREIRA, L. S., J. H. CATTÂNIO & M. A. JARDIM, 2015. Efeito da topografia e da precipitação na florística e na produção de liteira em Caxiuanã, Pará. **Revista Árvore** 39(6): 995-1005. DOI: http://dx.doi.org/10.1590/0100-67622015000600002.

FERREIRA, L. V., S. S. ALMEIDA, D. D. AMARAL & P. PAROLI, 2005. Riqueza e composição de espécies da floresta de igapó e várzea da Estação Científica Ferreira Penna: subsídio para o plano de manejo da Floresta Nacional de Caxiuanã. **Pesquisas, Botânicas** (56): 103-116.

FERREIRA, L. V., A. S. L. SILVA & S. S. ALMEIDA, 2012. Diagnóstico da vegetação da Floresta Nacional de Caxiuanã. In: INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE (ICMBio): **Plano de Manejo da Floresta Nacional de Caxiuanã**: Anexo 6, 1-6. ICMBio, Brasília.

FRANCO, A. C. V. & M. A. DAL SANTO, 2015. Contribuição da morfometria para o estudo das inundações na sub-bacia do rio Luis Alves/SC. **Mercator** 14(3): 151-167. DOI: http://dx.doi.org/10.4215/RM2015.1403.0009.

GOERL, R. F., M. KOBIYAMA & I. SANTOS, 2012. Hidrogeomorfologia: princípios, conceitos, processos e aplicações. **Revista Brasileira de Geomorfologia** 13(2): 103-111. DOI: http://dx.doi.org/10.20502/rbg.v13i2.166.

HORTON, R. E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. **Geological Society of American Bulletin** 56(3): 275-370. DOI: https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE), 2015. **Bases cartográficas contínuas de hidrografia**. Disponível em: http://downloads.ibge.gov.br/downloads_geociencias.htm. Acesso em: 1 maio 2017.

INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE (ICMBio), 2012. **Plano de Manejo da Floresta Nacional de Caxiuanã – PA**: volume de diagnóstico. Disponível em: http://www.icmbio.gov.br/portal/biodiversidade/unidades-de-conservacao/biomas-brasileiros/amazonia/unidades-de-conservacao-amazonia/1928-flona-de-caxiuana.html. Acesso em: 1 junho 2017.

JOÃO, X. S. J., 2013. Arcabouço geológico-tectônico e implicações metalogenéticas. In: X. S. J. JOÃO, S. G. TEIXEIRA & D. D. F. FONSECA (Org.): **Geodiversidade do estado do Pará**: 15-22. CPRM, Belém.

KALIRAJ, S., N. CHANDRASEKAR & N. S. MAGESH, 2015. Morphometric analysis of the River Thamirabarani sub-basin in Kanyakumari District, South West coast of Tamil Nadu, India, using remote sensing and GIS. **Environmental Earth Sciences** 73(11): 7375-7401. DOI: https://doi.org/10.1007/s12665-014-3914-1.

KELSON, K. I. & S. G. WELLS, 1989. Geologic influences on fluvial hydrology and bedload transport in small mountainous watersheds, northern New Mexico, USA. **Earth Surface Processes and Landforms** 14(8): 671-690. DOI: https://doi.org/10.1002/esp.3290140803.

LATRUBESSE, E. M., 2008. Patterns of anabranching channels: the ultimate end-member adjustment of mega rivers. **Geomorphology** 101(1-2): 130-145. DOI: https://doi.org/10.1016/j.geomorph.2008.05.035.

LEWIS, A. J., F. M. HENDERSON & D. W. HOLCOMB, 1998. Radar fundamentals: the geosciences perspective. In: F. HENDERSON & A. LEWIS (Ed.): **Principles & applications of imaging radar, manual of remote sensing**: 132-181. John Willey, New York.

LISBOA, P. L. B., 1997. **Caxiuanã**. Museu Paraense Emílio Goeldi, Belém.

MAGESH, N. S. & N. CHANDRASEKAR, 2014. GIS model-based morphometric evaluation of Tamiraparani subbasin, Tirunelveli district, Tamil Nadu, India. **Arabian Journal of Geoscience** 7(1): 131-141. DOI: https://doi.org/10.1007/s12517-012-0742-z.
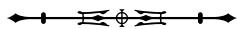
MANTELLI, L. R. & D. F. ROSSETTI, 2009. Significado tectônico de lineamentos de drenagem no sudoeste da ilha do Marajó. **Revista Brasileira de Geociências** 39(1): 2-13.

MARQUES NETO, R. M., F. S. GONÇALVES, R. M. CONCEIÇÃO, F. S. FERNANDES, J. R. M. VIEIRA & N. G. SIMAS, 2008. Morfometria do relevo na bacia do rio da Cachoeira no contexto do plano de manejo da Floresta Nacional de Passa Quatro (MG). **Raega** (16): 119-128. DOI: http://dx.doi.org/10.5380/raega.v16i0.10442.

MIALL, A. D., 1996. **The geology of fluvial deposits**. Springer-Velag, New York.

MORAES, E. N. R., 2006. **Diversidade, aspectos florísticos e ecológicos dos musgos (Bryophyta) da Estação Científica Ferreira Penna, FLONA de Caxiuanã, Pará, Brasil**. Dissertação (Mestrado em Botânica) - UFRA/MPEG, Belém.

OLIVEIRA, L. L., R. F. COSTA, F. A. S. SOUSA, A. C. L. COSTA & A. P. BRAGA, 2008. Precipitação efetiva e interceptação em Caxiuanã, na Amazônia Oriental. **Acta Amazonica** 38(4): 723-732. DOI: http://dx.doi.org/10.1590/S0044-59672008000400016.

PARETA, K. & U. PARETA, 2012. Quantitative geomorphological analysis of a watershed of Ravi River Basin, H. P. India. **International Journal of Remote Sensing and GIS** 1(1): 41-56.

PICCININ, J. & M. L. RUIVO, 2012. Os solos da Floresta Nacional de Caxiuanã. In: INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE (ICMBio). **Plano de Manejo da Floresta Nacional de Caxiuanã**: 120-127. ICMBio, Brasília.

PINHEIRO, M. N. M., 2015. Morfologia e morfometria de lagos e sua influência nas macrófitas aquáticas em Roraima, Brasil. In: I. C. G. VIEIRA, M. A. G. JARDIM & E. J. P. ROCHA (Ed.): **Amazônia em tempo**: estudos climáticos e socioambientais: 379-392. UFPA/MPEG/EMBRAPA (Série Amazônia em Tempo), Belém.

POHL, C. & L. GENDEREN, 1998. Review article multisensor image fusion in remote sensing: concepts, methods and applications. **International Journal of Remote Sensing** 19(5): 823-854. DOI: https://doi.org/10.1080/014311698215748.

PROST, M. T., 2012. Caracterização dos fatores abióticos: geomorfologia. In: INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE (Ed.). **Plano de Manejo da Floresta Nacional de Caxiuanã**: Anexo 4. ICMBio, Brasília.

RAI, P. K., K. MOHAN, S. MISHRA, A. AHMAD & V. N. MISHRA, 2017. A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. **Applied Water Science** 7(1): 217-232. DOI: https://doi.org/10.1007/s13201-014-0238-y.

REDDY, O. G. P., A. K. MAJI & S. K. GAJBHIYE, 2004. Drainage morphometry and its influence on landform characteristics in a basaltic terrain, Central India – a remote sensing and GIS approach. **International Journal of Applied Earth Observation and Geoinformation** 6(1): 1-16. DOI: https://doi.org/10.1016/j.jag.2004.06.003.

RODRIGUES, H. J. B., L. D. A. SÁ, L. P. RUIVO, A. C. L. COSTA, R. B. SILVA, Q. L. MOURA & I. F. MELLO, 2011. Variabilidade quantitativa de população microbiana associada às condições microclimáticas observadas em solo de floresta tropical úmida. **Revista Brasileira de Meteorologia** 26(4): 629-638. DOI: http://dx.doi.org/10.1590/S0102-77862011000400012.

ROSS, J. L. S., 1992. O registro cartográfico dos fatos geomórficos e a questão da taxonomia do relevo. **Revista do Departamento de Geografia** 6: 17-29. DOI: https://doi.org/10.7154/RDG.1992.0006.0002.

ROSSETTI, D. F. & M. M. VALERIANO, 2007. Evolution of the lowest amazon basin modeled from the integration of geological and SRTM topographic data. **CATENA** 70(2): 253-265. DOI: https://doi.org/10.1016/j.catena.2006.08.009.

SANTOS, C. A. & F. G. SOBREIRA, 2008. Análise morfométrica como subsídio ao zoneamento territorial: o caso das bacias do Córrego Carioca, Córrego do Bação e Ribeirão Carioca na região do Alto Rio das Velhas-MG. **REM: Revista Escola de Minas** 61(1): 77-85. DOI: http://dx.doi.org/10.1590/S0370-44672008000100013.

SCHUMM, S. A., 1956. Evolution of drainage systems and slopes in bad lands at Perth Amboy, New Jersey. **Geological Society of America Bulletin** 67(5): 597-646. DOI: https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2.

SCHUMM, S. A., J. F. DUMONT & J. M. HOLBROOK, 2000. **Active tectonics and alluvial rivers**. Cambridge University Press, Cambridge.

SCHUMM, S. A., 2003. **The fluvial system**: 1-332. The Blackburn Press, New Jersey.

SREEDEVI, P. D., K. SUBRAHMANYAM & A. SHAKEEL, 2005. The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. **Environmentl Geology** 47(3): 412-420. DOI: https://doi.org/10.1007/s00254-004-1166-1.

STRAHLER, A. N., 1952. Hypsometric (area-altitude) analysis of erosional topography. **Geological Society of America Bulletin** 63(11): 1117-1142. DOI: https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2.

STRAHLER, A. N., 1957. Quantitative analysis of watershed geomorphology. **Transactions of American Geophysics Union** 38(6): 913-920. DOI: https://doi.org/10.1029/TR038i006p00913.

STRAHLER, A. N., 1964. Quantitative geomorphology of drainage basin and channel network. In: V. CHOW (Ed.): **Handbook of applied hydrology**: 439-476. McGraw Hill, New York.

TEIXEIRA, S. & M. DANTAS, 2013. Origem das paisagens. In: X. S. J. JOÃO, S. G. TEIXEIRA & D. D. F. FONSECA (Org.): **Geodiversidade do estado do Pará**: 23-52. CPRM, Belém.

TEODORO, V. L. I., D. TEIXEIRA, D. J. L. COSTA & B. B. FULLER, 2007. O conceito de bacia hidrográfica e a importância da caracterização morfométrica para o entendimento da dinâmica ambiental local. **Revista Uniara** (20): 137-156.

VALERIANO, M. M. & O. A. CARVALHO JÚNIOR, 2003. Geoprocessamento de modelos digitais de elevação para mapeamento da curvatura horizontal em microbacias. **Revista Brasileira de Geomorfologia** 4(1): 17-29. DOI: http://dx.doi.org/10.20502/rbg.v4i1.17.

VALERIANO, M. M. & D. F. ROSSETTI, 2008. Topographic modeling of Marajó island with SRTM data. **Revista Brasileira de Geomorfologia** 9(1): 53-64. DOI: http://dx.doi.org/10.20502/rbg.v9i1.101.

VILLELA, S. M. & A. MATTOS, 1975. **Hidrologia aplicada**. Mc Graw Hill, São Paulo.