COMPARISON BETWEEN HYDROGRAPHICALLY CONDITIONED DIGITAL ELEVATION MODELS IN THE MORPHOMETRIC CHARATERIZATION OF WATERSHEDS

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ABSTRACT: The aim of this study was to compare the hydrographically conditioned digital elevation models (HCDEMs) generated from data of VNIR (Visible Near Infrared) sensor of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), of SRTM (Shuttle Radar Topography Mission) and topographical maps from IBGE in a scale of 1:50,000, processed in the Geographical Information System (GIS), aiming the morphometric characterization of watersheds. It was taken as basis the Sub-basin of São Bartolomeu River, obtaining morphometric characteristics from HCDEMs. Root Mean Square Error (RMSE) and cross validation were the statistics indexes used to evaluate the quality of HCDEMs. The percentage differences in the morphometric parameters obtained from these three different data sets were less than 10%, except for the mean slope (21%). In general, it was observed a good agreement between HCDEMs generated from remote sensing data and IBGE maps. The result of HCDEM ASTER was slightly higher than that from HCDEM SRTM. The HCDEM ASTER was more accurate than the HCDEM SRTM in basins with high altitudes and rugged terrain, by presenting frequency altimetry nearest to HCDEM IBGE, considered standard in this study.

KEY WORDS: digital elevation models, water resources, remote sensing, morphometry.

COMPARAÇÃO DE MODELOS DIGITAIS DE ELEVAÇÃO HIDROGRAFICAMENTE CONDICIONADOS NA CARACTERIZAÇÃO MORFOMÉTRICA DE BACIAS HIDROGRÁFICAS

RESUMO: O objetivo deste estudo foi comparar modelos digitais de elevação hidrograficamente condicionados (MDEHCs), gerados a partir de dados do sensor VNIR (Visible Near Infrared) do ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), da SRTM (Shuttle Radar Topography Mission) e de cartas topográficas do IBGE na escala 1:50.000, processados em Sistema de Informações Geográficas (SIG), visando à caracterização morfométrica de bacias hidrográficas. A área de estudo selecionada foi a sub-bacia hidrográfica do Ribeirão São Bartolomeu, sendo obtidas as características morfométricas a partir dos MDEHCs. Aplicaram-se o índice estatístico Raiz do Erro Médio Quadrático (REMQ) e a validação cruzada para avaliar a qualidade dos MDEHCs. A diferença percentual obtida nos dados morfométricos entre os modelos estudados foi inferior a 10%, exceto para a declividade média, que foi de 21%. De maneira geral, verificou-se boa concordância entre os MDEHCs gerados por dados de sensoriamento remoto e pelas cartas do IBGE. O MDEHC ASTER foi ligeiramente mais preciso que o MDEHC SRTM em bacias com elevadas altitudes e relevo acidentado, por apresentar frequências altimétricas mais próximas do MDEHC IBGE, considerado padrão neste estudo.

PALAVRAS-CHAVE: modelos digitais de elevação, recursos hídricos, sensoriamento remoto, morfometria.

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INTRODUCTION

The analysis of morphometric characteristics and of drainage network in a watershed is essential in the development of hydrological studies, being an area of great interest from researchers (MENDONÇA et al., 2007; KLINGSEISEN et al., 2008; BISPO et al., 2009; OLIVEIRA et al., 2010). According to MENDONÇA et al. (2007), biotic and physical characteristics of a watershed play an important role in the processes of the hydrological cycle, influencing, among others, infiltration, superficial and subsurface flow and evapotranspiration.

The morphometric characterization of river basins can be done manually or through integration of information of relief in environment of Geographic Information System (GIS). The automatic procedure is faster and less subjective, as it provides much more information than manual techniques (VALERIANO et al., 2006; MENDONÇA et al., 2007).

The relief information may be represented by a numerical structure of data corresponding to the spatial distribution of altitude and ground surface, called a digital elevation model (DEM). According to VALERIANO et al. (2006), the use of DEM in GIS has advantages, such as digital resources (speed, reliability and integration with other databases), reducing manual intervention and, thus, reducing subjectivity and the possibility of parametric representation. So, the DEMs have been used in studies of water resources, as in the design of drainage networks, watershed boundaries, calculation of slope, verifying the superficial flow and as part of hydrologic models (KLINGSEISEN et al., 2008; RIBEIRO et al., 2008; VAZE et al., 2010).

However, it is worth noting that, for the characterization of the drainage in basins, the altimetric models of the terrain should be conditioned hydrographically (HCDEM), allowing the outlines of the basins to be performed with greater precision, since they consider the land altimetry data in its processing steps, and, unlike the DEMs, they present a marked coincidence between the numerically derived drainage and the real hydrography, being exempt from sinks (spurious depressions) that block the path of superficial flow (MACHADO et al., 2010).

Demand for DEMs to support studies in the area of environmental management has increased significantly; however, there is not in Brazil a body responsible for standardization of the procedures used in creating these models, which are normally produced by the users (CHAGAS et al., 2010).

The most common data source for the generation of DEMs in Brazil is the contours and, complementarily, the river system and the elevation points obtained in topographic maps, especially those elaborated by the Brazilian Institute of Geography and Statistics (IBGE). However, the scales normally available are not suitable for more detailed studies, especially when dealing with watersheds. For this reason, data from remote sensing images are being increasingly used to generate HCDEMs, in order to overcome this deficiency.

According to CHAGAS et al. (2010), the traditional method of assessing the quality of a HCDEM is confronting a sample of points of elevation of HCDEM produced against known elevation points, from a more accurate source of data. The degree of agreement between these HCDEMs is analyzed by the root mean square error (RMSE). Despite being much debated in the literature (HOLMES et al., 2000; WISE, 2000), this approach has been used to compare the quality of HCDEMs produced from different sources and interpolation methods.

Based on this background, this study aimed to compare hydrographically conditioned digital elevation models generated from sensor data VNIR (Visible and Near Infrared) of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), of SRTM (Shuttle Radar Topography Mission) and of IBGE topographical maps at a 1:50,000 scale, with the aim of morphometric characterization of the sub-basin of the São Bartolomeu river, in Viçosa, state of Minas Gerais (MG).

MATERIAL AND METHODS

The survey was conducted using as a base the sub-basin of the São Bartolomeu river, located in the Zona da Mata Mineira, specifically in Viçosa-MG, and inserted in the watershed of the Doce River, between parallels 20º44' and 20º50' south latitude, and meridians 42º51' and 42º53' longitude west of Greenwich (Figure 1).

The sub-basin is formed by São Bartolomeu, Santa Catarina, Engenho, Posse, Araújo and Palmital rivers, showing drainage area of 55.1 km^2, representing approximately 18.4% of the surface of Viçosa city. It shows areas of high altitude and rugged terrain.

Processing of data obtained from topographic maps

It was used the vectorized topographic maps of Teixeiras (SF-23-X-B-V-1) and Viçosa (SF-23-X-B-V-3) at scale 1:50,000, available at IBGE website (http://www.ibge.gov.br) for the individualization of the sub-basin of the São Bartolomeu river.

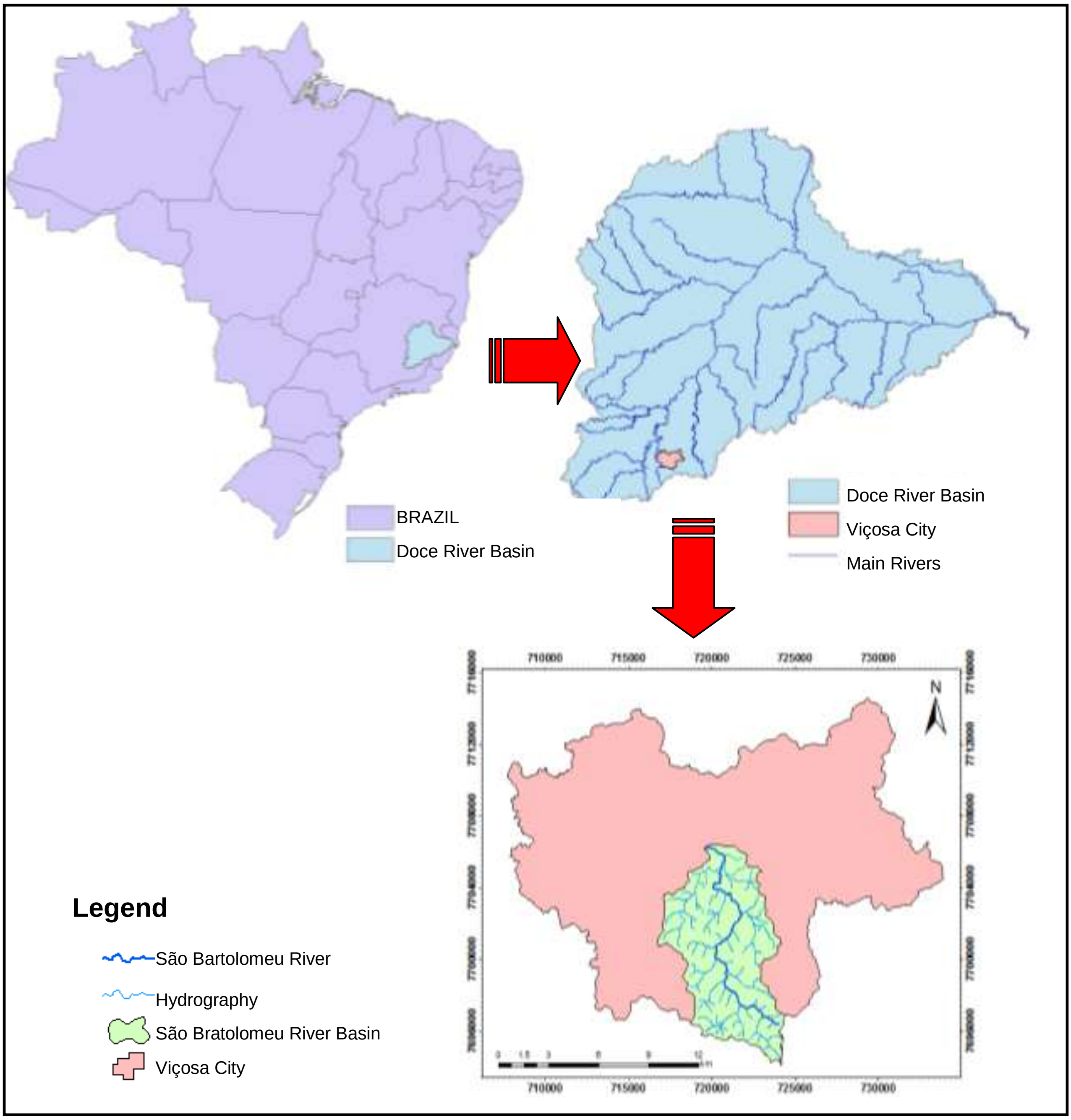

FIGURE 1. Location of the São Bartolomeu river basin in the Doce river basin, State of Minas Gerais, Brazil.

The georeferencing of letters was made in module ArcMap®, of 10® ArcGIS software (ESRI, 2010), taking as a basis the projected coordinates UTM (Universal Transverse Mercator), Zone 23 South, reference Datum of SAD 69 (South American Datum) and horizontal units in meters. An analysis of visual contours vector and, when necessary, corrections were made inconsistencies adjusting them to hydrography directed to superficial flow, with all arcs connected. The interpolator used in the study was the "Top to Raster".

As the level curves were obtained based on a map with a scale of 1:50,000, the DEM was generated with a spatial resolution of 10 meters. In this case, it was considered the graphic error for the human vision of 0.2 mm (MENDONÇA et al., 2007). The cell size was obtained by multiplying the graphic error value by the scale factor.

The DEM was considered hydrographically conditioned after consistency analysis, which compared the numerical and mapped hydrography. Then, the sub-basin was delimited automatically. In this study, the morphometric characteristics derived from the HCDEM obtained from topographic maps were considered standard, since, in Brazil, the official geodatabase is from the IBGE (CHAGAS et al., 2010).

SRTM and ASTER data processing

It was used data from the missions SRTM (Shuttle Radar Topography Mission) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) to obtain the DEMs from remote sensors. The SRTM DEM is available for free on the platform “Brasil em Relevo”, of the Brazilian Agricultural Research Corporation, in the electronic address <http://www.relevobr.cnpm.embrapa.br>. The scene obtained for the study, with a spatial resolution of 90 meters and WGS84 ellipsoid reference, was the SF-23-X-B. The ASTER DEM is also available for free from ASTER GDEM platform, the electronic address <http://www.gdem.aster.ersdac.or.jp/index.jsp>. The scene obtained for the study, with a spatial resolution of 30 meters and WGS84 ellipsoid reference, was ASTGTM_S21_W043_dem. The methodology used for the processing of DEMs from SRTM and ASTER platforms is shown in Figure 2.

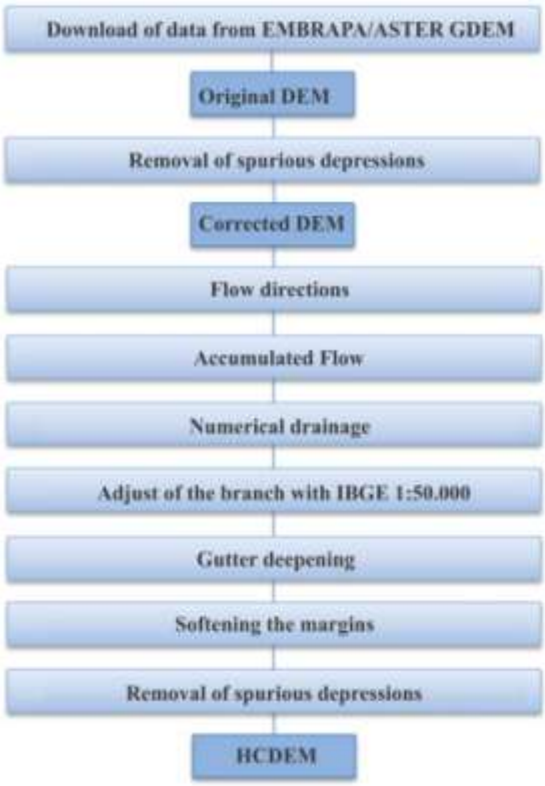

FIGURE 2. Flowchart for generation of HCDEMs ASTER/SRTM.

The DEMs accompanying the remote sensing data contain gaps in areas of the globe, caused mainly by the presence of bodies of water, rugged relief and the presence of clouds in images (LUEDELING et al., 2007). The flaws in the models coming from remote data are called "Sinks" or false depressions, areas surrounded by elevations with higher values. The false depressions represent a major problem in the generation of models for predicting the flow, and they must be removed to generate consistent DEM from the hydrological point of view (ALVES SOBRINHO et al., 2010). In ArcGIS 10® software, the specific function to remove these depressions is called "Fill". Then, it was determined the direction of flow through the function "Flow Direction". According to RENNÓ et al. (2008), the direction of flow defines hydrological relations between different points within a watershed. The topological continuity to the flow directions is necessary for a functional drainage to exist.

The cumulative flow was obtained by using the function "Flow Accumulation", using the previously determined direction of flow, and indicates the degree of confluence of flow, and it may be associated with the ramp length factor applied in two dimensions.

In the following, the numerical drainage was determined, i.e., the accumulated flow pattern and the potential location of rivers mesh. The methodology used to generate the numerical drainage, with a level of detail similar to mapped drainage (set of branching with IBGE), was obtained by iteration, as requested by CHAGAS et al. (2010). In this study, the numerical drainage for the SRTM and ASTER DEMs, compatible with the scale of 1:50,000 of IBGE, was determined with the initial accumulation of 10 to 100 cells (numeric drainage branching), respectively.

Then, a series of equations was used in "Raster Calculator" software in order to treat the DEM and generate the HCDEM (Table 1).

TABLE 1.Operations used with "Raster Calculator" function of ArcGIS 10® software.

Conditioning	Operations at matrix calculator
Gutter deepening	hidro_afin = thin([hidro]) hidro_1000 = ([hidro_afin] * 1000) m1 = [mde_fill] - [hidro_1000] m2 = fill([m1]) diresc_reb = flow direction([m2]) escacum_reb = flow accumulation([diresc_reb]) hidro_reb (ASTER) = con([escacum_reb] >= 100, 1) hidro_reb (SRTM) = con([escacum_reb] >= 10, 1) m3 = con(isnull([hidro_reb]), [mde_fill], [m2])
Softening the margins	zhr2 = [mde_fill] * Float([hidro_reb]) dif = [zhr2] - [m3] ms = int(con(isnull([hidro_reb]), [mde_fill], [m3] + [dif] - 10))
HCDEM	mdehc = fill([ms])

Armed with the SRTM and ASTER HCDEMs, we automatically defined, via the function "Watershed", the Sub-basin of São Bartolomeu River which was later converted to vector format, using the function "Raster to Features" of Spatial Analyst extension. In this format, it was determined the area and perimeter of the basin in the three considered HCDEMs.

Assessing the quality of HCDEMs

According to CHAGAS et al. (2010), the evaluation of the accuracy of HCDEMs generated from different databases may be accomplished by simple visual recognition, cross-validation based on neighborhood relations, overlapping of contours and/or drainage network, by statistical comparison with control points, analyzing the inexistence of systematic errors and the presence of random errors. Thus, considering the elevation points chosen at random from the IBGE topographic maps and mapped drainage network, it was decided by the crossover and statistical analyzes, detailed below.

The crossover analysis was performed comparing the numerical drainage network of the HCDEMs evaluated with the mapped drainage network of IBGE, aiming to visually assess the level of coincidence by overlapping cells.

Statistical analysis obtained values derived from the difference between the elevation of HCDEMs and use of 80 randomly selected points of elevation in topographic map of IBGE, enrolled in the study as ground truth. It was used as statistical index of mean, minimum and maximum values the standard deviation and root mean square error (RMSE) (eq.(1)):

$$REMQ = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \qquad (1)$$

In which, d is the elevation difference between the HCDEMs evaluated and the rated points, and n is the number of elevation points tested.

Morphometric characteristics of the watershed

With the information of matrix and vector of HCDEMs from IBGE, SRTM and ASTER, it was possible to determine and compare the results of the following morphometric characteristics: drainage area (A), perimeter (P), total length of waterways (Lt); length of main river (Lp); compactness coefficient (Kc); form factor (Kf); drainage density (Dd); mean slope (Im); and altitude (Hm) (BAENA et al., 2004).

RESULTS AND DISCUSSION

The treatment accomplished in DEMs of IBGE, SRTM and ASTER assured hydrologic consistency, resulting in models with no spurious depressions and compatible numerical hydrography with mapped hydrography at 1:50,000 scale of IBGE, as shown in Figure 3.

It is observed in Figure 3 that the overlapping of cells in hydrography in HCDEM IBGE is more constant compared visually with others HCDEMs studied. This allows us to say that hydrographic conditioning is better achieved in HCDEM IBGE, making it the parameter in the morphometric study of the sub-basin of the São Bartolomeu River. It was also verify that the numerical hydrographic coming from the HCDEM ASTER better represented the mapped hydrography when compared to SRTM HCDEM, due to better overlap of cells, visually observed in the models. On the other hand, the automatic delineation of the drainage network reached by ALVES SOBRINHO et al. (2010) showed satisfactory results from the hydrological point of view, from SRTM data, compatible with the drainage obtained in topographic maps.

Figure 4 shows the HCDEMs generated for the sub-basin of the São Bartolomeu River and the histogram of elevation between them. It was observed small differences in HCDEMs generated, particularly as regards the shape of the sub-basin of the study. The most significant differences were found in values of elevation of the models (Figures 4a, 4b and 4c).

According to the elevations histogram shown (Figure 4d), the HCDEM ASTER overestimated the frequency of altimetric cells between 600 m and 650 m, when compared to HCDEMs IBGE and SRTM.

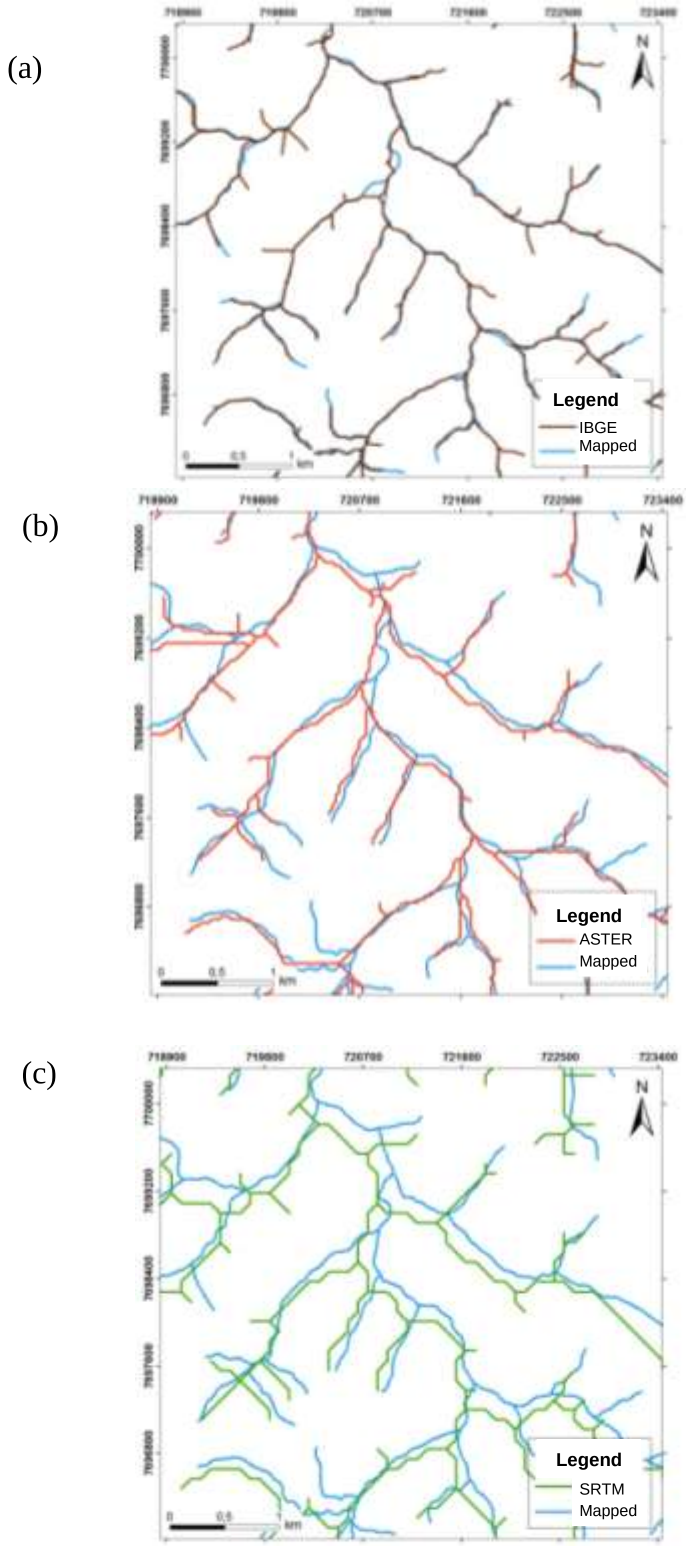

FIGURE 3. Comparison between mapped hydrography (topographic maps) and numerical hydrography: (a) HCDEM IBGE; (b) HCDEM ASTER and (c) HCDEM SRTM.

At intermediate elevations, between 650 and 850 meters, HCDEMs showed constant altimetric frequency. However, in mountainous areas above 850 meters, there is less adjustment of SRTM and ASTER HCDEMs when compared to HCDEM IBGE. Above 900 feet, it was not found altimetric information of HCDEM SRTM, compromising important analyzes in the basin as the study of the slopes and, consequently, the time estimate of the concentration of the basin. The difference in HCDEM IBGE for the SRTM and ASTER HCDEMs, considering the maximum elevation, was 23 meters and 5 meters, respectively.

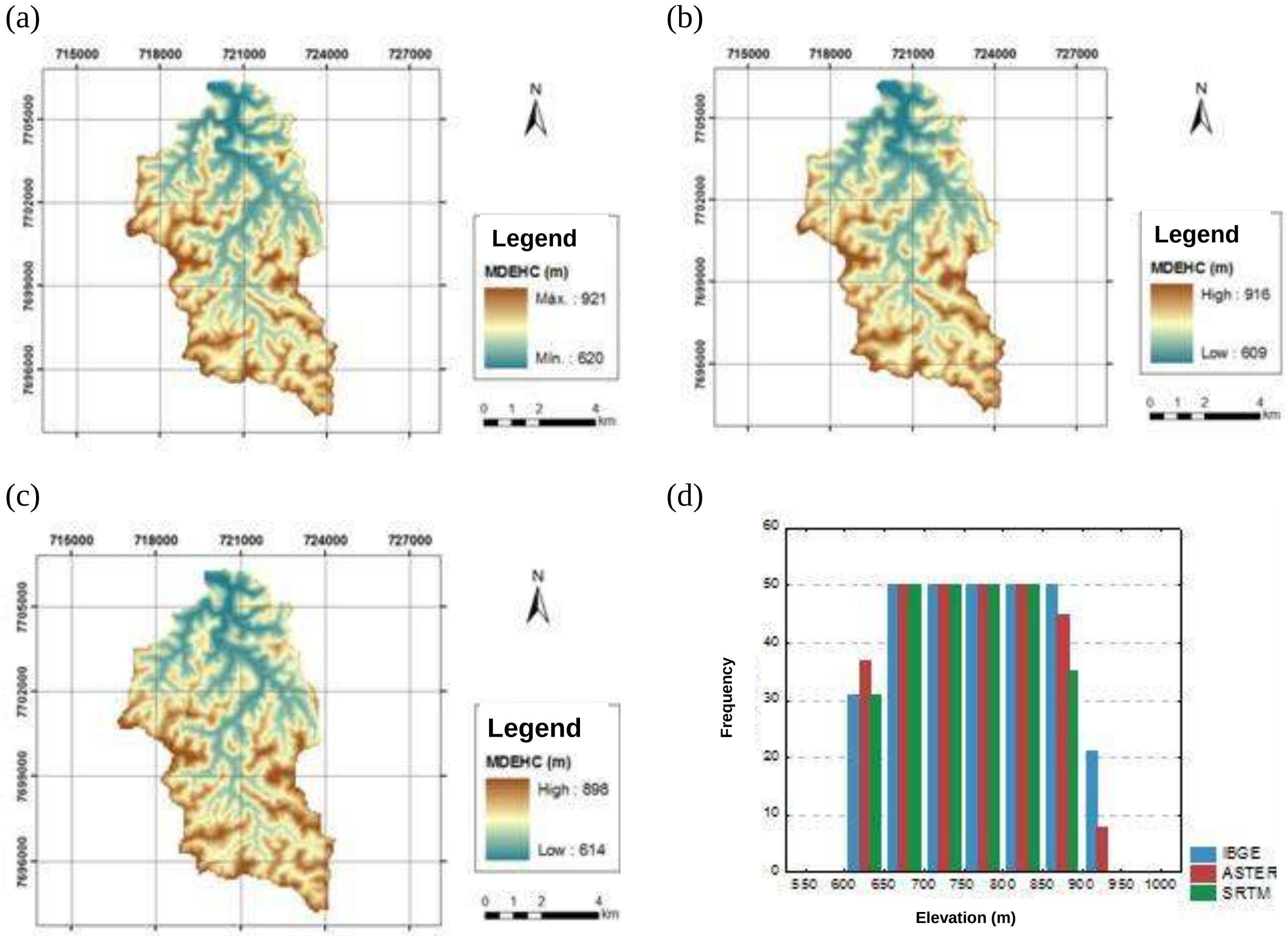

FIGURE 4. HCDEMs generated and frequency histogram of the altimetric values: (a) HCDEM IBGE; (b) HCDEM ASTER; (c) HCDEM SRTM and (d) histogram.

Table 2 shows the elevation differences between the HCDEMs evaluated and the 80 points rated the standard deviation of these differences, and the RMSE statistical index, used to verify the accuracy of HCDEMs in the estimate of elevations in the basin of the São Bartolomeu River.

TABLE 2. Descriptive statistics and RMSE for samples of terrain in São Bartolomeu basin.

HCDEM	Elevation difference - d (m)		Standard deviation	RMSE (m)
	Minimum	Maximum		
IBGE	0.00	17.00	3.06	4.00
ASTER	0.00	41.00	9.05	18.00
SRTM	0.00	74.00	18.76	33.00

It is observed in Table 2 that the HCDEM IBGE showed the lowest RMSE, and is, therefore, considered the most consistent model. The accuracy of digital models of elevation from topographic maps is directly related to the interpolator used. This way, we justify the low value of the RMSE index, since the interpolator "Top to Raster" is known as one of the best interpolators to generate altimetric models (PIRES et al., 2005).

The HCDEM SRTM showed a value of RMSE quite high in comparison to the reference elevation points, showing the worst performance among HCDEMs evaluated.

According to CHAGAS et al. (2010), the overall accuracy of the DEM is dependent on the total relief, real landscape and resolution of the DEM, as well as the accuracy of elevation and hydrography data. In areas where the elevation data are dense, errors in the DEM is approximately 10m, however, in the ones that present complex elevation data, errors may exceed 100m. These occur when the interpolation procedure has to resolve conflicts between maintaining the fidelity of elevation data and maintaining the water flow, following the break lines indicated (hydrography). Thus, the main reason for the high value of RMSE of the HCDEM SRTM, when compared to ASTER HCDEM and IBGE HCDEM, refers to its lower spatial resolution (90 m x 90 m).

The ASTER HCDEM presented good results, since the assessments of vertical quality of altimetric models derived from ASTER sensor indicate that the values between 5m and 20m may be achieved when using appropriate software, images of good quality and suitable ground control points (CHAGAS et al., 2010).

The results found in this study for the HCDEM ASTER is quite discordant from those obtained by CHAGAS et al. (2010), who found a RMSE for ASTER DEM equal to 37m, justifying the result by the characteristics of relief, by the presence of clouds in images, by the lack of adequate ground control points and even by the software employed itself.

Comparing the morphometric results obtained based on the HCDEMs, it was observed in Figure 5 that the percentage difference was less than 10%, except for the variable mean slope, which was 13.8%, between HCDEMs ASTER/IBGE, and 20.5% between HCDEMs SRTM/IBGE. Negative values mean that the result was underestimated, while positive values indicate overestimation.

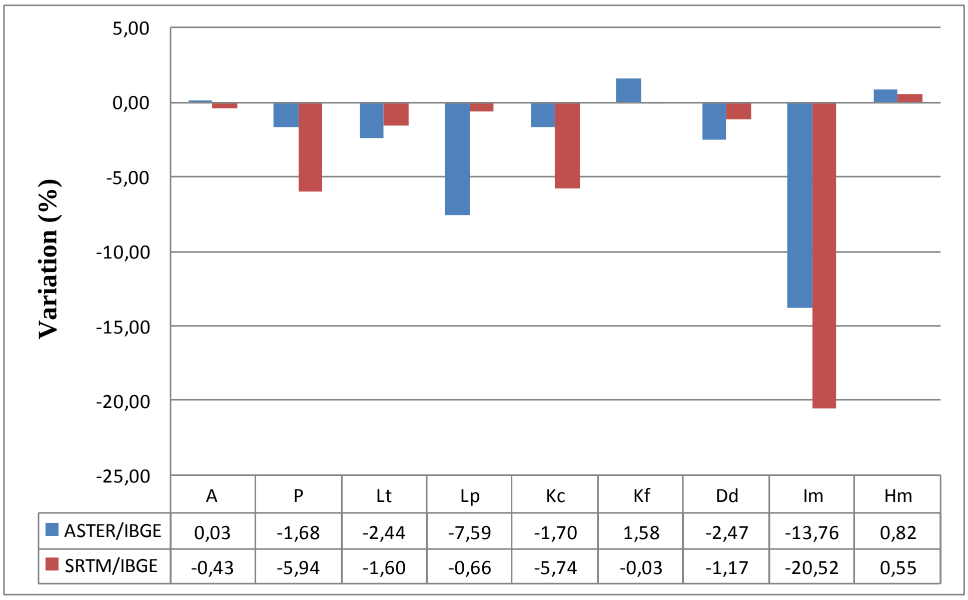

FIGURE 5. Comparison in terms of variation of morphometric characteristics estimated by the models.

It is also observed in Figure 5 that the HCDEM ASTER, when compared to HCDEM IBGE, overestimated the values of form factor and mean elevation indices, unlike other morphometric indices, which had their values underestimated, except for the area of basin that showed results similar to HCDEM IBGE. Similar results were obtained with the SRTM HCDEM, being only dissenter in the estimation of the form factor, which showed similar results compared to the IBGE HCDEM.

The ASTER HCDEM showed variations greater than 5% in the estimate of the length of the main river and the mean slope of the basin. On the other hand, HCDEM SRTM showed variations greater than 5% in estimating the perimeter, the coefficient of compactness, and also the mean slope of the basin.

Regarding the morphometric characteristics related to the drainage network, the values were underestimated by both models when compared to IBGE standard. The variation found for estimating the total length of watercourses was 2.4% to HCDEM ASTER and 1.6% to SRTM HCDEM, representing a mean loss of 2 km of drainage. The accuracy found in the estimate of the total length of the drainage is due to the similarity between the numerical and mapped drainage.

The ASTER HCDEM showed greater variation in the estimate of the length of the main river (8%), being justified by the model difficulty in estimating the source of the river, located in very steep relief. According to KÄÄB et al. (2002), these errors are predictable considering the fact that these regions are totally hidden or shaded, making it difficult to read by the sensor that gets the 3B band (spectral range: 0.76 to 0.86 μm). This variation corresponds to a loss of 1.3 km of the São Bartolomeu River. Moreover, the HCDEM SRTM showed better accuracy in estimating this morphometric feature, although it had larger displacement in relation to the mapped hydrography.

The greatest deficiency found in HCDEMs derived from remote sensing data is the difficulty in estimating the maximum, minimum and mean slopes of the basin. Results of studies by ALCARAZ et al. (2009) showed that the accuracy of DEMs derived from remote sensing is highly dependent on the slope of the land. Thus, in very high and steep terrain, the accuracy specified at 16 meters for SRTM DEMs and 14 meters for ASTER DEMs should be considered only as a guideline. BAENA et al. (2004) estimated the mean slope of the basin of the Paraíba do Sul River with a variation of 16%.

The results of mean slope found in this study are similar to those found by OLIVEIRA et al. (2010), despite having happened the opposite, i.e., an overestimation of the SRTM DEM compared to the generated model with topographic maps. In this study, the SRTM and ASTER HCDEMs, when compared to HCDEM IBGE, underestimated values of mean slope of 14 and 21%, respectively.

The best results for this assessment were obtained to HCDEM ASTER, which showed good agreement with the morphometric characteristics obtained with HCDEM IBGE. The HCDEM SRTM showed satisfactory results and slightly below the HCDEM ASTER.

In general, there was good agreement between the HCDEMs generated by remote sensing data with HCDEM standard, evaluated in relation to obtaining the morphometric characteristics. Thus, these models are a viable and practical alternative for hydrological modeling, to minimize costs and time of execution of the work, assisting in the planning and management of water resources.

CONCLUSIONS

The processing of digital elevation models, making them hydrographically conditioned is a fundamental process in determining the morphometric characteristics in watersheds.

The ASTER HCDEM was slightly more accurate than the SRTM HCDEM in basins with high altitudes and mountainous terrain, by presenting altimetric frequencies closest to HCDEM IBGE, considered standard in this study.

The HCDEMs generated from topographic maps are critical in studies related to the slope of the watershed, since it is still inadequate to estimate this variable by physical models generated through remote sensors.

Using SRTM and ASTER data in a GIS environment allows morphometric characterization of watersheds assisting the planning and management of water resources, being a practical and viable alternative for hydrological modeling, because it minimizes costs and time to carry out the study.

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