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Assessment of Digital Elevation Model for Digital Soil Mapping in a Watershed with Gently Undulating Topography

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ABSTRACT: Terrain attributes (TAs) derived from digital elevation models (DEMs) are frequently used in digital soil mapping (DSM) as auxiliary covariates in the construction of prediction models. The DEMs and information extracted from it may be limited with regard to the spatial resolution and error magnitude, and can differ in the behavior of terrain features. The objective of this study was to evaluate the quality and limitations of free DEM data and to evaluate a topographic survey (TS) underlying the choice of a more appropriate model, for use in DSMs at a scale of 1:10,000. The study was conducted in an area of 937 ha in the watershed of Lajeado Giruá, in southern Brazil. The DEMs: DEM-TS, DEM-Topographic Map (TM), DEM-ASTER, DEM-SRTM, and DEM-TOPODATA were evaluated with regard to the precision elevation by statistical tests based on field reference points, the root mean square error (RMSE), identification of the number and size of spurious depressions, and the application of the Brazilian Cartographic Accuracy Standards Law (BCASL) to define the scale of each DEM. In addition, the TA derived from each DEM was compared with the TA from DEM-TS, considered to be terrain reality. The results showed that the elevation data of DEM-TS had the best quality (RMSE = 1.93 m), followed by DEM-SRTM (RMSE = 5.95 m), DEM-Topographic Map (RMSE = 8.28 m), DEM-TOPODATA (RMSE = 9.78 m) and DEM-ASTER (RMSE = 15.57 m). The DEM-TS was well-represented at a 1:10,000 scale, while the DEM-Topographic Map and DEM-SRTM fitted 1:50,000, the DEM-TOPODATA 1:50,000 and the DEM-ASTER a 1:100,000 scale. The results of DEM-SRTM and DEM-TOPODATA were closest to terrain reality (DEM-TS) and had the lowest number of spurious depressions and RMSE values for each evaluated attribute, but were inadequate for not fitting detailed scales compatible with small areas. The techniques for the acquisition of elevation data of each DEM and mainly the flat to gently undulating topography were factors that influenced the results. For a DSM at a scale of 1:10,000 in similar areas, the most appropriate model is DEM-TS.

Keywords: terrain modeling, DEM quality, DEM scale, terrain attributes, soil mapping.

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INTRODUCTION

The demand for soil properties at fine resolutions of information for large areas is increasing (Hartemink, 2008). Therefore, terrain attributes (TA) derived from digital elevation models (DEM) are being increasingly used as auxiliary covariates in the spatial prediction of soil classes and properties (Kempen et al., 2011; ten Caten et al., 2013; Teske et al., 2014), due to the high ratio of TA with soil genesis and the wide availability of DEMs (McBratney et al., 2003; Behrens et al., 2010).

The DEM quantitatively represents the continuous variation in the landscape relief (Moore et al., 1993). A DEM can be generated from topographic data of field surveys, interpolation of vector bases (e.g. elevation points, contour lines and hydrography) extracted from topographic maps, pairs of stereoscopic images on aerial photographs and by satellite images obtained by optical sensors, orbital radar or laser scanner (Hutchinson and Gallant, 2000).

The coverage of Brazil by topographic maps at a 1:50,000 scale is only 14 % of total area and only 1 % at 1:25,000; most of the underlying surveys were carried out over 30 years ago (Archela and Archela, 2008). This reality is also common in other regions of the world where large-scale topographic maps are missing. An alternative to these locations would be the use of a freely available global DEM, e.g., ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) obtained by the optical stereoscopic technique; SRTM (Shuttle Radar Topographic Mission) obtained by interferometry; or by data TOPODATA, obtained by refining the original SRTM data for Brazil. There is also the possibility of obtaining a DEM from commercial datasets, e.g., from images of the QuickBird satellite, ALOS (Advanced Land Observing Satellite) and SPOT (Satellite Pour l'Observation de la Terre), where the spatial resolution of the acquired images is high (2.5-5.0 m), but the costs are also high and the elevation quality is not necessarily better than that of the freely available DEM (Iorio et al., 2012).

Information derived from a DEM may have practical limitations since, each DEM has a range of suitability that is related to the spatial resolution and the magnitude of its errors (Hutchinson and Gallant, 2000; Wise, 2000; Valeriano, 2008). Holmes et al. (2000) showed that a small amount of elevation error in the DEM can severely affect the TA derived from the model, such as the index of topographic moisture, slope, flow accumulation and all interpretations depending on that information.

The prediction performance of classes and soil properties can be influenced by the terrain features, the scale at which pedogenic processes occur in the landscape and whether the DEMs can represent the features in the terrain (McBratney et al., 2003; Smith et al., 2006). Moreover, the error magnitude in the DEM is not always known by users; when this information is available, it is region-specific. In addition, there is no standardization of methodologies for generating the DEM, or the assessment of the quality and limitations of the information derived from the DEM for specific locations, which is often neglected (Lin and Oguchi, 2006).

Faced with this problem, attempts have been made to assess the quality of DEMs with a view to presenting more reliable data and making their limitations known for subsequent application in DSMs (Holmes et al., 2000; Chagas et al., 2010; Pinheiro et al., 2012; Teske et al., 2014). The most common approach to this problem is the comparison of known and more accurate elevation points (i.e. values considered true) with their respective DEM points and a qualitative evaluation of the land surface characteristics. In general, the index commonly used in the evaluation is the root mean square error (RMSE) of the elevation values. The identification of spurious depressions, drainage features and derived contour lines are also used as criteria in the evaluation of DEMs. Another possibility is to evaluate the performance of predictive models soil classes generated for from the TA by different DEM (Teske et al., 2014). Other studies in the area of mapping (Pinheiro, 2006; Iorio et al., 2012; Moura et al., 2014) have used the Brazilian Cartographic Accuracy Standards Law

(BCASL) to evaluate the elevation quality and to define the scale and accuracy class of the DEM. However, a drawback of most of these studies is the lack of a survey for on-site collection of reference data to assess the DEMs.

The protocol for soil surveys is based on the underlying mapping scale (Embrapa, 1995), suggestions of DEM resolution according to the mapping scale (McBratney et al., 2003) and on multi-scales for digital terrain analysis in DSM studies (Behrens et al., 2010). Therefore, the need arises to know the accuracy and scale of the DEMs to define soil sampling, detail level of soil surveys and their properties and increase in the accuracy of the DSM. The quality of DEMs for large land areas was evaluated by Chagas et al. (2010) and Pinheiro et al. (2012), which may be used, for example, in soil surveys at the level of recognition (scales from 1:750,000 to 1:100,000) or at a semi-detailed level (scales ≤1:50,000).

For Brazil and most parts of the world, no DEMs with a resolution lower than 30 m are available for free, which is why DEMs with coarse resolutions (≥30 m) are used in soil mapping at a detailed level. In addition, there is a lack of studies on the use of these DEMs for small land areas with little topographic variation, for which soil surveys at a scale ≥1:20,000 are needed. There is also a lack of observations on the elevation accuracy of DEMs from the point of view of the range specified by the BCASL and the non-use of field data as a reference for evaluation of the DEMs.

The purpose of this study was to evaluate the quality of elevation and TA data and limitations, with regard to the scale of four freely available DEMs compared to a DEM obtained by a topographic survey (TS). This diagnosis is intended to assist the selection of the most appropriate DEM to derive TA for studies of environmental modeling and in DSM at a scale of 1:10,000 at the level of a small watershed with little relief variation.

MATERIALS AND METHODS

Description of the study area

The study was conducted in an area of 937 ha in the municipality of Giruá, state of Rio Grande do Sul (RS), Brazil (Figure 1). The area belongs to the sub-region of Missões, a physiographic region of the RS plateau, at elevations between 339-420 m. The climate is predominantly Cfa according to the Köppen classification, characterized as humid subtropical climate without a clearly defined dry period. The terrain is flat to gently undulating, with steep slopes near the drainage, often with slopes from 3-10 % (Figure 2a). The geology of the area was shaped by the formation of the *Serra Geral*. The predominant soil classes in the area are *Latossolos Vermelhos Distroférricos típicos* (Santos et al., 2013), an Rhodic Ferralsol (Dystric, Clayic) (IUSS Working Group WRB, 2015) and *Gleissolos Háplicos Tb Distrófico típicos* (Santos et al., 2013), an Gleysol (Clayic, Humic) (IUSS Working Group WRB, 2015). The predominant land uses in the area are native forest, native pasture and annual crops.

Digital elevation models (DEMs)

A digital elevation model with a spatial resolution of 30 m was generated from a topographic survey (TS), using 663 points marked statically in the terrain with a topographic GPS Receiver – Global Positioning System, model Leica GS20, with a frequency of L1, and precision of ±0.10 m positioning error and ±0.30 m vertical error. These points were subject to correction (i.e. adjustment of geodetic observations) in the positions indicated by satellite measurements in the field with a GPS receiver, and later interpolated by the nearest neighbor method to generate the DEM-TS (Figure 2b).

The other four DEMs, with 30 m resolution, were obtained as follows: 1) DEM- Topographic Map (TM) (Figure 2c), generated from the contour lines (interval 20 m) of the topographic map of Giruá (SH21-X-B-III/1/SE – 1:50,000 scale), available at the

Mapping Base of Rio Grande do Sul (Hasenack and Weber, 2010). The contour lines were interpolated using the Thin Plate Spline method (TIN); 2) DEM-ASTER (Figure 2d), obtained from the active sensor database ASTER GDEM v2 (resolution 30 m), available for the entire globe, of the United States Geological Survey (USGS); 3) DEM-SRTM (Figure 2e), obtained from the mission database of the Shuttle Radar Topography Mission (SRTM v4.1), interpolated in this study to a resolution of 30 m by the interpolator Cubic Spline Interpolation; 4) DEM-TOPODATA (Figure 2f), obtained from the database of the TOPODATA Project, available at INPE at a resolution of 30 m (Valeriano and Rossetti, 2012).

The elevation of TS and DEM points was represented in relation to a reference ellipsoid, with the exception of the DEM-TM points, which represent the orthometric height. To this end, the geoid undulation of each point was calculated for subsequent transformation of ellipsoidal height to orthometric height. These procedures were performed with the MapGeo software (IBGE, 2010). According to IBGE, the mean error for geoid undulation in the region is 0.20 m. The DEMs were geoprocessed with software SAGA GIS (SAGA, 2010) and the statistical analyses were performed in R (R Core Team, 2014).

Evaluation of the quality of elevation data of DEMs

Accuracy of elevation data, number of analyses and extent of spurious depressions of the DEMs were compared, as suggested by Wise (2000), as well as the quality of the TA: slope, planar curve, soil moisture content, factor LS and convergence DEM-specific. These were chosen for being the key TA used in DSM (Behrens et al., 2010; ten Caten et al., 2012), having been studied in the DEM evaluation for use in DSM (Pinheiro et al., 2012; Teske et al., 2014) and for being directly related to water movement in the soil, with an influence on the soil formation process (Moore et al., 1993; Wilson and Gallant, 2000).

Statistical tests according to the Cartographic Accuracy Standard – Digital Cartographic Products (CAS-DCP), according to Technical Specifications for Geospatial Data Acquisition Vector (Brasil, 2011), were applied only to the elevation data. The evaluation of TA derived from each DEM was used as reference (terrain reality) TA values derived from DEM-TS. The evaluation was based on parameters of descriptive statistics and the root mean square error (RMSE).

The statistical tests are based on comparisons of the elevation values derived from each DEM to those reference points (RP). In the study area, 41 RPs were marked (Figure 2a), which were used to compare the DEM elevation values. These points are independent of the points underlying the construction of the DEM-TS.

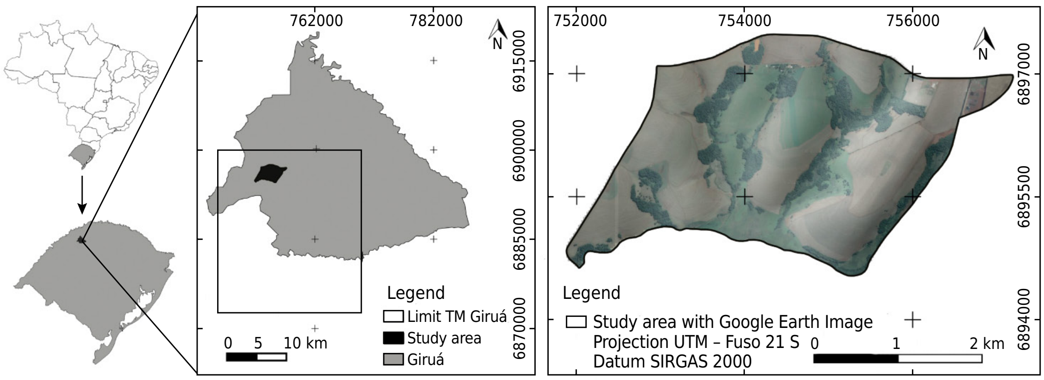

Figure 1. Location of the study area in the municipality of Giruá, Rio Grande do Sul state, Brazil, limit indication of Giruá Topographic Map (TM) and expanded study area with the Google Earth image.

The first step was to calculate the elevation errors (EE) as the difference between the values of the reference elevation (E_{REF}) of the elevation value of each DEM (E_{DEM}), the error mean (M_{EE}) and the standard deviation of errors (S_{EE}). Statistical tests to check the quality of digital products were: 1) calculate the RMSE; 2) trend test; 3) accuracy test, and 4) application to the standard CAS-DCP to define the scale of each DEM.

The RMSE of the EE values of the 41 assessed points (n = 41) was calculated by equation 1:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} EE_i^2}{n}} \qquad \text{Eq. 1}$$

The objective of the Trend Test is to identify systematic errors in the elevation values, by testing the following hypotheses: H0: $M_{EE} = 0$, is not biased; H1: $M_{EE} \neq 0$, is biased. To test this hypothesis, the value of "t_h" must be calculated using equation 2:

$$t_h = \frac{\overline{EE}}{S_{EE}} \times \sqrt{n} \qquad \text{Eq. 2}$$

where M_{EE} is the error mean; S_{EE} the standard deviation of errors; and *n* the number of points used in the assessment, i.e., 41 points. The hypothesis was tested with the Student's *t*-test from the tabulated values, by checking whether the "t_h" value is within the interval

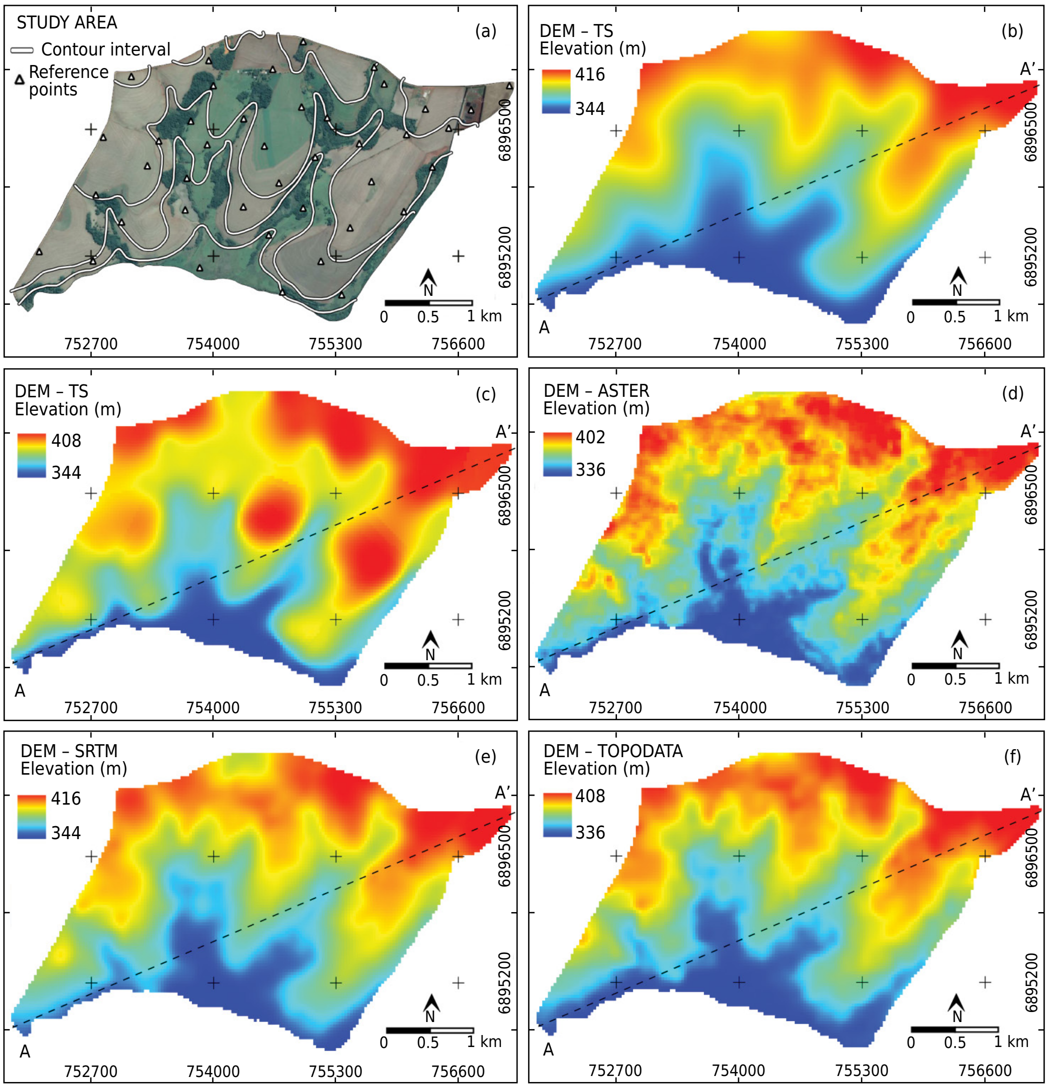

Figure 2. (a) Study area with the locations of 41 reference points (RP) and contour line (20 m) from the Topographic Map (TM); (b) DEM-TS; (c) DEM-TM; (d) DEM-ASTER; (e) DEM-SRTM; (f) DEM-TOPODATA; the dashed line represents the DEM transect A-A'.

of acceptance, or rejection of the null hypothesis. Thus, if the value "$t_{h\ calculated}$" value is less than the "$t_{tabulated}$" for n-1 degrees of freedom and at significance level α, the data have no tendency to systematic errors. This type of error is related to factors that can influence data sampling, e.g., tree crowns and the presence of clouds.

In the accuracy test, the S_{EE} of EE was compared to the standard deviation (SD) specified by the CAS-DCP for each scale and class, to test the following hypothesis: H0: $S^2_{EE} = \sigma^2_H$ and H1: $S^2_{EE} > \sigma^2_H$, where σ_H is the predetermined standard error for each scale and class, and S_{EE} corresponds to the standard deviation of the EE values of each DEM evaluated. This hypothesis was tested by the chi-squared test (χ^2), with tabulated values, at a significance level of 90 %. The standard deviation was calculated using equation 3:

$$\chi^2 EE = \frac{S^2_{EE}}{\sigma^2_H} \times (n - 1) \qquad \text{Eq. 3}$$

After this step, the $\chi 2_{EE}$ value was tested within the acceptance range by the following expression: $\chi^2_{EE} \leq \chi^2_{(n-1;\alpha)}$. If the value did not meet the above expression, the null hypothesis was rejected, since the DEM elevation data did not meet the predetermined accuracy.

The application of BCASL for quality control of mapping products is based on the CAS-DCP (Brasil, 2011). The CAS-DCP values are determined by BCASL for each scale and class. According to the norm for a DCP, to meet the predetermined criteria for CAS-DCP, 90 % of the errors of the collected points in the assessed DCP, compared to RP marked in the field with high-precision equipment, should have EE errors equal to or lower than those predicted by CAS-DCP. The classes are based on the increasing precision of elevation data of the DCP, i.e., the precision levels are represented by the classes A, B, C and D for the same scale, with decreasing accuracy from class A to D. For example, for a CAS-DCP of 1 m (scale 1:5,000 – Class B), 90 % of the assessed points must have EE values smaller than 1 m, otherwise this DCP does not fit in B on this scale. The values of CAS-DCP for the scales of this study are presented in table 1.

RESULTS AND DISCUSSION

The topographic profiles of each DEM are shown in figure 3a and the boxplots with descriptive statistics, Student's t-test of elevation data of the reference points (RP), and elevation data derived from each DEM, in figure 3b. The relief of the study area was represented differently by the DEMs (Figure 3a), as evidenced by descriptive statistics, mainly by the mean, minimum and maximum elevation values (Figure 3b). These results are in line with those of Chagas et al. (2010) and Teske et al. (2014), who showed that the relief is represented differently by each DEM. In addition, Teske et al. (2014) showed that DEMs with a high variation in elevation values generated less accurate prediction models of soil types with a lower number of predicted map units. This clearly demonstrates the need for evaluation of the DEMs to select the most suitable for DSM.

There was no significant difference between the mean elevation values of the RPs and the DEM-TS (means of 385.13 and 385.17 m; Figure 3b). This indicates that the elevation values of these DEMs are consistent with those of RPs, considered terrain reality in this study. However, the mean elevation values of DEM-TM (376.95 m), DEM-ASTER (370.37 m), DEM-SRTM (381.10 m), and of DEM-TOPODATA (380.54 m) differed significantly from each other and from the RPs and DEM-TS.

The elevation values of DEM-TM, DEM-ASTER, DEM-SRTM and DEM-TOPODATA were underestimated relative to the RPs and DEM-TS, in particular those of DEM-ASTER. In an evaluation of the vertical accuracy of a DEM, Mukherjee et al. (2013) observed the same behavior for the DEM elevation values obtained by SRTM and ASTER in an area in India. According to these authors, this is associated with the presence of vegetation, artifacts on the surface and the flat terrain; DEM-ASTER data are particularly influenced by these factors, because the elevation data of this DEM are acquired by stereoscopy (Guth, 2010). The DEM-TOPODATA data may also be influenced by these factors, since the SRTM mission data are based on TOPODATA values. In areas with little variation in elevation, TOPODATA elevation data may have been affected by the refinement of spatial resolution from 90 to 30 m (Valeriano and Rossetti, 2012). In this case, the technique may not have altered the elevation values of the original pixel (90 m) of SRTM and, consequently, the new values generated by refinement for a pixel of 30 m of TOPODATA are not near the terrain values (Valeriano, 2008). This may have resulted in the higher variation and underestimation of the elevation values (Figure 3b) of DEM-TOPODATA in relation to RPs, resulting in poor quality of this DEM for the area, as indicated by the RMSE of 9.78 m. In this study, the flat to gently undulating relief of the study area may have influenced the poor performance of DEM-TOPODATA. In an evaluation of the adjustment of DEMs to scales according to the precision elevation in an area covering three counties in Mato Grosso do Sul, with gently undulating relief, Iorio et al. (2012) found higher RMSE values for DEM-TOPODATA (19.83 m) than for DEM-ASTER (17.23 m) and SRTM (16.69 m). According to these authors, the DEMs fitted the scale of 1:100,000; but it is worth remembering that DEMs obtained by remote sensing techniques should be used with caution at large-scales.

With regard to DEM-TM, a high amplitude (27.13 m) was observed in the set of EE values (Figure 4). This indicates that the elevation values are underestimated at some terrain points and overestimated at others. An analysis of each elevation value extracted from this DEM and compared to the elevation data of RPs showed that at 66 % of the points, the elevation values were underestimated, reflecting the positive sign of the mean EE (Figure 3a). The DEM elevation values derived from topographic maps tend to be overestimated for flat relief (Pinheiro, 2006). In this study, only 34 % of the points were affected by this trend.

Table 1. Scales tested in this study, their respective contour intervals (CI), standard deviation (SD) and Cartographic Accuracy Standard – Digital Cartographic Products (CAS-DCP), according to the Brazilian Cartographic Accuracy Standards Law (BCASL)

Scale	CI	SD	CAS-DCP	SD	CAS-DCP	SD	CAS-DCP	SD	CAS-DCP
		Class A[(1)]		Class B		Class C		Class D	
1:50,000	20 m	3.33	5.50	6.66	10.00	8.00	12.00	10.00	15.00
1:25,000	10 m	1.67	2.70	3.33	5.00	4.00	6.00	5.00	7.50
1:10,000	5 m	0.84	1.35	1.67	2.50	2.00	3.00	2.50	3.75
1:5,000	2 m	0.34	0.54	0.66	1.00	0.80	1.20	1.00	1.50

[(1)] Classes determined according to the value of the CAS-DCP and acceptable standard error (SE). The accuracy in CAS-DCP values and errors decreases from class A to D. SD and CAS-DCP values are shown in meters (m).

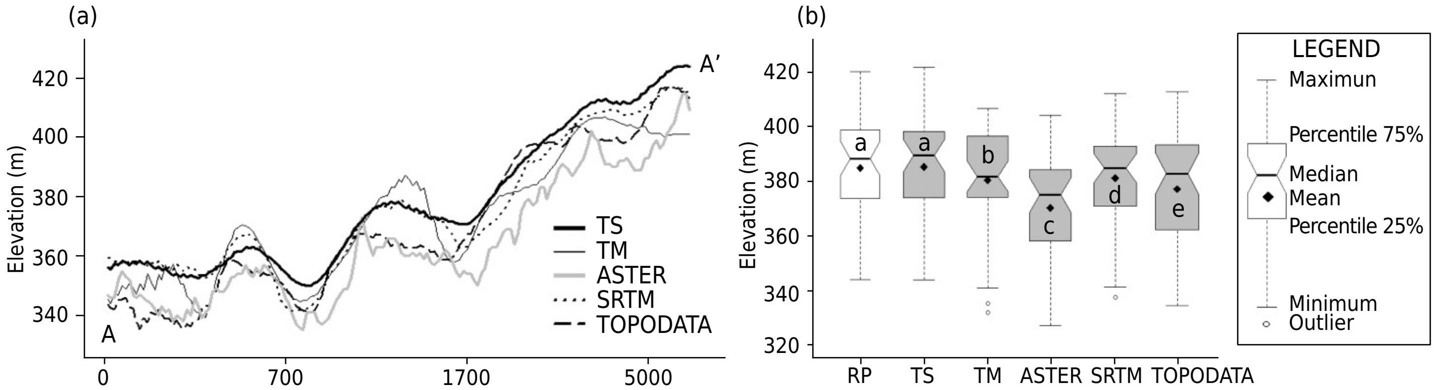

Figure 3. (a) Topographic profile produced from the transect A-A’ of the five DEMs; (b) boxplots with the result of the Student’s t test (significance level α = 0.05) for the altitude values of reference points (RP) and the five DEMs.

This low quality of DEM-TM may be related to the sparse sampling of the terrain by contour lines with contour intervals of 20 m in the study area, due to the flat to gently undulating terrain. Observations at each of the 41 RPs showed higher EE at points in the middle of the distance between two contours. This problem was also mentioned by Druzina (2007), who evaluated the quality of DEM-SRTM, DEM-TM and DEM-ASTER in Porto Alegre, state of Rio Grande do Sul. The author observed that in areas with flat terrain, the RMSE of DEMs generated from the map was higher (5.64 m) than in the area with mixed relief (RMSE = 4.61 m), and the elevation values were underestimated relative to the control points. For DEM-SRTM and ASTER, the author reported an RMSE of 3.40 and 4.62 m for flat areas; 8.26 and 6.69 m for mixed areas; and 10.96 and 6.52 m for rugged terrain areas, respectively.

RMSE of DEM-TM was lower (8.28 m) than that of DEM-ASTER (15.57 m) and DEM-TOPODATA (9.78 m). However, in relation to DEM-SRTM (5.95 m), the RMSE of DEM-TM was higher. The topographic map, used in this study to generate the DEM-TM, was obtained by the photogrammetry technique in 1975. According to Subramanian et al. (2005), this may result in restrictions to the use of radar interferometry with synthetic aperture for data sampling by the SRTM mission. In a study conducted in Honduras by Jarvis et al. (2004) using GPS landmarks, the accuracy of DEM-SRTM was greater than that of the DEM obtained from topographic maps (scale 1:50,000). These authors also observed that DEM-SRTM was more detailed in the representation of the soil surface.

The model DEM-ASTER produced higher EE values than the RPs and the other DEMs, with an RMSE of 15.57 m (Figure 4), and performed worst of all evaluated DEMs. This indicates that this DEM fails to represent the terrain reality in this study area and consequently, the TA extracted from it. The topographic profile of ASTER (Figure 3a) showed that the elevation values were underestimated. These data were corroborated by Slater et al. (2009), in an evaluation of this model at 20 different locations. These authors found that in almost all areas, the mean elevation of ASTER was below the elevation data measured in the field, i.e., EE showed a positive trend (Figure 4). Similarly, Guth (2010) studied the quality of DEMs obtained from remote sensing data and observed that ASTER provided lower elevation values than SRTM.

The results for DEM-ASTER may be related to the process of obtaining the elevation data from ASTER, as discussed above. In an assessment of DEM for DSM, Chagas et al. (2010) found the worst result for ASTER. The terrain features, presence of clouds in the ASTER images and lack of adequate control points were the causes of these results. Here, the presence of vegetation at some points in the terrain, especially in the valleys, associated with the flat to gently undulating relief in most of the area, was responsible for the poor performance of DEM-ASTER.

Mean	Min	Max	SD	SE	RMSE	t_h	Avaliation TT	DEM
8.19	-7.32	18.72	5.41	0.84	9.78	9.70	with a trend	TOPODATA
4.03	-6.94	11.96	4.43	0.69	5.95	5.83	with a trend	SRTM
14.77	-4.82	22.32	5.01	0.78	15.57	18.87	with a trend	ASTER
4.59	-7.75	19.37	6.98	1.09	8.28	4.21	with a trend	TM
-0.02	-4.82	4.75	2.42	0.37	1.93	0.12	with a trend	TS

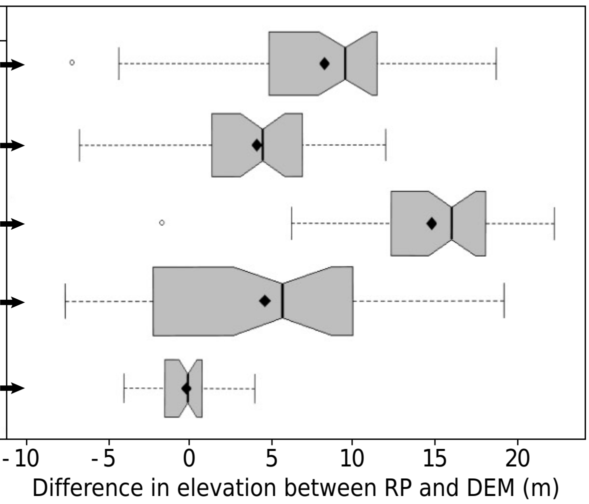

Figure 4. Descriptive statistics of elevation error values (EE) represented by the boxplot, value of root mean square error (RMSE), t_h value (calculated by the Student's t test) result and the trend test (TT) based on the t_h value for the five DEMs.

The elevation data derived from DEM-TS, for having points of elevation, regarded as an ideal data source for the interpolation techniques to generate a DEM (Hutchinson and Gallant, 2000) had, as expected, the best quality of all DEMs evaluated in this study. This result was confirmed by the mean EE being close to zero and lower RMSE (1.93 m; Figures 4a and 4b), confirming the small difference between the elevation data of RPs and of DEM-TS, i.e., the values are consistent with the terrain reality of the field in this study area. However, minor discrepancies of this DEM resulted in an RMSE of 1.93 m. Because the DEM-TS was generated from high-precision GPS field data, the elevation values are assumed to be accurate. In this case, the most likely explanations for the discrepancies related to errors in the interpolation are the elevation points, low number of points and poor knowledge about the software.

In the trend test (TT), all DEMs tended to systematic errors in the elevation values (Figure 4), except for DEM-TS. In this DEM, the $t_{h\ calculated}$ was less than $t_{tabulated}$. Systematic errors indicate the influence of external factors on the acquisition of field data, such as image shifting, the presence of clouds and errors in interpolation methods (Dixon, 1995), which can compromise the data quality. Because of the way the data of DEM-TM, DEM-ASTER, DEM-SRTM and DEM-TOPODATA were acquired, these DEMs are more susceptible to systematic errors than a DEM generated from a TS, considered the ideal data source for the construction of DEMs (Hutchinson and Gallant, 2000). Therefore, the diagnosis of elevation data of a DEM by this test can assist in choosing the most appropriate DEM for each study and in the need for a more robust assessment of the elevation accuracy of the DEM.

The quality of DEM-TM, DEM-SRTM and DEM-TOPODATA found in this study (Figure 4), agrees with some studies in the literature where DEMs generated from these sources have better quality than the DEM constructed with ASTER data (Chagas et al., 2010; Moura et al., 2014). The generation of DEMs by the stereoscopic technique, e.g., DEM-ASTER, has some disadvantages; for example, the influence of the cloud cover, tree crowns and atmospheric absorption wavelength in relation to Interferometric synthetic aperture radar (InSAR) used for example in the SRTM, considered the most advanced technique for generating terrain data (Hutchinson and Gallant, 2000). The data source of DEM-ASTER has a high amount of artifacts that are quantified as elevation values, which is aggravated at sites with a more gentle relief, hampering the characterization of the relief (Guth, 2010).

The comparison of DEMs by the Accuracy Test (AT) has as a prerequisite to setting a scale and class (Table 1), and is defined according to the standard deviation (SD) values of each DEM investigated. Here, it was decided to start the test from the 1:50,000 scale – Class A for all evaluated DEMs (Table 1), due to the size of the study area, and to use the topographic map on the same scale. From this, the most suitable scale and class for each tested digital cartographic product (DCP) were evaluated up to the largest possible scale according to BCASL and CAS-DCP.

The AT indicated that the DEM-TS met the specifications for the 1:50,000 scale in the four classes (A, B, C, and D). The scale of 1:25,000 only fit for the classes B, C and D and 1:10,000 only for class D. The DEM-TM was only accurate at a scale of 1:50,000 in classes B, C and D. The DEM-SRTM adjusted the specification of AT only for the scale of 1:50,000 in the classes B, C and D and for 1:25,000 in Class D. The DEM-TOPODATA adjusted the specification of AT only for the scale of 1:50,000 in class D. The DEM-ASTER did not adjust the specification of AT at any of the scales analyzed in this study, but may be adjusted to the 1:100,000 scale, according to standard CAS-DCP. The accuracy of DEM was inadequate for the scale of 1:5,000 in all classes.

According to the CAS-DCP standard, the maximum range that can be used for the DEM-TS of this study area is 1:10,000 – Class D, where a standard error of the lower elevation values or equal to 2 m is accepted. For DEM-TM, the maximum scale was 1:50,000 – Class B. This scale has low terrain detailing and is not recommended for use in DSMs in small areas and low relief variation. However, for larger areas (e.g. large river basins and municipalities) the DEM-TM at a scale of 1:50,000 can be used as base map for semi-detailed soil survey projects such as, for example, the study of Flores et al. (2007). The DEM-SRTM can be used at a scale of 1:50,000 in Class B, C and D and DEM-TOPODATA only in class D for semi-detailed soil surveys, with greater restrictions in terms of accuracy.

These results indicate that the DEMs should be used in DSM in ranges compatible with the accuracy of elevation data, i.e., the DEMs cannot be used at scales larger than those defined by the AT, since the TA values would not be accurate enough to represent the terrain adequately. This assessment of the DEM quality according to scale is necessary because the DEM scale interferes with the morphometric analysis of small watersheds (Zanata et al., 2011). Thus, DEM-based DSM studies should take the DEM quality into account and its range to minimize the error distribution in the resulting secondary information. Moreover, this information can be an orientation in future studies of DSM in areas with these characteristics. The adjustment of a DEM to a scale enables the development of future studies of, for example, digital mapping of properties with higher quality and reliability of the resulting information. This is according to McBratney et al. (2003) and Smith et al. (2006), who reported a direct relationship between the accuracy of DSM studies with landscape features, and analyzed whether these are represented correctly by the DEMs.

Our results on the elevation quality and limitations in relation to the scale of the DEMs may have implications for the DSM. According to Teske et al. (2014), DEMs with a high variation in elevation values generate less accurate soil class prediction models and fewer predicted mapping units. A small number of elevation errors in the DEM can severely affect the TA derived from the model and all interpretations related to this information (Holmes et al., 2000). This clearly shows the need for evaluation of the DEMs for selection of the most appropriate for the DSM.

Assessing the quality of DEMs based on elevation data and RMSE values only, however, is considered unsatisfactory and could compromise the results (Wise, 2000). This was observed by Pinheiro et al. (2012), who evaluated the quality of the DEM derived from the topographic map, ASTER and SRTM in a qualitative assessment based on the aspects of the surface and a number of spurious depressions, for a DSM in a watershed of 125,078 ha, with relief variation from flat to rugged. These authors observed a better performance of DEM-TM and hybrid DEM (map data + data points extracted from SRTM + points extracted from topographic map) than the DEM-SRTM and DEM-IBGE obtained by the photogrammetry technique. Similarly, Chagas et al. (2010) evaluated a DEM in a watershed of 28,000 ha, with flat to rugged relief, and found RMSE values of 12.04, 14.23 and 36.69 m for DEM-SRTM, DEM-TM and DEM-ASTER, respectively. However, in the assessment of the distribution of the drainage system, contours and presence of spurious depressions, they observed the best results for the DEM generated with topographic map data, confirming the need to assess the DEM quality by additional indicators, aside from elevation.

Thus, the DEMs were assessed in this study by identifying the spurious depressions, as suggested by Wise (2000) (Table 2). The data show a significant difference between the number and size (i.e. the number of pixels in depressions) of spurious depressions of DEM-TS and the other DEMs. The number of depressions was 78 times higher in DEM-ASTER and 25 times higher in DEM-TM than in DEM-TS, indicating a depression with a size of two pixels only. The causes of these errors in the DEM may be associated with the interpolation methods used to obtain the models (Dobos et al., 2000). For Hengl et al. (2004), the high number of spurious depressions in DEMs obtained by remote sensors is common, due to gross errors arising from the sensor data collection, particularly in the case of ASTER. Only 0.02 % of the pixels of DEM-TS had spurious depressions in the total area and the DEM-SRTM and DEM-TOPODATA less than 0.5 % of the pixels, showing the good performance of these DEM for the study area.

These results have direct effects on the characterization of land surface aspects of the terrain and on the flow direction, which define the hydrological relationships in the landscape (Wise, 2000), and are directly related to soil formation processes and the variability of soil properties (Wilson and Gallant, 2000). Here, the terrain has a relief with little variation; associated with a spatial resolution of DEMs of 30 m, the presence of a large number of large spurious depressions can significantly affect the characterization of the relief area, and consequently, the soil-landscape relationship and the spatial soil prediction models adjusted from TA derived from these DEMs.

The descriptive statistics and RMSE of TA derived from the five DEMs are shown in table 3. In this case, the values of DEM-TS attributes (taken as reference values) were compared to those of other DEMs. Noting the statistical parameters of the five TA, the DEM-TS, DEM-TM, DEM-SRTM, and DEM-TOPODATA have similar results, differing from DEM-ASTER. Analyzing the RMSE values for each attribute, the lowest errors in relation to DEM-TS were observed for DEM-SRTM and DEM-TOPODATA, i.e., the values were closer to DEM-TS, considered to be terrain reality. The RMSE values of DEM-TM were intermediate and those of DEM-ASTER the highest. The results for DEM-TM were related to the low amplitude of the relief and the presence of spurious depressions, where the analysis of the terrain by

Table 3. Descriptive statistics of the results of terrain attributes (TA) derived from each DEM

DEM	Mean	Min[(1)]	Max[(2)]	SD[(3)]	SE[(4)]	RMSE[(5)]
Slope (degrees^0.5)						
TS	0.22	0.08	0.37	0.18	0.04	–
TM	0.24	0.05	0.48	0.22	0.05	0.20
ASTER	0.28	0.03	0.48	0.21	0.05	0.22
SRTM	0.22	0.04	0.35	0.16	0.03	0.17
TOPODATA	0.24	0.04	0.42	0.17	0.04	0.17
Planar curve (m^{-1})						
TS	0.05	-0.78	0.57	0.25	0.02	–
TM	-0.62	-77.34	31.25	11.90	0.91	11.82
ASTER	-1.26	-60.07	68.59	21.86	1.68	21.79
SRTM	0.05	-0.93	1.12	0.33	0.10	0.34
TOPODATA	0.35	-93.48	84.99	17.18	1.32	17.10
Index of topographic moisture (non-dimensional)						
TS	8.14	5.82	17.13	1.80	0.14	–
TM	8.15	6.05	17.54	1.71	0.13	2.05
ASTER	7.79	4.67	14.52	2.00	0.15	2.24
SRTM	8.11	5.62	14.34	1.44	0.11	1.63
TOPODATA	8.11	5.94	15.35	1.69	0.13	1.86
Factor LS (non-dimensional)						
TS	1.44	0.05	4.64	0.93	0.08	–
TM	1.69	0.06	8.29	1.57	0.12	1.37
ASTER	2.04	0.025	6.94	1.40	0.11	1.57
SRTM	0.59	0.012	1.70	0.36	0.003	1.06
TOPODATA	1.45	0.02	0.97	0.97	0.007	1.20
Convergence (non-dimensional)						
TS	0.34	-35.69	23.07	7.81	0.60	–
TM	1.10	-32.35	24.90	7.26	0.56	9.94
ASTER	0.88	-32.00	42.45	10.34	0.79	10.11
SRTM	0.35	-16.59	24.34	6.81	0.52	8.35
TOPODATA	0.32	-29.93	47.71	9.01	0.69	8.37

[(1)] Min: minimum; [(2)] Max: maximum value; [(3)] SD: standard deviation; [(4)] SE: standard error; [(5)] RMSE: root mean square error, calculated as the difference between the TA derived from the DEM-TS (reference) and the TA of each DEM.

contour lines is severely aggravated (Wise, 2000; Druzina, 2007; Valeriano, 2008). For DEM-ASTER, the results are affected by the low precision of elevation data (Figure 4) and the high number of spurious depressions (Table 3).

These TA are directly related to erosion and deposition processes, the speed of surface flows, reflected in the soil erosion rate, residual water content in the soil profile and soil formation processes (Wilson and Gallant, 2000). In DSM studies, these TA are used to build predictive models of soil classes and properties, and in this case, values that do not adequately represent the soil can compromise the performance of the prediction models (McBratney et al., 2003).

These differences between the DEMs will have consequences on DSM at the detailed and semi-detailed level, due to the differentiated terrain representation for each DEM and differences between the TA derived from them. Thus, the setting of class prediction models and soil properties from TA extracted from these DEMs will have different performances. This was stated by Teske et al. (2014) in an evaluation of the DEMs TOPODATA, SRTM, ASTER and TM, at resolutions between 90 m and 30 m for use in DSM of soil classes in an area of 6,850 ha on a scale of 1:20,000. They observed a high ratio between the elevation data and mapping units, and found that DEMs with a wide amplitude in elevation values generate decision tree models with less selected TA, reflected in the reduction of predicted soil classes. On the other hand, Giasson et al. (2013) found small differences between the number of TA selected by the decision tree model and the Kappa index in a comparison of the DEMs ASTER (30 m), SRTM (30 m) and SRTM (90 m) for DSM at a scale of 1:50,000 in an area of 53,200 ha.

Our results showed that the use of free DEMs obtained by remote sensing, with low resolution, is more limited in areas with little topographic variation and scales ≥1:10,000 than that of DEM-TS. However, the results of DEM-SRTM and DEM-TOPODATA were similar to those of DEM-TS with regard to the evaluation of TA, but in the assessment of the scale, they adjusted to 1:50.000. According to Valeriano (2008), these DEMs were constructed to provide terrain data on a global scale, i.e., for applications in large areas, at scales between 1:100,000 and 1:250,000. Limiting factors are the high time and cost demand to obtain the TS. The use of Unmanned Aerial Vehicles (UAV) to obtain land elevation data may be addressed in future research. This can be a potential research area regarding landscape modeling in Brazil.

CONCLUSIONS

Open source DEMs are limited in terms of quality of the elevation data for DSM at 1:10,000 in areas with little topographic variation, but can be used for studies in these areas for DSM at scales from 1:25,000 to 1:50,000. The exception was the DEM-ASTER, which should be used only at scale of 1:100,000 under the results of this study.

The DEM-TS was the most appropriate model to represent the terrain surface and derive the terrain attributes for environmental modeling and fitting of the prediction models for DSM at 1:10.000 in the study area.

The DEMs differ in the terrain representation, for which the defining factors for the model quality were the manner of elevation data acquisition and (mainly) the topography features. Studies on DSM using information from TA derived from DEMs should take into account the model accuracy in relation to the scale.

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