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Conversion of the Digital Surface Model to the Hydrologically Conditioned Digital Elevation Model for the Marinheiro Stream Watershed in Sete Lagoas, Brazil

Hugo Henrique Cardoso de Salis[1], Adriana Monteiro da Costa[2], João Herbert Moreira Vianna[3], Marcos Antonio Timbó Elmiro[2]

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A B S T R A C T

A correct and accurate cartographic representation of the relief of watersheds is increasingly required due to the increased human actions on water resources. The objective of this work was to propose a conversion of the digital surface model (DSM) to the hydrologically conditioned digital elevation model (HCDEM) for the Marinheiro Stream Watershed in Sete Lagoas MG, Brazil, as a subsidy for hydrological and environmental analyses in this region. The methodology was developed in seven stages: a) Automatic classification of the Geoeye image; b) Ordinary kriging of the DSM points for areas without arboreous vegetation; c) Obtaining of the contour lines; d) Obtaining of points of exposed soil areas of the DSM and obtaining of the drainage network; e) Obtaining of the hydrologically conditioned digital elevation model (HCDEM); f) Correcting of the topographic profile of the drainage network region; and g) Analysis of the results. According to the results, the conversion of the model minimized the canopy effects and increased the coherence of the representativeness of the relief surface. The standard deviation found was 3.9 m, confirming the better performance of the HCDEM over the DSM, which presented a value of 4.95 m. Therefore, according to the validation points obtained in the field, the product of this study has a consistent basis for accurate and reliable hydrological, geomorphological, and geo-ecological analyses in the evaluated watershed.
Keywords: Geoprocessing, Environmental analysis, TanDEM-X.

Conversão do modelo digital de superfície (MDS) a modelo digital de elevação hidrologicamente condicionado (MDEHC) para a bacia hidrográfica do Córrego do Marinheiro, Sete Lagoas – MG

R E S U M O

O aumento das ações antrópicas sobre os recursos hídricos está exigindo, cada vez mais, a correta e precisa representação cartográfica do relevo de uma bacia hidrográfica. O objetivo principal do presente trabalho é apresentar uma proposta para conversão de modelo digital de superfície (MDS) para modelo digital de elevação hidrologicamente condicionado (MDEHC) para a bacia hidrográfica do Córrego do Marinheiro, Sete Lagoas – MG, como subsídio para análises ambientais e hidrológicas na área. A metodologia foi desenvolvida em sete etapas principais, quais sejam: a) Classificação automática da imagem Geoeye; b) Krigagem ordinária dos pontos do MDS para as áreas sem vegetação arbórea; c) Obtenção das curvas de nível; d) Obtenção de pontos correspondentes às áreas de solo exposto do MDS e obtenção da rede de drenagem; e) Obtenção do Modelo digital de elevação hidrologicamente consistido (MDEHC); f) Correção do perfil topográfico na região da rede de drenagem; e g) Análise dos resultados. Os resultados encontrados indicaram que o processamento realizado permitiu minimizar efeitos do dossel no modelo e aumentar a coerência na representatividade da superfície do relevo. O desvio padrão, de 3,9 m, confirma o melhor desempenho do MDEHC em detrimento do MDS, com valor obtido igual a 4,95m. Foi possível concluir que, de acordo com os pontos de validação obtidos em campo, o produto deste estudo apresentou uma base consistente para futuras análises hidrológicas, geomorfológicas e geoecológicas na bacia com acurácia e confiabilidade.
Palavras – chave: Geoprocessamento, Análise ambiental, TanDEM-X.

[1]Master student at the Graduate Program in Analysis and Modeling of Environmental Systems. Federal University of Minas Gerais (UFMG), Belo Horizonte, Minas Gerais, Brazil. E-mail: hugohcsalis@gmail.com (corresponding author). [2]Professor at the Federal University of Minas Gerais (UFMG), Department of Cartography, Graduate Program in Analysis and Modeling of Environmental Systems. E-mail: drimonteiroc@gmail.com; timboelmiro@gmail.com. [3]Researcher at the Brazilian Agricultural Research Corporation (EMBRAPA), EMBRAPA Maize and Sorghum. E-mail: joao.herbert@embrapa.br

Introduction

A correct and accurate cartographic representation of the relief of watersheds is increasingly required due to the increased human actions on water resources. This representation provides important information for the diagnosis and management of environmental resources. Digital elevation models and digital surface models are ways of characterizing the relief of a watershed, which have become key elements to understand a region. The first represent the land at the ground level without interference of constructions and vegetation, and the second represent the relief considering these components (Ribeiro & Ferreira, 2014).

Digital surface models result from technological advances and efforts to automatically obtain elements and geomorphological characteristics of the terrain through mathematical representations derived from local latitude, longitude, and altitude information (X, Y and Z) (Johnston and Rosenfeld, 1975). Some digital models of surface present a high amount of spurious depressions, and others present information of the terrain considering constructions and vegetation cover, which need previous corrections from the hydrological point of view (Chagas et al., 2010). Once the corrections are made, the digital surface model will present hydrological consistency, i.e., it will allow the production of a hydrological model compatible with the reality that can be used for analyzes and studies in various areas.

The hydrologically conditioned elevation model can have different purposes, such as morphometric characterization of watersheds, calculation of annual losses of soils, delimitations of permanent preservation areas along watercourses and hilltops, regionalization of flows, calculation of topographic factors and landscape units, and mapping of flood risk areas (Baena et al., 2004, Guimarães & Da Penha, 2009, Elebson et al., 2011, Pinto & Rossete, 2012, Coutinho et al, 2014).

In this context, the objective of this work was to propose a conversion of the digital surface model (DSM) to the hydrologically conditioned digital elevation model (HCDEM) for the Marinheiro Stream Watershed in Sete Lagoas MG, Brazil, as a subsidy for hydrological and environmental analyses in this region.

Material e methods

The study area encompasses the Marinheiro Stream watershed (Figure 1), which has an area of 1,480 ha and is in the municipality of Sete Lagoas, state of Minas Gerais, Brazil, between the flat coordinates 581100.3 to 587493.5 East and 7841747.5 to 7847420.3 North, geodetic datum SIRGAS-2000 and projection UTM 23 south.

This watershed is in the Cerrado biome, but also presents fragments of native vegetation with predominance of montane semideciduous forest, that is typical of the Atlantic Forest biome (Costa et al., 2015). It also presents anthropic areas with annual crops and pastures (Scolforo, 2008).

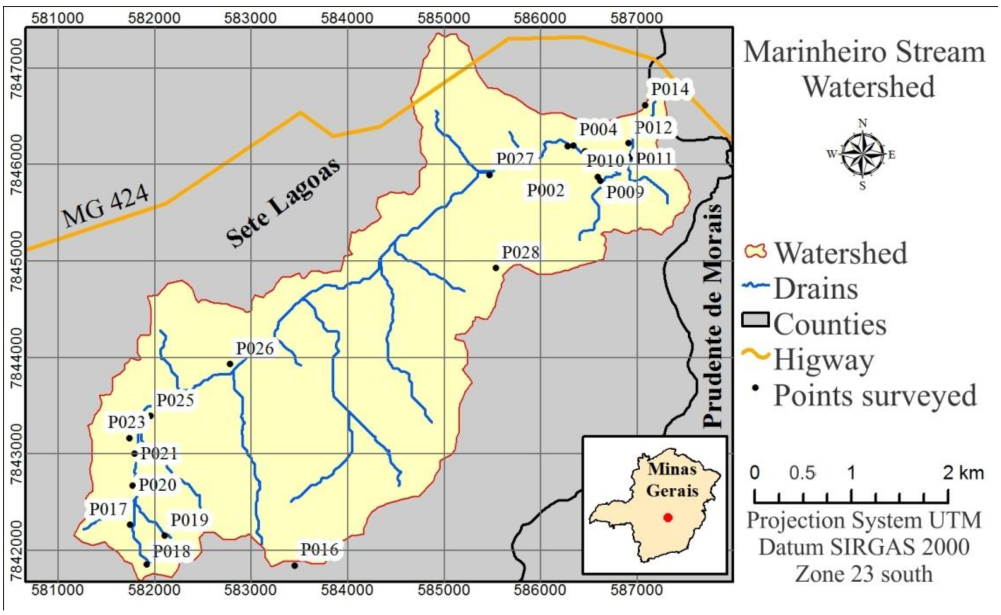

Figure 1. Location of the study area

The materials used in the study were: a) Digital Surface Model (DSM) of 2014, from the TanDEM-X satellite of the German Aerospace Center, with spatial resolution of 12 m (Wessel, 2013); b) scenes of the Geoeye satellite (spatial resolution of 0.5 meters) from May, 2015; c) Ashtech Promark 2 single frequency GPS (L1); and d) Arcgis software version 10.3 (ESRI, 2013).

The method was developed in seven stages: a) Automatic classification of the Geoeye image; b) Raster conversion for points and ordinary kriging of the DSM points for areas without arboreous vegetation; c) Obtaining of the contour lines; d) Obtaining of points of exposed soil areas of the DSM and obtaining of the drainage network; e) Obtaining of the hydrologically conditioned digital elevation model (HCDEM); f) Correcting of the topographic profile of the drainage network region; and g) Analysis of the results.

In the first stage, the automatic classification of the Geoeye image, the first step was the preprocessing of the scene, using filtering and contrast enhancement to attenuate the effects of cloud shadows and relief in bands 1, 2 and 3. Subsequently, training samples were selected and the automatic classification was performed using the Arcgis 10.3 software, through the maximum likelihood classifier. Finally, post-processing and refinement were performed, with replacement of image cells based on neighboring cells.

In the second stage, the raster format of the DSM was converted to the dots-type vector format, then, the points of areas with arboreous vegetation were cut off, crossing the DSM with the classified image. Finally, ordinary kriging was performed for interpolation of the points without the areas with arboreous vegetation, assuming that the constant mean is unknown. The formula used for the kriging was based on the following equation (Royle et al., 1981):

$$x_p = \sum_{i=1}^{N} \lambda_i X_i$$

wherein Xp is the interpolated variable; Xi is the value of the variable in the *i*th neighbor location; λi is the unknown weight, established based on the semivariogram for the value measured at the *i*th location; and N is the number of measured values.

In the third stage, the contour lines were obtained from the raster resulting from the interpolation of the points without the areas with arboreous vegetation, adopting a vertical equidistance of 10 m. Then, the drainage network was obtained using the "Stream Order" command of the Arcgis 10.3 and the refinement of the result was performed to obtain the lines that did not correspond to the water drainage channels of the watershed based on field analysis.

Subsequently, the points of the locations with exposed soil in the DSM were obtained, considering that this class represents the elevation of the land surface in the Marinheiro Stream watershed, with negligible interference of vegetation or constructions in the area.

In the fifth step, the data was re-interpolated using the "Topo to raster" command of the Arcgis 10.3. This method is designed specifically for the creation of HCDEMs from information obtained from points representing the elevation surface, contour lines, drainage network, and polygon of the watershed boundary (Hutchinson, 2011).

In the sixth stage, the first step was to obtain the drainage network from the HCDEM and apply the "negate" command to invert the raster values of the hydrography by multiplying them by -1. The inversion was performed to correct the spurious depressions in the watercourse regions of the watershed, using the command "Fill". The hydrography was then returned to its original value and the corrected cells were replaced in the original HCDEM.

The last stage was to compare the results obtained from the HCDEM with the DSM values and the values of 25 precise validation points that were surveyed in the Marinheiro Stream watershed using a single frequency geodetic GPS.

Results and discussion

The classification of the Geoeye image for the Marinheiro Stream watershed by the maximum likelihood classifier generated five classes of land use and cover: cultivated area, water body, arboreous vegetation, pastures, and exposed soil (Figure 2). Each land use and occupation class have the potential to directly affect the altimetric precision of the local relief information, which highlights the importance of knowing their spatial extent.

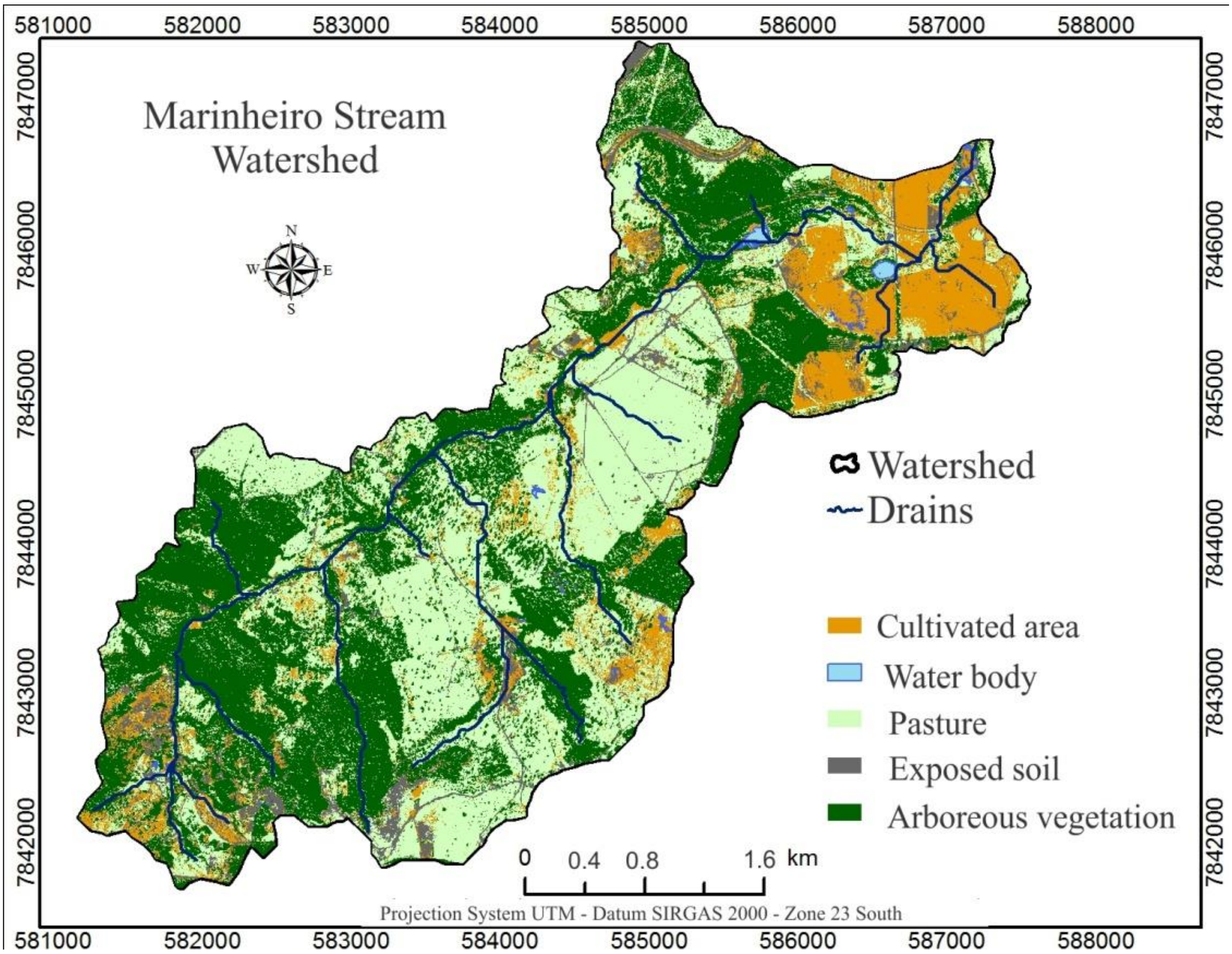

Figure 2. Spatial distribution of land use and occupation in the Marinheiro Stream watershed, Sete Lagoas MG, Brazil

According to Figure 2, the arboreous vegetation class is the one that can alter the altimetry values of the area due to its height dimensions. Moreover, this class is distributed throughout the watershed and its presence is more concentrated in high areas, near the headwaters, along the main watercourse, and in the northeast part of the watershed, which presents a remnant fragment of planted forest in an adult stage of development.

The arboreous vegetation class is, spatially, the most comprehensive in the area, representing 40.5% of the watershed, approximately 100.6 ha (Table 1).

The second most comprehensive class is pasture, accounting for 38% of the watershed. The exposed soil, cultivated area, and water body classes combined represented 21.4% of the watershed.

Table 1. Area and percentage of land use and occupation classes in the Marinheiro Stream watershed, Sete Lagoas MG, Brazil.

Class	Area (hectares)	%
Cultivated area	213.1	14.4
Water body	4.4	0.3
Pasture	599.4	40.5
Exposed soil	562.4	38
Arboreous Vegetation	100.6	6.8
Total	1.480	100

The methodological procedures adopted made possible to obtain a HCDEM that disregards the presence of large-sized arboreous vegetation, minimizing the effects of pasture and cultivated areas, and preserves the altimetric values of the exposed soil areas (Figure 3).

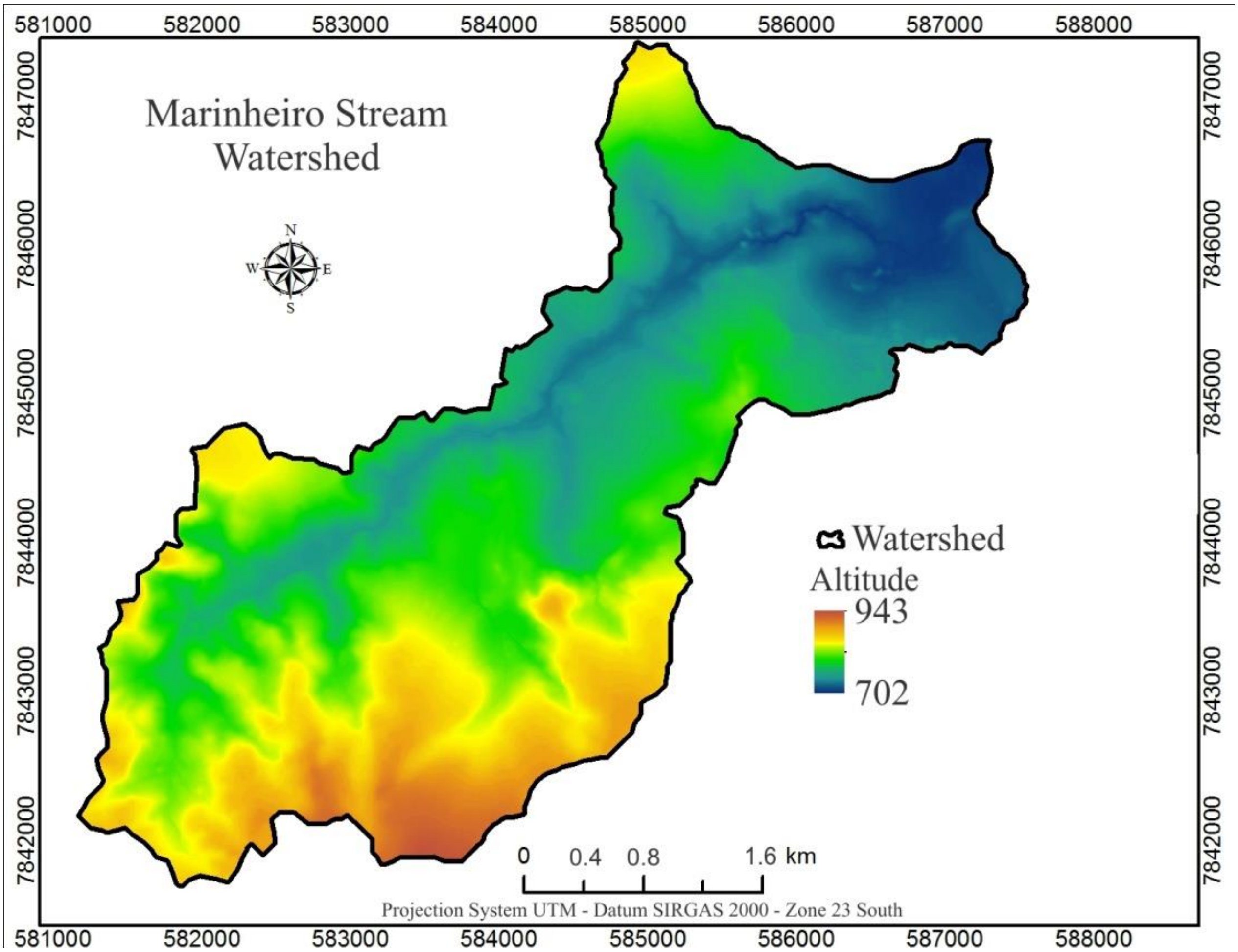

Figure 3. Hydrologically conditioned digital elevation model for the Marinheiro Stream watershed, Sete Lagoas MG, Brazil

Figure 3 shows the altimetric spatial distribution of the Marinheiro Stream watershed, indicating a range of altitudes varying between 702 and 943 meters. The mean altitude found was 801 m and the standard deviation was 53 m. These values directly affect the landscape representation and determine the relationships between geomorphological elements, and their dynamics. The spatial distribution of the altitude classes of the Marinheiro Stream watershed, compared to the DSM values, is presented in Table 2.

According to Table 2, the 760 to 790 m altimetric class represents 19.2% of the area and has the greatest spatial coverage. Moreover, based on the spatial distribution of the 9 determined altimetric classes, no significant numerical differences between HCDEM and DSM were found. This indicated that the proposed method provided only local refinements (Figure 4) and preserved the methodological parameters for obtaining the data of the DSM (TanDEM-X). The initially surveyed topographic data did not undergo significant changes that invalidated the interferometric technique originally used to obtain the primary data.

Table 2. Spatial distribution of the altitude classes according to the HCDEM and DSM in the Marinheiro Stream watershed, Sete Lagoas MG, Brazil.

Altitude class (m)	HCDEM		DSM	
	Hectares	**%**	**Hectares**	**%**
702 to 730	142.9	9.7	143.56	9.6
730 to 760	221.6	15	222	14.5
760 to 790	284.8	19.2	284.16	19.4
790 to 810	196.3	13.3	196.84	13.1
810 to 840	243.3	16.4	242.72	16.6
840 to 870	220.6	14.9	220.52	15.2
870 to 900	115.4	7.8	115.44	7.8
900 to 930	48.5	3.3	48.84	3.4
930 to 960	6.6	0.4	5.92	0.5
Total	1480	100	1480	100

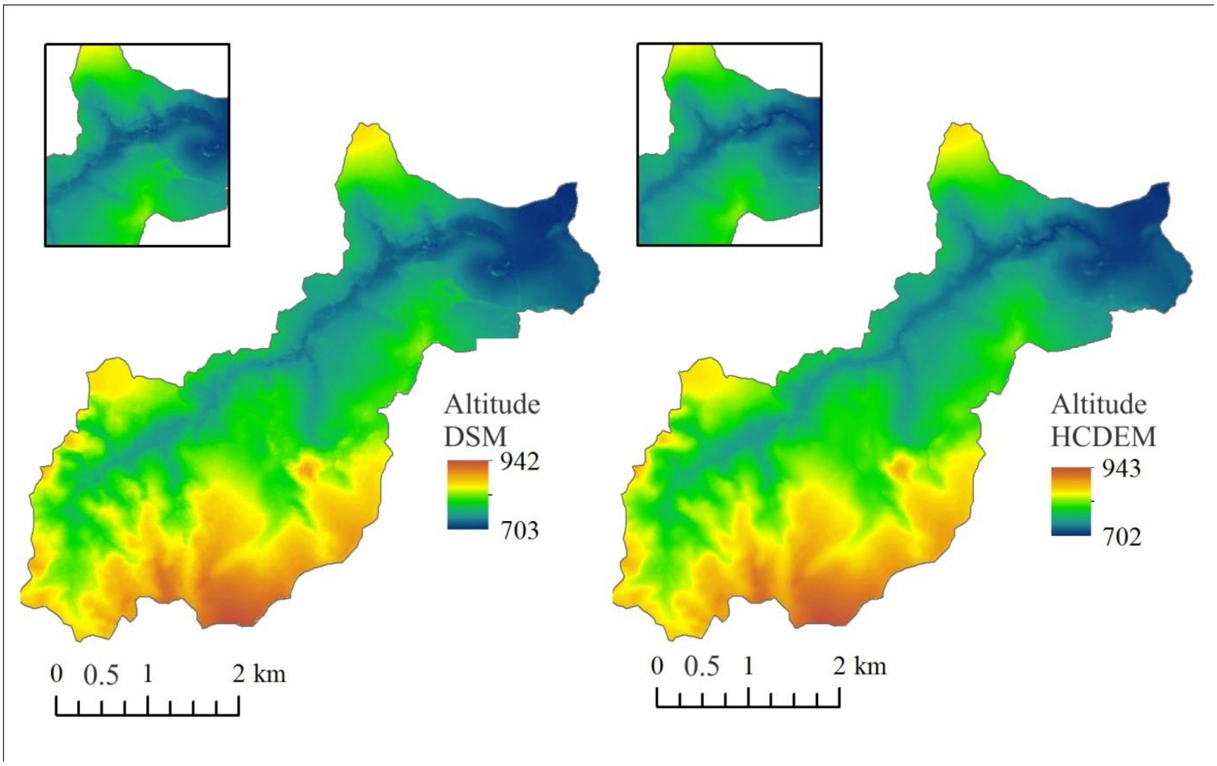

Figure 4. Visual comparison between the DSM and the HCDEM for the Marinheiro Stream watershed, Sete Lagoas MG, Brazil

Figure 4 shows the improvement of the vertical accuracy obtained by the processing of the DSM, obtaining the HCDEM. The representation of the surface is more detailed in the HCDEM due to the removal of canopy interference from arboreous vegetation. In addition, noises in regions near the water courses were attenuated and the drainage network profile was corrected to determine the preferred path of water in the drainage areas.

The maximum and minimum altitudes in both models show similarities, indicating no significant effect of the arboreous vegetation in the highest and lowest portions of the Marinheiro Stream watershed. Pasture areas predominate in the higher regions, and cultivated areas predominate in the lower regions (Figure 2). The correction of the uncertainties in the topographic representation of the DSM presented sporadic altimetric differences to the results obtained in the HCDEM (Figure 5).

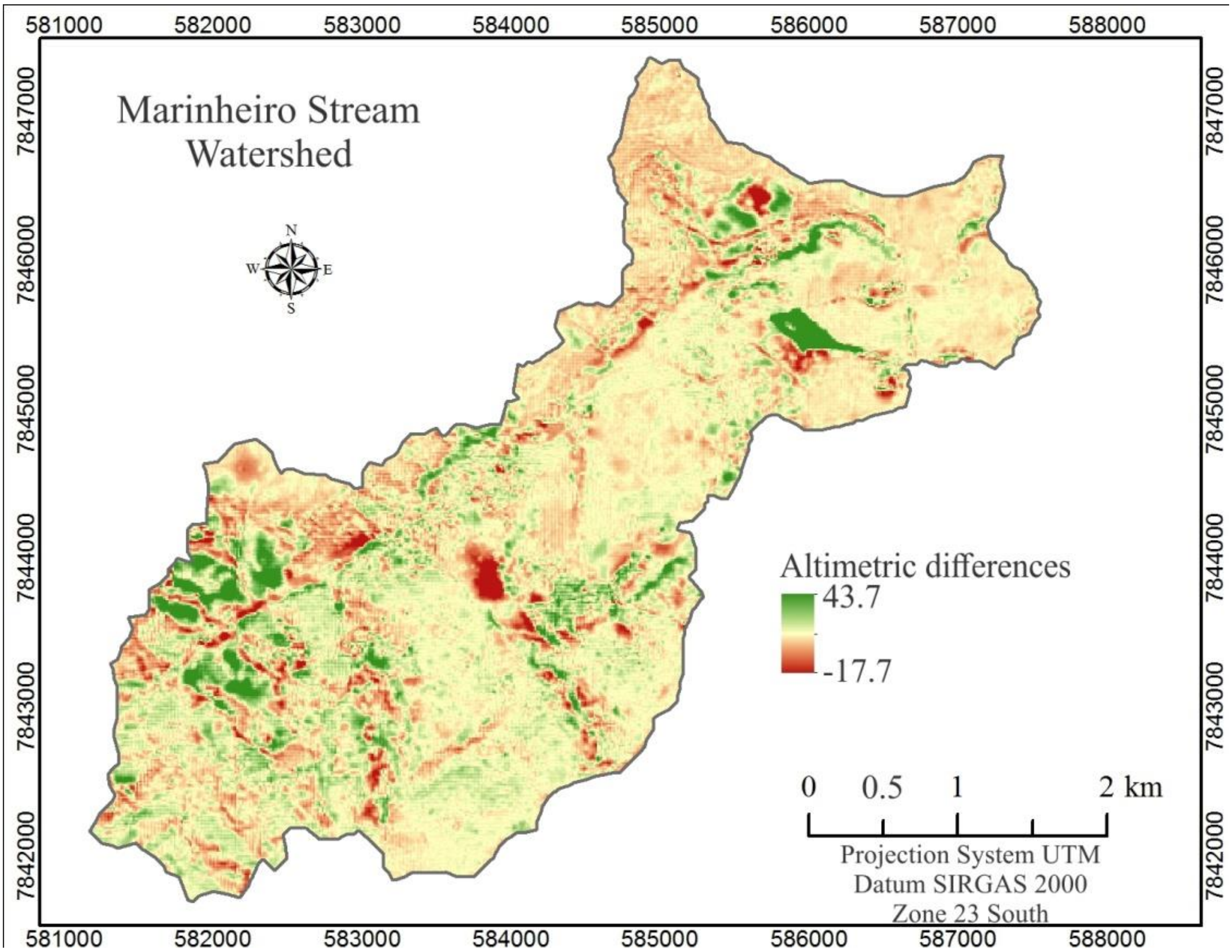

Figure 5. Spatial distribution of the altimetric differences between the DSM and the HCDEM for the Marinheiro Stream watershed, Sete Lagoas MG, Brazil.

The altimetric differences presented in Figure 5 highlight regions with green and red shades. The regions in green shades (upper limit of 43.7 m) are areas with greatest positive differences between the DSM and the HCDEM; they represent portions of the watershed with presence of high arboreous vegetation and overestimated relief by the original data regarding the ground level. The regions highlighted in red shades (lower limit of -17.7 m) are areas with the greatest negative differences and that present spurious depressions in the watershed. The mean value of these differences was 12.5 m, which may be consistent with the average heights of native forest species present in the watershed, which form, spatially, the predominant class in the watershed area (Lima et al., 2008; Carvalho et al., 2010).

The initial data of the present study were converted from the Datum WGS-84 south zone 23, to Datum SIRGAS 2000, south zone 23, both presenting altimetric representations with ellipsoidal basis, as well as the geodesic points obtained in the field. The results of the accuracy evaluation of the obtained data are presented in Table 3.

According to Table 3, the greatest altimetric difference between the validation points obtained by the geodetic GPS and the DSM was -15.26 m (Point 16); this indicates that the DSM overestimated by more than fifteen meters the real surface in this point. The greatest difference obtained in the HCDEM was -9 m (Point 20); this indicates that the processing minimized the canopy effects in the model and increased the coherence in the representativeness of the relief.

The mean differences found confirm the previous analysis. The average difference between the 25 validation points surveyed with the GPS and the DSM was -3,22 m; and the average difference between them and the HCDEM was smaller, -1,08 m. According to these results, the DSM overestimate the mean height at these points in more than three meters; and the HCDEM presented a mean overestimated height of approximately 1 meter. The standard deviation of 3.9 m confirms the better performance of the HCDEM over the DSM, which presented a value of 4.95 m.

A study carried out in a coastal plain in the northern state of Rio de Janeiro developed a terrain digital model (TDM) and compared it with the TDM provided by the Brazilian Institute of Geography and Statistics; the results showed a significant vertical uncertainty for the latter, indicating the need of using methods that produce consistent digital representations of the relief (Folharini et al., 2015).

Cardoso et al. (2016) developed a HCDEM for the Rio Doce River basin, in the states of Minas Gerais and Espírito Santo, and compared it with the digital elevation model of this basin. Their results showed the need for models with satisfactory quality for the correct development of the methodology that generate the hydrological model, since they found a change in the water flow direction by changing the MDE to the HCDEM

Table 3. Ellipsoidal heights obtained through points surveyed using a geodetic GPS, DSM and HCDEM.

Point	Ellipsoidal heights (m)			Difference (m)	
	Geodetic GPS	DSM	HCDEM	GPS ≠ DSM	GPS ≠ HCDEM
1	721.27	725.46	720.38	-4.19	0.89
2	721.93	721.71	716.58	0.21	5.35
3	718.29	724.78	713.91	-6.49	4.38
4	714.61	720.46	716.97	-5.85	-2.36
5	716.65	715.83	713.31	0.82	3.35
6	712.37	710.98	710.44	1.39	1.93
7	713.23	712.85	710.87	0.38	2.36
8	713.05	712.87	711.80	0.18	1.25
9	711.61	714.14	714.11	-2.53	-2.49
10	713.56	710.03	711.38	3.53	2.18
11	709.14	708.82	709.13	0.32	0.01
12	706.74	707.19	706.99	-0.45	-0.25
13	701.79	705.43	702.00	-3.64	-0.21
14	703.88	705.86	706.31	-1.98	-2.43
15	946.46	945.41	942.53	1.05	3.93
16	818.77	834.03	822.51	-15.26	-3.73
17	848.39	851.03	850.94	-2.63	-2.55
18	850.46	855.33	854.36	-4.87	-3.90
19	807.18	814.84	812.65	-7.66	-5.47
20	775.97	786.22	784.98	-10.24	-9.00
21	771.89	781.12	780.81	-9.23	-8.92
22	766.88	774.79	771.56	-7.91	-4.68
23	749.52	751.76	753.61	-2.25	-4.09
24	722.78	729.19	727.39	-6.41	-4.61
25	821.10	817.89	818.86	3.21	2.23
Mean				-3.22	-1.08
σ				4.59	3.93

Final considerations

The surveying of the points representing the land use and occupation class characterized by forest formations (arboreous vegetation) increased the accuracy of the representation of the relief in the study area through the HCDEM.

The data processing in the HCDEM was possible because of the proximity between the dates of obtaining of the digital surface model (2014) and the Geoeye image (2015), thus, no significant changes in the land surface occurred in the interval between these data, especially changes in the high vegetation cover, and constructions.

According to the validation points obtained in the field, the product of this study has a consistent basis for accurate and reliable hydrological, geomorphological, and geo-ecological analyses in the evaluated watershed.

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