

DEM-based Geomorphological Mapping and Landforms Characterization of a Tropical Karst Environment in Southeastern Brazil

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Abstract

This work presents a 1:10,000 geomorphological mapping of an area in southeastern Brazil, based on morphometric analysis of Digital Elevation Models (DEMs), while classical methods focus on photo interpretation. Data derived from the DEM include elevation, slope gradient, slope aspect, vertical and horizontal curvatures, amplitude, elongation and wavelength of landforms. These parameters were used along with slope shape and drainage patterns to classify the landforms according to the Land Systems method, in which portions of the landscape that presents similar terrain attributes are grouped from regional (low detail) to local (high detail) scales, respectively, Land Systems, Land Units and Land Elements. The São Paulo State geomorphological map at 1:1,000,000 scale is considered the best reference source, and was compared with the results obtained in this project. Two Land Systems, four Land Units and twelve Land Elements were identified in the study area. In this area, karst terrain occurrence are common and easily identified due their characteristics of drainage patterns, amplitude and slope gradient. Karst terrain boundaries defined in this study do overlap with those defined in the state map, however the morphometric analysis allowed a better description of the terrain attributes used to define them. The terrain attributes derived automatically from the DEM enabled an accurate geomorphological classification of the study area. The methodology presented in this paper is considered effective for mapping landforms at a detailed scale and can be employed in regional scale mapping using coarser resolution DEMs.

Keywords: Geomorphology, Geomorphometry, Karst, Digital Elevation Model, Land Systems, Ribeira River

1. Introduction

The technological development in the past decades allowed an exponential growth of computational resources in the Earths Surface analysis and mapping, where airborne (i.e., LiDAR, UAVs) and satellite-based topographic data support the analysis of physical features

of landscape the directly from Digital Elevation Models (DEMs).

Topographic data remains the primary source of information for many Earth Science studies such as geomorphology and landscape development (Franklin, 1987; Pike, 1995; Evans, 1998; Schmidt and Andrew, 2005; Erskine et al., 2007; Minár and Evans, 2008; Pike et al., 2009); risk assessment (Metternicht et al., 2005; Ghuffar et al., 2013; Wang et al., 2013); landslide identification and mapping (McKean and Roering, 2004; Glenn et al., 2006; Ardizzone et al., 2007; Eeckhaut et al., 2007; Booth et al., 2009; Sterzai et al., 2010; Jaboyed-

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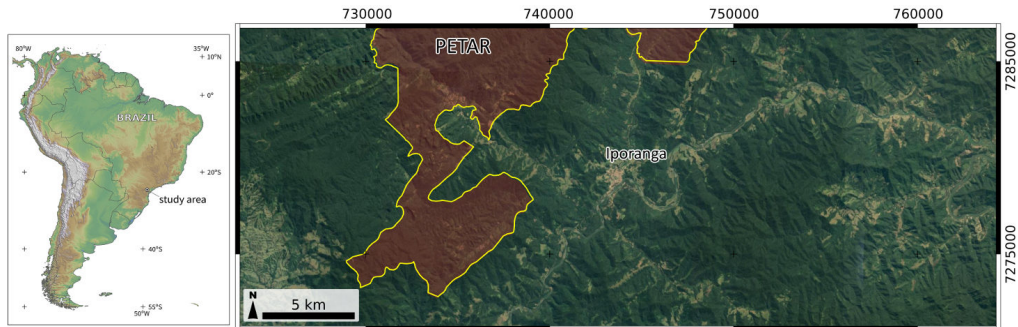


Figure 1: Location of study area in Southeastern Brazil, highlighting the southern portion of the Upper Ribeira State Park (PETAR).

off et al., 2012; Guzzetti et al., 2012); and morphotectonics (Hiruma and Riccomini, 1999; Modenesi-Gauttieri et al., 2002; Grohmann et al., 2007). While terrain attributes derived from DEMs enable an accurate characterization of the landscape in both regional and local scales, the occurrence of errors and artifacts due to data noise, pixel size, re-projection, interpolation method and others, still pose a substantial problem (Garbrecht and Martz, 1994; Hengl, 2006; Raafaub and Collins, 2006; Grohmann and Steiner, 2008; Hebler and Purves, 2009), which must be addressed before any analysis.

This research main goal was to generate a geomorphological map based exclusively on a DEM-derived attributes, and compare it to the traditional (i.e., manual) geomorphological mapping method. A state-wide geomorphological map at 1:1,000,000 scale, considered the best regional morphological map available encompassing the entire study area, was used for comparison.

The area selected for this study is a hilly and forested region in southeastern Brazil, known by the occurrence of karst features Natural Reserves. A 1:10,000 geomorphological map was created with terrain attributes derived from a DEM, based on the classification of areas with similar physical features and terrain attributes.

Terrain attributes derived automatically from the DEM enabled an accurate geomorphological classification of the study area. The methodology presented in this paper is considered effective for mapping landforms at a detailed scale and can be employed in regional scale mapping using coarser resolution DEMs.

2. Study Area

The study area is located in the southern portion of the São Paulo State, SE Brazil, within the upper Ribeira river valley (Fig. 1). The region is characterized by a landscape of hills and ridges with dense Atlantic Forest coverage preserved in conservation units, agricultural areas, and small towns and villages. The climate is subtropical humid, with hot and rainy summer and without a typical dry season in the winter (Cfa and Cfb of Koppen, 1948). The main conservation unit in the area is the Upper Ribeira State Park (PETAR – *Parque Estadual Turístico do Alto Ribeira*), created in 1958 with the purpose of protecting the caves and surrounding forest.

Geologically, the area is within the Mantiqueira Province, Apiai Domain (Hasui, 2012), and is composed mainly by supracrustal rocks of low to medium metamorphic degree of the Açungui Group and gnaiss-migmatite basement (Fig. 2A). The Açungui Group comprises intercalated layers of metasediments in NE-SW oriented bands controlled by shear zones (Campanha and Sadowski, 1999; Heilbron et al., 2004). The carbonate rocks in the area belong to the Middle Proterozoic Lajeado Subgroup (Campanha and Sadowski, 1999). Predominance of carbonate rocks occur in the West portion of the study area while pelitic rocks are abundant at East.

The geomorphology of the region (Fig. 2B), located in the transition zone between the Atlantic Plateau (locally known as the Guapiara Plateau) and the Coastal Lowlands, is marked by a mountainous landscape with maximum altitude above 1000 m and deep valleys with up to 800 m in amplitude. A pattern of

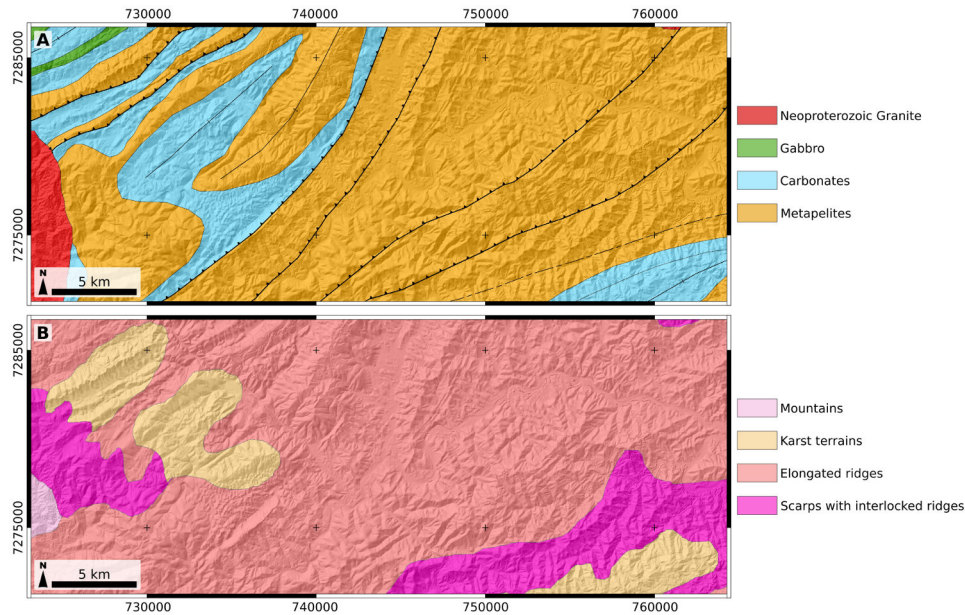


Figure 2: A) Simplified geological map of the study area. Modified from Campanha and Sadowski (1999) and Karmann and Ferrari (2000). B) Geomorphological map for the study area (Ponçano, 1981, original scale of 1:1,000,000).

polygonal karst with deep blind valleys and karstic canyons distinguishes the Ribeira Valley karst from other Brazilian karst regions Auler and Farrant (1996); Karmann and Ferrari (2000). According to Karmann and Ferrari (2000), the Ribeira Valley karst “stands out for its steep hydraulic gradients, its important allogenic recharge and incised underground drainage with vadose canyons up to 60 m deep, where vertical caves or abysses and huge collapse halls are common”.

3. Methods

3.1. Morphometric Analysis

The input data for morphometric analysis and morphological mapping consisted of a DEM with 10 m of spatial resolution, generated by interpolation of contour lines and height points digitized from a 1:10.000 topographic map. The interpolation was carried out with Regularized Splines with Tension (Mitasova and Mitas, 1993; Mitasova and Hofierka, 1993; Mitasova et al., 2005), a robust method which allows the adjustment of mathematical parameters for tension and smoothness of the resulting surface.

Using a combination of ArcGIS v.10 (ESRI, 2011) and GRASS-GIS v.6.4 (Neteler et al.,

2012; GRASS Development Team, 2015), the following terrain attributes were derived from the DEM: hypsometry, slope, plan (horizontal) and profile (vertical) curvatures. The drainage network and watershed basins were calculated in ArcGIS with a threshold of 100 cells. Morphostructural lineaments (O’Leary et al., 1976) were interpreted from a set of eight shaded relief images with illuminant positioned at 45° intervals, since the scene illumination will enhance linear features which are perpendicular to lighting, in spite of parallels ones (Grohmann, 2004; Smith and Wise, 2007). Other parameters such as extent, elongation and wavelength of individual landforms were manually extracted with ArcGIS on-screen measuring tools.

3.2. Geomorphological Mapping

Geomorphological mapping was carried out according to the *land systems* method, based on the classification of areas with similar physical features and terrain attributes, which are distinct from the adjacent portions (Christian et al., 1953; Christian, 1958; Ponçano et al., 1979; Ponçano, 1981).

Land systems exhibits the main structures of a landscape in a regional scale, being divided into minor and more detailed land portions,

namely *land units* and *land elements*. A land unit is a homogeneous tract of land at a given scale (Zonneveld, 1989) that can be described similarly in terms of its topography, soil, lithology and vegetation (Christian, 1958), such as scarps, hills and alluvial fans. Land elements are the components of land units and can be represented, for instance, by the crest, hillside or footslope of a given scarp (Ponçano, 1981).

3.3. Karst Landform Mapping

Karst landforms are the most significant landscape features in the study area due their hydrological and morphological attributes. Surface drainage in karst terrains is an important mapping feature since the underground drainage is predominant. Sinkholes and surges impose a chaotic pattern to the stream network that allows the identification of karst areas.

Carvalho Júnior et al. (2013) proposed a method for automatic delimitation of karstic landforms based on simple DEM operations. First, a depression-filling algorithm is applied to a DEM. Such algorithms are commonly utilized as a pre-processing step in geomorphological or hydrological analysis to produce a “depressionless” DEM in which the elevation of cells contained in depressions are raised to the lowest elevation value on the boundary of the depression (Jenson and Domingue, 1988; Planchon and Darboux, 2001; Lindsay et al., 2004; Lindsay and Creed, 2006).

The procedure will fill all depressions in the DEM, not only those considered as erroneous data, but also those that represent real topographic features such as river valleys and karstic depressions (dolines, poljes, polygonal basins). A second step is a subtraction between the filled and the original DEMs. This will result in a map of the filled areas, which is then compared with the geology and geomorphology of the study area to delineate karst terrains (Carvalho Júnior et al., 2013; Kakavas et al., 2015, 2018).

4. Results and Discussions

4.1. Morphometry

The hypsometric map of the study area, classified in elevation intervals of 50 m, is presented in Fig. 3A. Elevation is commonly below 450 m

with altimetric amplitude around 300 m, although it can reach 900–1,100 m in the central-west, Northwest and Southeast portions of the area, with amplitude around 400–500 m, and frequently associated with karstic landforms. In the karstic areas, drainage carving is common, as well as the presence of escarpments without a main orientation or structural control.

The slope map of the area is presented in Fig. 3B. Low slopes values are associated with streams and valleys in karstic areas and the Ribeira river. Slope angles above 20° are predominant. High slope values, usually above 40°, are common in the whole area with a high concentration in the North-Northwest portion, within karstic areas or associated with shear zones and geological contacts between carbonate and non-carbonate rocks.

Maps of horizontal and profile curvatures are in Fig. 3C and Fig. 3D, respectively. Convex horizontal curvatures indicate flow divergence and rounded landforms while concave ones represent accumulation zones in the footslopes. Convex vertical curvatures represent acceleration flow towards the footslope, and concave, deceleration. The horizontal curvature map shows predominance of convex and flat surfaces; convex forms occur in the whole study area and does not have a lithological or structural control. Flat surfaces describe hillsides, streams and valleys. Concave surfaces are commonly related to high slope and high amplitude occurring mainly in the East-Southeast portion of the area.

On the profile curvature map, flat and concave surfaces are predominant and mainly related to areas of high drainage density. Flat surfaces are abundant in the whole study area with no evidence of a lithological or structural control. Concave surfaces are related to valleys and degradation relief, are also lithology independent and their presence in karst terrains can be related to depressions such as dolines and poljes. Convex surfaces are uncommon, occurring essentially on hilltops.

4.2. Lineament Analysis

Interpreted lineaments for the study area are shown in Fig. 4, along with rose diagrams of frequency and length of lineaments per 10° interval. Two main trends are observed, at NE and at NNW. Lineaments oriented from NNE to ENE are predominant and related to

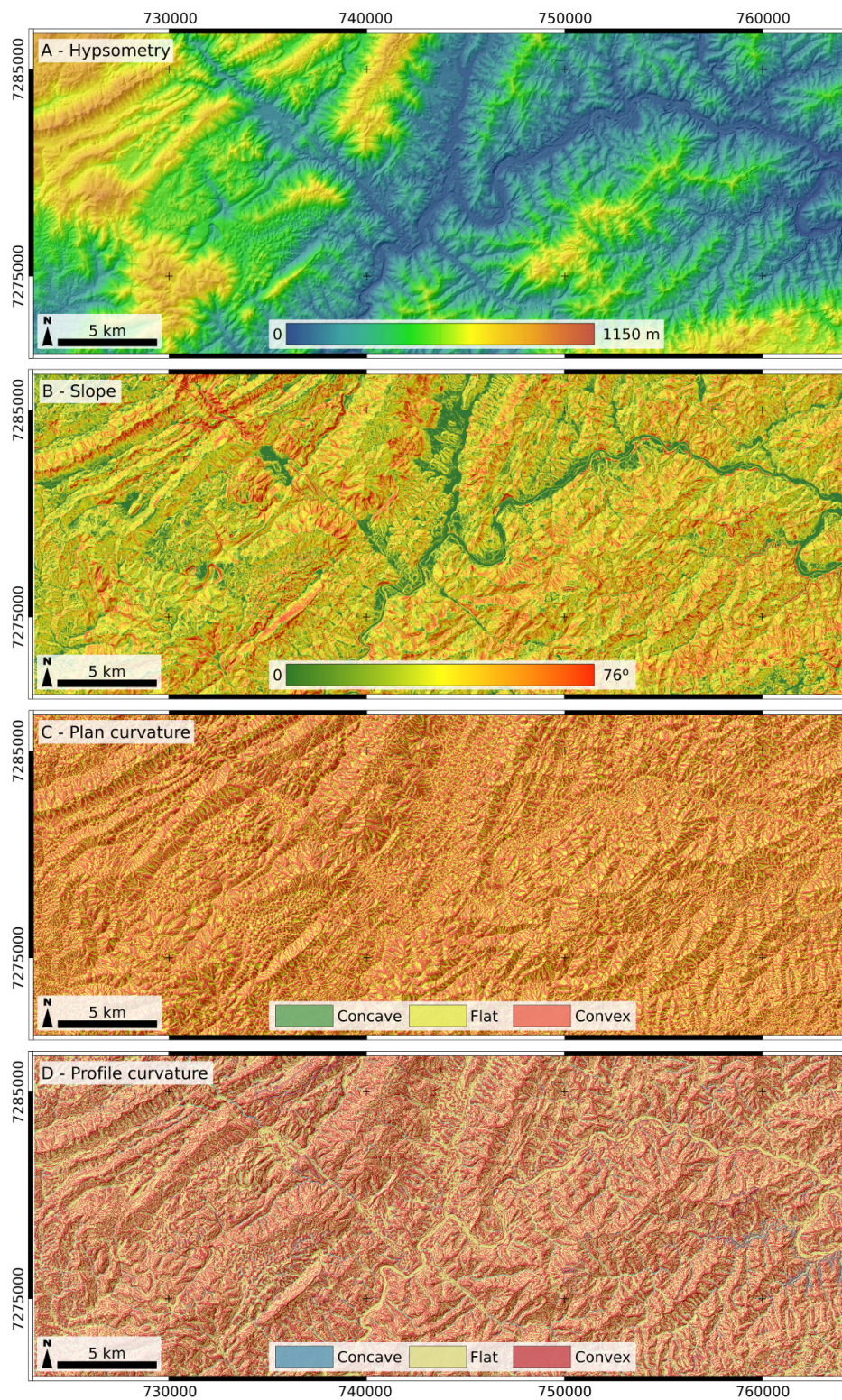


Figure 3: Morphometric maps of the study area. A) Hypsometry; B) Slope; C) Plan curvature; D) Profile curvature. UTM coordinates, zone 22J (Southern hemisphere).

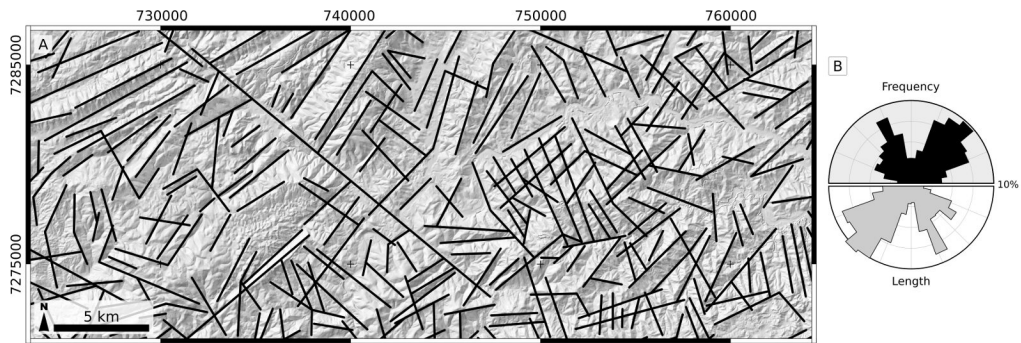


Figure 4: A) Interpreted lineaments over shaded relief image; B) Rose diagram.

the general structural trend of the Mantiqueira Tectonic Province (Campanha and Sadowski, 1999). NNW to WNW lineaments are less abundant and are related the Ponta Grossa Arch, a NW-SE massive tectonic feature over 600 km long, marked by dike swarms of the Serra Geral Formation and magnetic alignments (e.g., Riccomini et al.; Strugale et al., 2007).

4.3. Local Geomorphological Map

Based on the classification of areas with similar physical features and terrain attributes (the *land systems* method), a geomorphological map was generated for the study area at a scale of 1:10,000 (Fig. 5). Two land systems, four land units and twelve land elements were identified in the study area. The terrain attributes for each land system, unit and element are described in Table 1. Original names for the land systems, units and elements (in Portuguese) are presented as well.

Land systems were classified as Ridge Terrain (*Relevo de Serras*) and Degradation Terrain (*Relevo de Degradação*). Ridge Terrain shows the highest elevations, amplitudes and slopes in the study area and can be divided into two land units: Elongated Ridges (*Serras Alongadas*) and Karstic Terrains (*Relevos Cársticos*).

Elongated Ridges are the typical unit of this land system with elongated landforms, intense stream escarpment, steep slopes and high relief amplitude of landforms. These ridges are composed mainly by metasedimentary rocks of the Açungui Group, with structure (metamorphic foliation, shear zones) parallel to the elongation of landforms.

The land unit of Karstic Terrains is marked by a distinct surface roughness from adjacent

areas. Generally, karst areas are smoother and with lower elevations, amplitudes and slopes angles than those within the ridges. A dendritic drainage pattern is recognizable but it is not well defined and occurs in a disperse way through the land elements, controlled by karstic landforms such as sinkholes and depressions. Land elements in this unit are elongated landforms, sometimes lenticular, developed over carbonate rocks.

The land system of Degradation Terrain is predominant in the study area and is composed by two land units, Hills with Restricted Ridges (*Morros com Serras Restritas*) and Hills and Hillocks (*Morros e Morrotes*).

The land unit of Hills with Restricted Ridges occurs in a significant portion of the area, with high elevations, amplitudes and slopes (although slopes are lower than those in the Elongated Ridges land unit). The landforms are elongated although with significant sphericity, showing dendritic and radial drainage patterns. The radial drainage pattern is observed only in this land unit and indicates the presence of isolated topographic highs within a landscape dominated by hills, mounds and hillocks.

Hills and Hillocks is the predominant land unit in the study area, marked by a gentler and less eroded landscape with the lowest elevations of the area and moderate values of slope and amplitude. It is developed over non-carbonate metasedimentary rocks, with local occurrences of igneous (granitic) rocks. Land elements are generally smaller than those observed in the other units and can be elongated or rounded, with convex forms of hilltops and hillsides. This land unit represents a transition between Elongated Ridges and Hills with Restricted Ridges units.

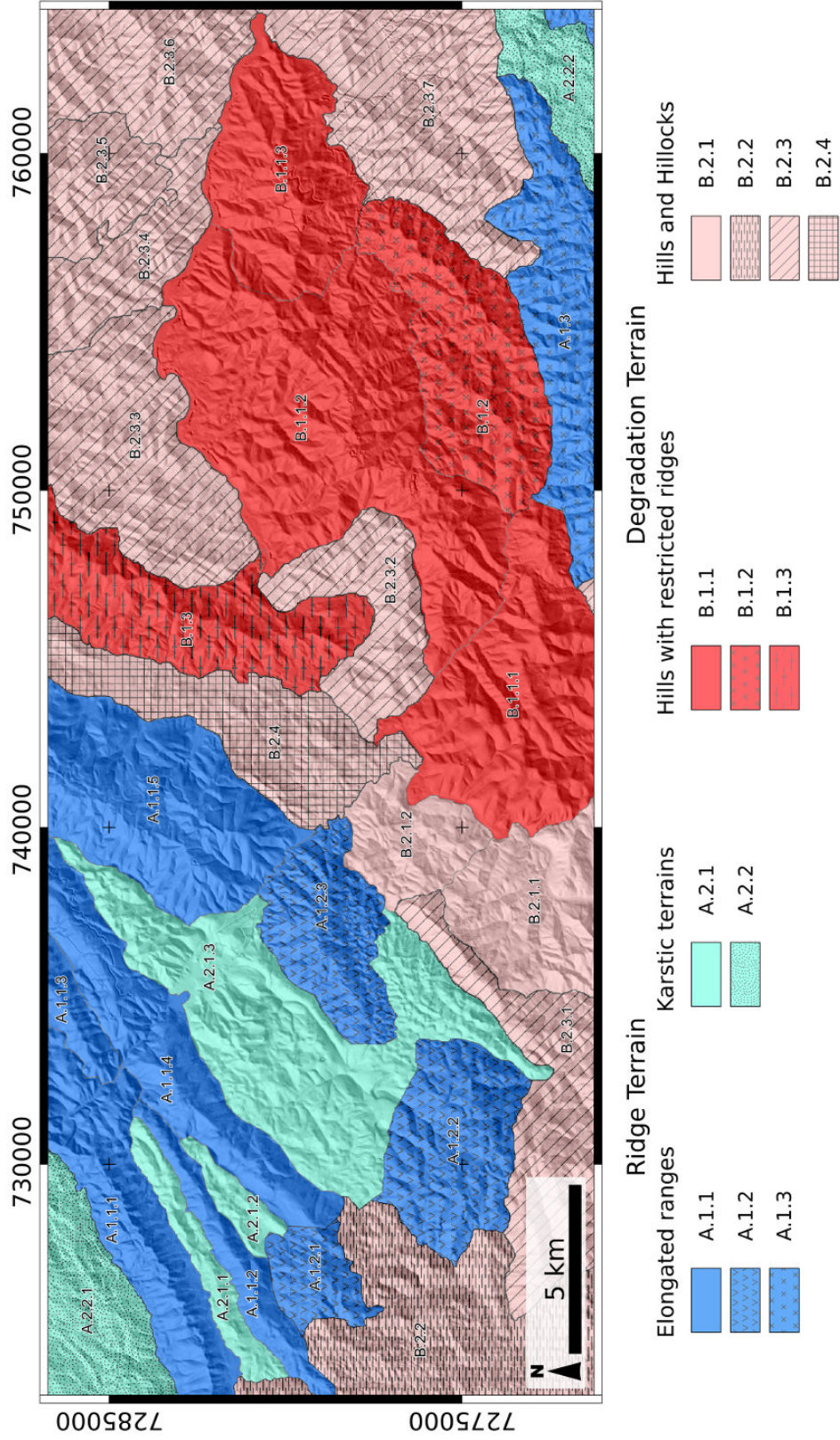


Figure 5: Local geomorphological map for the study area, generated at an original scale of 1:10,000. See Table 1 for a description of Land Systems, Units and Elements

Table 1: Description of Land Systems, Units and Elements of the geomorphological map generated in this study.

Land Systems	Land Units	Land Elements	Mapped Elements
A: Ridge Terrain	A.1: Elongated Ridges: Dendritic and parallel drainage patterns; maximum elevations above 800 m, locally above 1000 m; mean slope greater than 25°, usually above 35°	A.1.1 - Amplitudes usually above 500 m, maximum of 900 m; main slope greater than 30-35°, usually greater than 45°; elongated and NE-SW oriented landforms, wavelength between 1,000 and 2,000 m, mean elongation lower than 0.3; predominant convex surfaces	A.1.1.1 - Palmital A.1.1.2 - Roncador A.1.1.3 - Ouça Parda A.1.1.4 - Biquinha A.1.1.5 - Sem Fim
		A.1.2 - Maximum amplitudes above 600 m; mean slope greater than 20°, maximum at 35-40°; rounded and spheric landforms, wavelength between 2,000 and 4,000 m and mean elongation above 0.6; predominant convex surfaces	A.1.2.1 - Bandeira A.1.2.2 - Santo Antonio A.1.2.3 - Bairro da Serra
		A.1.3 - Maximum amplitudes below 700 m; mean slope greater than 20°, locally above 30°; elongated and slightly rounded landforms, wavelength between 3,000 and 4,000 m and mean elongation lower than 0.3; concave, flat and mainly convex surfaces	A.1.3 - Andorinhas
	A.2: Karstic Terrains: Unidentified drainage pattern, possibly dendritic; maximum elevations above 500 m, but hardly exceeds 800 m; mean slopes greater than 20° varying from 5 to 35°	A.2.1 - Mean amplitude above 300 m, hardly exceeds 500 m; main slope greater than 15°, locally exceeds 35-40°; usually elongated landforms, wavelength between 700 and 3,000 m and mean elongation greater than 0.45; predominant convex surfaces, locally concave and flat	A.2.1.1 - Furnas A.2.1.2 - Santana A.2.1.3 - Lajeado-Bombas
		A.2.2 - Maximum amplitudes below 400 m; mean slope below 20°, locally above 35°; elongated slightly rounded landforms, wavelength between 2,000 and 4,000 m and mean elongation greater than 0.4; concave and convex surfaces	A.2.2.1 - Apiaí A.2.2.2 - Tapagem
		B.1: Hills with Restricted Ridges: Predominant dendritic drainage pattern with some radial pattern; maximum elevation above 600 m, peaks at 800 m; mean slope greater than 20°, hardly exceeds 40°	B.1.1 - Mean amplitudes between 500 and 800 m; mean slope above 20° usually greater than 35°; rounded and stretched landforms, wavelength between 5,000 and 9,000 m and mean elongation greater than 0.65; flat, concave and mainly convex surfaces B.1.2 - Maximum amplitudes below 500 m; mean slope greater than 20° locally above 30°; elongated and rounded landforms, wavelength greater than 3,000 m and mean elongation of 0.5; convex and concave surfaces B.1.3 - Maximum amplitudes above 600 m; mean slope greater than 15-20°, maximum at 35°; elongated landforms, wavelength greater than 2,000 m and mean elongation lower than 0.3; concave and convex surfaces
B: Degradation Terrain	B.2: Hills and Hillocks: Dendritic drainage patterns, locally parallel and radial patterns; maximum elevations above 400 m usually exceeds 600 m; mean slope greater than 15°, occasionally above 30°	B.2.1 - Amplitudes vary between 200 and 500 m; mean slope between 15 and 20°, locally greater than 30°; elongated and sub-rounded landforms, wavelength between 500 and 2,000 m and mean elongation between 0.4 and 0.5; convex and predominant concave surfaces	B.2.1.1 - Descalvado B.2.1.2 - Taquaruiva
		B.2.2 - Amplitudes vary between 300 and 600 m; mean slope greater than 15°, locally greater than 35°; elongated and sub-rounded landforms, wavelength between 800 and 2,000 m and mean elongation of 0.4; concave, convex and mainly flat surfaces	B.2.2 - Itaoca
	B.2.3 - Amplitudes vary between 400 and 700 m; mean slope greater than 20°, usually above 30-35°; sub-rounded slightly stretched landforms, wavelength between 1,000 and 4,000 m and mean elongation greater than 0.5; concave, convex and flat surfaces	B.2.3.1 - Figueira B.2.3.2 - Agudos Grandes B.2.3.3 - Sulino B.2.3.4 - Pedra Santa B.2.3.5 - Pilões B.2.3.6 - Ivaporunduva B.2.3.7 - Eldorado	
	B.2.4 - Amplitudes lower than 500 m; mean slope below 20°, maximum at 35°; elongated landforms, wavelength lower than 3,000 m and mean elongation below 0.3; convex and flat surfaces	B.2.4 - Caboclos	

4.4. Automatic identification of karst areas

The automatic karst landform mapping method of Carvalho Júnior et al. (2013) generates a depression map, highlighting not only karst landforms but also valleys and drainages (Fig. 6A). True karst depressions occur in the Northwest sector of the study area, restricted to the carbonate rocks, in a network of polygonal karst depressions (Karmann, 1994; Ferrari et al., 1998). These carbonate rock areas, locally know as Furnas-Santana and Lajeado-Bombas were mapped into five morphological zones by Karmann (1994): Fluvial, Contact, Fluviokarst, Transition and Polygonal (or composite depressions).

Areas identified as karst depressions over carbonate rocks show irregular shape and correspond to the Transition and Polygonal zones of Karmann (1994) (Fig. 6B). The local geomorphological map from this work also shows a good agreement between land elements interpreted as karstic terrains and Karmann's Polygonal, Fluviokarst and Transition zones

(Fig. 6C).

5. Conclusions

This paper presented a 1:10,000 geomorphological map created with terrain attributes derived from a Digital Elevation Model and compare it with the existing 1:1,000,000 map which was based on the traditional methods of fieldwork and photointerpretation. The study area was selected due to its characteristic landforms, such as karstic terrains, and the availability of 1:10,000 topographic maps to derive the DEM.

Automatic delimitation of karst landforms resulted in a map of depressions with good correspondence to karstic zones previously identified by Karmann (1994) and with those identified in this work.

Compared to the São Paulo state 1:1,000,000 geomorphological map of (Ponçano, 1981), the 1:10,000 scale mapping carried out this project identified the same Land Systems and Units,

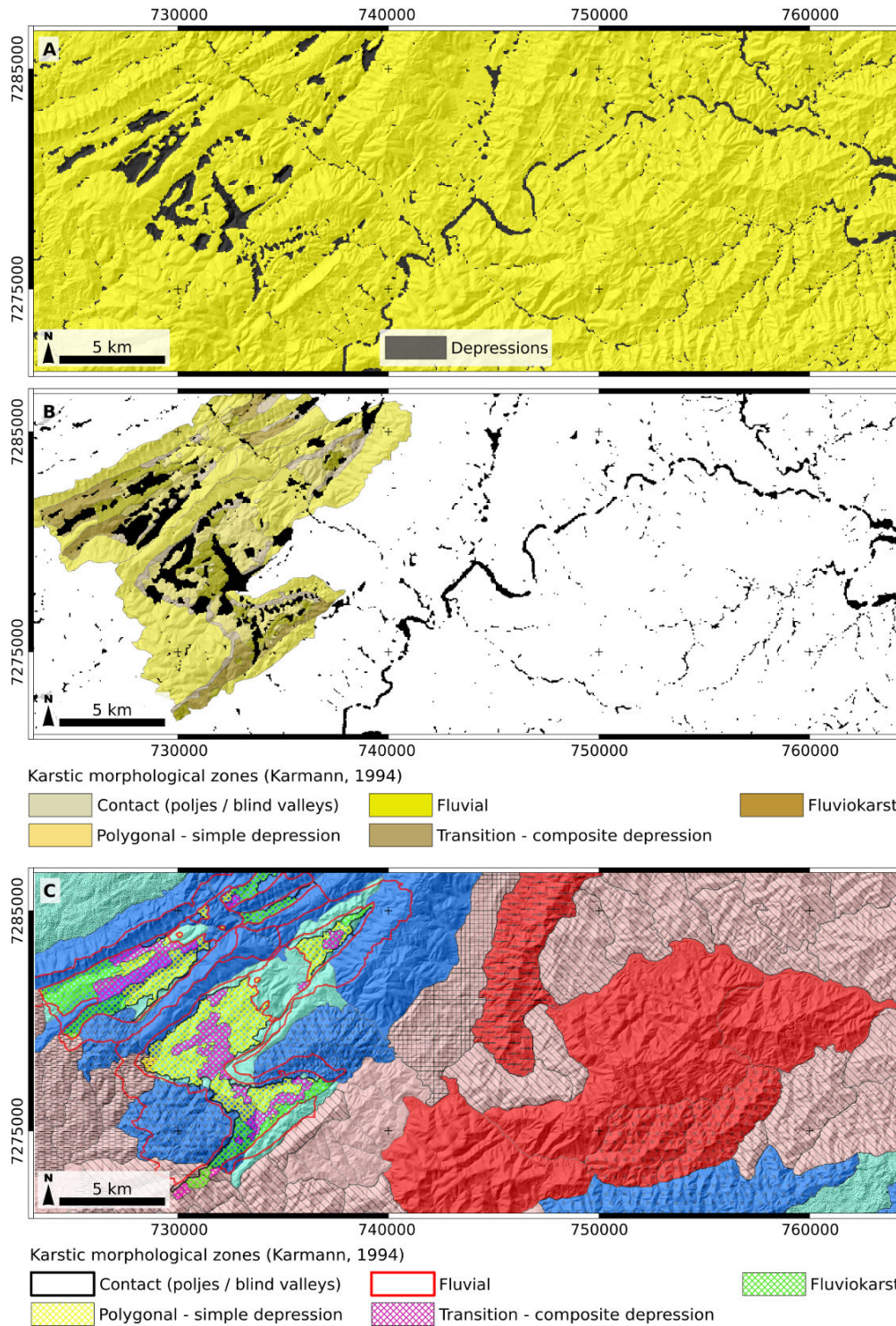


Figure 6: Automatic identification of karst areas. A) Depression Map; B) Depressions over Morphological Zones of Karmann (1994); C) Depressions over Morphological Zones of Karmann (1994) and Local Geomorphological Map from this work.

with the expected differences in their delimitation (i.e., boundaries, extension) due its larger scale. The small mapping scale of the 1981 map leads to cartographic generalization and the characterization of Land Elements can be vague, with unspecific terrain attributes for the landforms.

In the 1981 map, which was created with traditional methods of fieldwork and interpretation of aerial photographs, Land Systems are described by their morphological attributes and lithology, while Land Units and Land Elements are based on relief amplitude, slope, morphological features and drainage patterns. In this project, created with modern GIS tools and DEM geomorphometric analysis, the description and grouping of Land Units were based on similarities in DEM-extracted terrain attributes such as elevation, drainage patterns and slope angles. Specific terrain attributes like landform wavelength, mean elongation and hillslope shape were used to define the Land Elements.

The terrain attributes derived automatically from the DEM enabled an accurate geomorphological classification of the study area. The methodology presented in this paper is considered effective for mapping landforms at a detailed scale and can be employed in regional scale mapping using coarser resolution DEMs.

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