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ORIGINAL ARTICLE

Regional and local topography subdivision and landform mapping using SRTM-derived data: a case study in southeastern Brazil

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Abstract Topographic subdivisions and landforms are important relief characteristics that serve as a basis for several types of regional and local planning. This paper presents an assessment of the application of a global landform classification method on a regional scale using Sao Paulo State as the study area and on a local scale using the city of Sao Paulo as the study area. In addition, a new approach that includes elevation derivatives for local analysis is presented. The study hypothesizes that the automated object-based classification of topography from shuttle radar topography mission (SRTM) data method could also be used for local mapping when supported by elevation derivative data. SRTM data were used in the regional approach and post-processed elevation data derived from SRTM were used for the local analysis. The results were compared with the best available geomorphological maps and topographic surface descriptions of the region. The new method resulted in a regional-scale product in which the boundaries and features of the topography matched those in the geomorphological maps and in the literature. The method did not perform well when classifying the local topographic subdivisions of Sao Paulo, even when using the interpolated elevation data. However, the surface edges and shapes identified in the topographic maps were represented in the resulting map. To refine the results, a new approach was proposed using data derived from a digital elevation model, such as drainage densities, horizontal and vertical curvatures, and slope gradients. The use of these products in the image segmentation process and classification criteria was fundamental for obtaining the results. Theoretical thresholds were used to define the relief classes, and landform characteristics were taken into account in developing the landform map. The success of this new approach is attributed to the comprehensive database that supported the topographic subdivision analysis. In summary, this study indicates that a method developed for use on a global scale can be replicated for use on a regional scale but not on a local scale. The new approach produced reasonable results and can be used in other regions. Greater detail can be obtained using various thresholds of horizontal and vertical curvatures, for example, when delineating hazard areas. The products have potential applications in urban planning, ecological-economic zoning, urban drainage, hazard mitigation, environmental issues, erosional dynamics and transportation planning.

Keywords Landform · SRTM · Image segmentaion · GEOBIA · Sao Paulo · Planning

Introduction

A landscape is conceptualized as an integrated system that is defined by the dynamic combination of the homogeneous components of land cover and support among physical, biotic and anthropic environments (Monteiro 2001). The shape, size, type, distribution and arrangement of those components define the basic aspects of the landscape. A landscape can be subdivided into homogeneous units or objects based on its particular spatial characteristics (Lang and Blaschke 2009).

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The edges of homogeneous units can be mapped using several criteria for clustered components or attributes that exhibit high degrees of correlation (Ferreira and Rossini-Penteado 2011). Currently, several methods for landscape structure assessments are available and are mostly based on geographic information processing and remote sensing data. The quality of the bounded unit affects the entire analysis process and its derivation (Lang and Blaschke 2009).

When considering only the physical aspects of a landscape, the relief allows for the delineation of homogeneous areas with a particular set of dynamics and restrictions regarding their land use. The literature (Lucena 1998; Ferreira and Rossini-Penteado 2011) contains a definition of basic subdivision units (BSUs). BSUs correspond to basic cells suitable for geotechnical and geo-environmental assessments and permit the use of GIS and remote sensing techniques (Vedovello 1993, 2000). The physiographic subdivisions are defined by distinct homogeneous areas of land (Vedovello and Mattos 1993; Vedovello 1993, 2000).

Vedovello and Mattos (1993) proposed a satellite-image-based procedure for physiographic subdivision and geotechnical characterization. The method is advantageous compared with previous methods, e.g., those proposed by Venezziani and Anjos (1982) and by Soares and Fiori (1976). The procedure is comprehensive and the results derived from the geotechnical analysis can be integrated with ecological, socioeconomic and other variables, as seen in the studies by Crepani et al. (1996), Spörl and Ross (2004) and Manfré et al. (2013), which involved the analysis of environmental fragility and erosion vulnerability. The BSUs in these studies were obtained by systematic photo-interpretation of textural and tonal elements in satellite images or aerial photos. The analysis of the image is based on the homogeneous differences, entropy and asymmetry of textural and tonal elements. The analysis also takes into account other landscape properties, such as the type, density, arrangement and structuration degree of textural elements (Soares and Fiori 1976; Vedovello 1993, 2000).

In Brazil, a few studies have been performed using these techniques and BSUs as the unit of analysis. Lands for refuse disposal in a dense urban area were identified (IG and SMA 1999; Brollo 2001), an integrated system of geo-environmental information was applied to coastal management, and guidelines for socio-environmental restoration were developed in mining areas (Ferreira et al. 2005).

Several other authors (Kemper and Macdonald 2009; Sharma 2009; Brookes 2010; Partridge et al. 2010) used physiographic subdivisions in preliminary stages of study. Physiographic subdivisions are commonly used as the analysis unit, particularly in environmental studies. Other approaches have recently been proposed by various authors (Saadat et al. 2008; Dragut and Eisank 2012; Camargo et al. 2012) and involve the use of shuttle radar topography mission (SRTM) data or digital topographic data and an analytical methodology.

The SRTM data cover the entire globe and serve as an important dataset for preliminary and topographic studies after being converted to a freely available global DEM. The data are useful for urban, transportation and watershed planning. The SRTM dataset was developed during a mission involving NASA and the Italian and German space agencies. The data were collected in February 2000 to provide global elevation coverage at a resolution of 90 m, except in the USA where the resolution is 30 m and the error is less than 6 m (Werner 2001; Rabus et al. 2003; Farr et al. 2007).

In addition to the DEM, several derivatives can be developed using this information, such as slope, orientation, shading, curvature and drainage. Because a DEM contains continuous information, it is possible to use interpolation methods that enhance the resolution of the data. Valeriano and Rossetti (2011) used an interpolation model to obtain high-resolution data for Brazil (resolution of 30 m). This product and the method to obtain it are freely available from the website of the Remote Sensing Department of INPE (Space Research National Institute, Brazil).

Saadat et al. (2008) proposed a quantitative approach to landform classification based on DEM and advanced spaceborne thermal emission and reflectance radiometer (ASTER) satellite images. Slope gradients, relief and stream network patterns were used as identifying parameters. The ASTER imagery was used to delineate landforms of various types and to determine the presence or absence of gravel. The authors used a watershed as the study area, and very accurate results were achieved. Once the data are freely available, this approach could be replicated throughout Iran.

Dragut and Eisank (2012) proposed a method that uses global SRTM data, an automatic scale factor detector and object-based image analysis (OBIA) to classify topography worldwide. This approach involves the decomposition of the ground surface into homogeneous objects. Elevation data are automatically segmented, and the ideal scale parameter is identified using local variance difference analysis. The classification criteria are based on mean elevation values and their standard deviations. The results include boundaries that correspond to natural discontinuities on a regional scale. In the same context, Camargo et al. (2012) classified landforms based on various geomorphometric and textural attributes obtained from ASTER/Terra images. The results were assessed against a reference map, and a strong agreement between the two maps was revealed; thus, the technique was effective for extracting landforms.

OBIA allows for the classification of images based on homogeneous image areas (objects). Several variables and image characteristics, such as texture, context and spectral statistics, can be analyzed (Blaschke et al. 2000). According to Farr et al. (2007), SRTM data were also tested for use in urban areas because such data are not greatly affected by building interference. The technique can replace traditional visual interpretations in delineating physiographic subdivisions. A few authors used the LANDSAT TM 5 mid-infrared band to perform these interpretations. In urban areas, however, interpretation of the terrain is adversely affected by buildings.

Regarding the availability of elevation data and the robustness of object-based approaches for delineating topographic subdivisions in large areas, it is also important to develop methods that may be replicated in regional or local analysis of topographic subdivisions. In addition, specific results can be generated with the goal of analyzing specific physiographic aspects of a region, such as erosion, hazards, environmental conservation and hydrology. This study was performed to evaluate the method for regional and local analyses developed by Dragut and Eisank (2012) and to develop a local approach that identifies hazard areas, erosional processes and landforms.

Methodology

The SRTM data, which cover the state of Sao Paulo in their original resolution, were obtained from the website of the United States Geological Survey. The interpolated SRTM data for the city of Sao Paulo were obtained from the website of the Brazilian National Institute for Space Research (INPE). The model was developed using the eCognition Developer 8 platform (Trimble 2009). The study areas (Sao Paulo State and Sao Paulo City) were selected based on their geomorphologic heterogeneity and on the availability of geomorphological maps and topographic surface descriptions for validating the analysis. The locations of Sao Paulo City and Sao Paulo State are shown in Fig. 1.

The method for classifying the overall topography of homogeneous areas followed the work of Dragut and Eisank (2012). In the original work, the authors presented a method to define scale parameters for segmentation processes and used three different scale factors for each level of classification: 901 for Level 1, 181 for Level 2 and 80 for Level 3, according to the topographic variability at the global scale. In this research, a similar approach was applied on a regional (Sao Paulo State) and a local (Sao Paulo city) scale. The SRTM data, with a resolution of 90 m, were used to regionally analyze Sao Paulo State. TOPODATA (INPE—Instituto de Pesquisa Espaciais. TOPODATA—Banco de Dados Geomorfométricos do Brasil 2011), with a resolution of 30 m, was used to locally analyze Sao Paulo City.

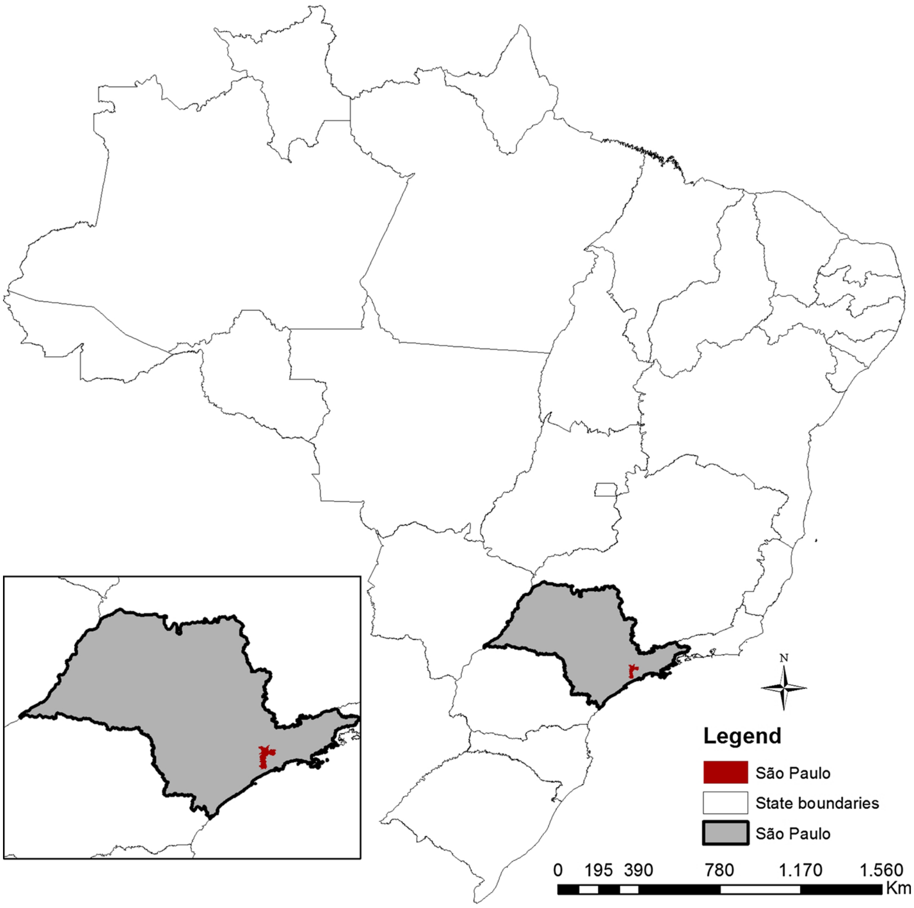
To analyze Sao Paulo State, the homogeneity criteria of shape and compactness were adjusted to zero. Compared with Dragut and Eisank (2012), the only difference in this case involved the scale factors for the segmentation. This method accounts for the general aspects of the topography and classifies it in absolute terms. In a regional approach, the classification becomes relative, depending on the boundaries of the study area. The boundaries of Sao Paulo State mostly correspond to natural discontinuities (e.g., large rivers and the coast). Therefore, the application of this method to the state, due to its natural edges and extension, is expected to produce reasonable results. The results were assessed using geomorphologic descriptions and maps of the areas. The research by Martinelli (2009) and Ross and Moroz (1997) was used as a reference for the geomorphologic descriptions when evaluating the adaptation on a regional scale.

For the local-scale analysis, the topography of Sao Paulo City is extracted from the state landform map. The verification was performed based on the geomorphological study of Sao Paulo City by Ab'Saber (1957, 1969), Silveira's (2008) revision of Ab'Saber's work and the geotechnical map of Sao Paulo City (scale 1:10,000) (PMSP—Prefeitura Municipal de São Paulo and IPT—Instituto de Pesquisas Tecnológicas 1991), which was provided by the Environmental Secretary of Sao Paulo City. This map provided geological and soil information, which is important for assessing the physiographic components of the landscape. According to Alves and Castro (2003), the geology and relief are related, primarily due to climatic variations during the Quaternary (Bigarella 1964; Bigarella et al. 1965; Tricart 1972; Büdel 1982).

A similar procedure was applied for interpolating the SRTM data (TOPODATA, resolution of 30 m) that cover Sao Paulo City. The local data result in different terrain characteristics, which are addressed in the method based on statistical parameters, such as the elevation mean and variance. Generally, the segmentation scale parameters may be defined using subjective trial-and-error exploratory methods (Meinel and Neubert 2004). The scale parameters are very important for the segmentation process (i.e., to divide remote sensing images into discrete regions or objects) and are fundamental for the classification and statistical accuracy (Blaschke 2003; Addink et al. 2007). The scale factor for the image segmentation was set to 52, i.e., a value producing no local variance change (Fig. 2) in the analyzed area.

The definition of the spatial subset is important because the boundaries of Sao Paulo City do not completely correspond to natural features, such as valleys and watershed

Fig. 1 Locations of Sao Paulo City and Sao Paulo State



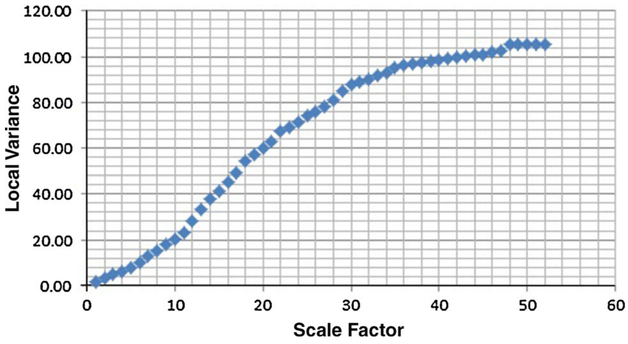


Fig. 2 Scale factors and local variance for the Sao Paulo City subset

divisors. Therefore, a reasonable definition of the analyzed area should consider the natural discontinuities beyond the city boundaries. This step is important because of the first classification criterion, which requires the use of the mean elevation in the analyzed subset. The resulting map was again compared with the geotechnical map and the geomorphologic descriptions of Sao Paulo City (Ab'Saber 1957, 1969; Silveira 2008).

A different approach that includes the use of DEM-derived data was developed. The objective was to improve the segmentation results and to facilitate the definition of the classification criteria. According to Valeriano (2003a), the generation of SRTM-derived products comes with several restrictions and must be performed carefully, particularly in regions where the data have a lower resolution. Therefore, the TOPODATA products that were generated following the method of Valeriano (2002, 2003a, b) and Valeriano and Carvalho Júnior (2003) were used in this study.

In addition, the classes defined by Dragut and Eisank (2012) were proposed for classifying landforms on a global scale; therefore, they were not suitable for local applications. The specification of the landform classes in this study is based on the need for a multi-purpose map that could be used for various urban planning purposes and for other areas.

Therefore, based on particular methods presented in the literature, such as that of Saadat et al. (2008), variables other than elevation may be used to delineate regions with homogeneous relief. A new approach is proposed in this paper to decrease the relativity of the analysis. Because of the local characteristics of the terrain, the values are locally extracted and are variable from one delineated study area to the next. With this goal in mind, the second level of the classification criteria was defined based on geomorphologic reference thresholds (Christofoletti 1974, 1979; Moreira and Pires Neto 1998), which are particular values of the slope gradient and elevation. Gently sloping and steep features are delineated using a slope threshold of 6.5°, and high and low features are delineated using an elevation threshold of 760 m. The resulting landform classes were ramps, low hills, high hills, mountains and tablelands. These classes were further subdivided into high and low classes based on the mean elevations of the image objects, as shown in Fig. 3.

The segmentation in this new approach was defined using several variables in addition to the numerical elevation (ZN): the drainage density (DD), horizontal curvature (HN), vertical curvature (VN) and the slope gradient (SN). All of these values were derived from interpolated SRTM data and are available in the TOPODATA dataset (INPE 2011). The use of these auxiliary data is consistent with the assumption of relief subdivision and is an attempt to render more evident topographic features (Valeriano 2003a; Valeriano and Carvalho Júnior 2003).

Segmentation is an important step in the OBIA classification procedure. To produce good results, it is important to identify the best set of variables for defining the homogeneous image regions (objects). Thus, all of the selected variables were assigned the same weight for the segmentation process to equalize the topographic characteristics. Following Dragut and Eisank (2012), the shape and compactness factors were set to zero, thereby eliminating the effects of any defined shapes on the image objects. In addition, to preserve the analysis parameters, a scale factor of 52 was used, i.e., the same factor used in the local approach of Dragut and Eisank (2012).

In accordance with the geomorphologic definitions (Christofoletti 1974), a decision-tree classification scheme was developed, as shown in Fig. 11. The first-level threshold was maintained because the elevation represents a relief classification criterion that has been presented by several authors (Camargo et al. 2009). Thus, the relativity of the analysis was maintained because the mean elevation varies according to the selected subset. The following criterion, however, reduces the local relatively by merging classes: level 3—high hills and low hills. In the second classification level, the thresholds of Christofoletti (1974, 1979) and Moreira and Pires Neto (1998) were used to define the relief subdivisions, which resulted in the following classes:

- Ramps
- Low hills
- High hills
- Tablelands
- Mountains

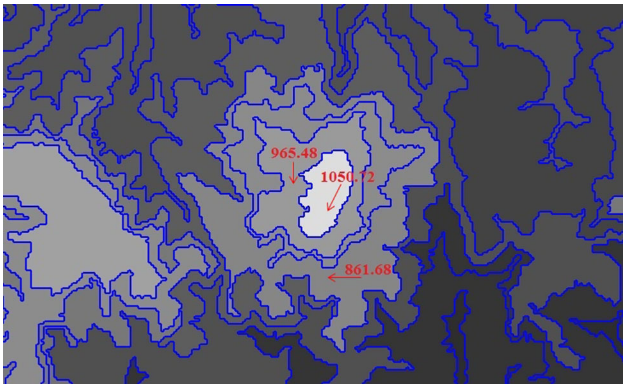


Fig. 3 Example of image objects and their elevation mean values

For the second-level classification, Dragut and Eisank (2012) proposed the use of the standard deviation of the elevation. The computed mean and standard deviation served as the thresholds for defining the classes. The elevation's standard deviation represents the slope gradient because it represents the pixel variances around the mean of each object. Therefore, the use of the slope gradient is an intrinsic feature of this method. The direct use of the slope gradient permits the application of reference values in extracting the relief physiognomy.

To apply a landform-based approach and to produce a map with direct land use planning applications, the curvature of the relief was the primary consideration. Therefore, concave and convex areas of the mountains and hills (low and high) were delineated based on the mean values of the vertical curvature. For the ramps, the mean values of the horizontal curvature were used to delineate the erosional plains and flood plains. The tablelands defined in level 2 were not subdivided because they already constitute an important landform class. The negative or positive values of the vertical and horizontal curvatures were the criteria used to determine whether a slope was concave or convex. Greater detail and better delineation of hazard areas may be produced by defining classes according to the highest values of these variables.

For the third level of the landform classification, the methods described by Ross (1994) and Crepani et al. (1996) were used because they can divide the landscape into areas with erosion potential. One of the primary objectives of the relief subdivision was to develop units of analysis for erosional potential and other areas of focus, such as ecological-economic zoning, residential planning, emergency management, environmental protection and urban drainage. Therefore, horizontal and vertical curvatures were used as criteria to define particular classes. For this purpose, concave and convex slope classes were defined in addition to areas of erosion and flood plains. The results were validated against the relief descriptions and maps.

Table 1 Summary of the data applied in the methods

Scale	Data	Approach	Segmentation layers	Classification variable	Data resolution
Regional (São Paulo State)	SRTM	Dragut and Eisank (2012)	ZN	Level 2, Level 3 ZN StDv	90 m
Local (São Paulo City)	TOPODATA	Dragut and Eisank (2012)	ZN, SN, DD, HN and VN	Level 2, Level 3 ZN StDv	30 m
Local (São Paulo City)	TOPODATA	New proposition	ZN, SN, DD, HN and VN	Level 2 SN mean, Level 3 HN, VN mean	30 m

ZN numerical elevation, *SN* numerical slope, *DD* drainage density, *HN* numerical horizontal curvature, *VN* numerical vertical curvature

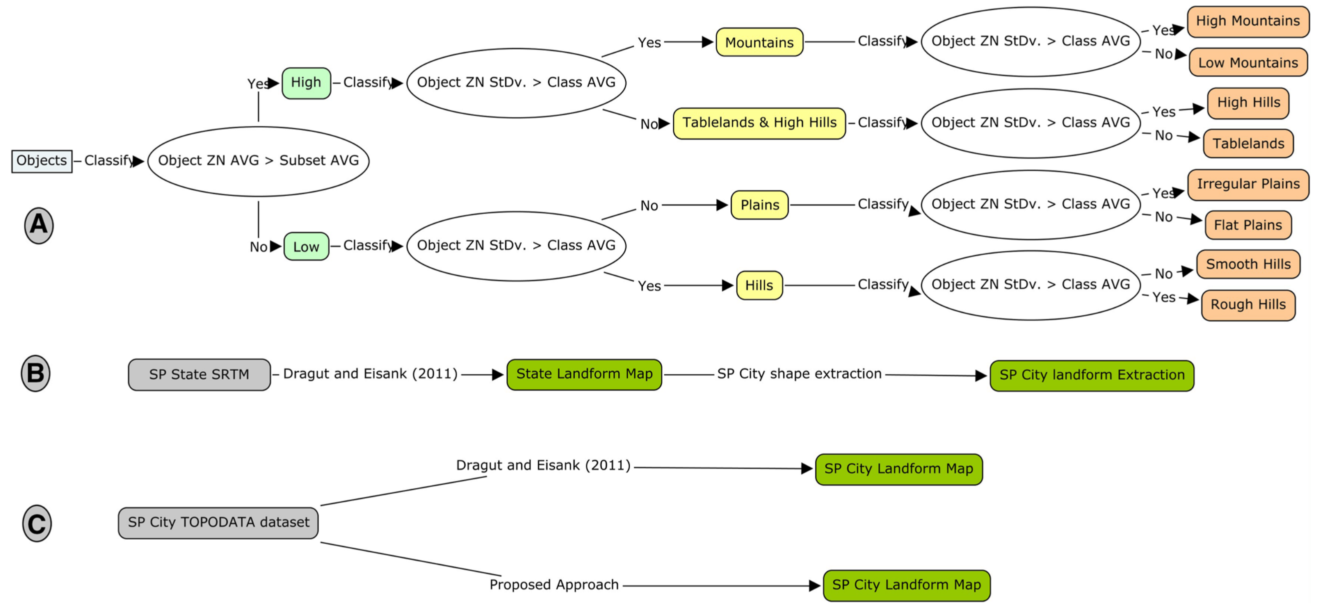


Fig. 4 Scheme of the applied methodology for this paper: the methodology of Dragut and Eisank (2012) (**a**), the steps for regional and derived local approaches using original SRTM data (**b**) and the steps using the interpolated SRTM data (**c**)

Table 1 and Fig. 4 present a summary of the methodological criteria and data used in each approach.

Results

The map of the Sao Paulo State relief subdivisions is presented in Fig. 5; it was developed using a regional application of the method of Dragut and Eisank (2012). The map shows a large homogeneous plains area and tablelands that divide the east-central and eastern parts of the state. The edges of several known physiographic features, such as the south-central cuestas, the Ribeira (south) and Paraiba (east) Valleys, and the Mantiqueira (east) and Atlantic (coast) Sierras, are apparent.

Figure 6 presents the landform map of Sao Paulo State, which is a more refined topographic classification map. Particular relief edges that appear in Fig. 5 are emphasized by the refined classes in this map, and other edges are also represented. The edges of river plains and a few of the state's reservoirs and dams are shown. The largest portion of the state is classified as irregular plains.

The resulting topographic subdivision map generally represents the relief of Sao Paulo State. In a comparison with the geomorphologic maps (Almeida 1964; IPT 1981; Ross and Moroz 1997; IBGE 2000), several relief shape boundaries are consistent and the classifications of the two maps are similar. The most evident components are as follows: the Paraiba Valley, which is located on the extreme eastern side of the state; the Ribeira de Iguape Valley, which is located in the southern part of the state; the Coastal Plains (southeastern boundaries); the Mantiqueira and Atlantic Sierras (located in the extreme eastern part of the state) and the cuestas in the south-central part of the state.

The landform map of Sao Paulo State shows the relief in greater detail, i.e., it subdivides each of the classes presented in Fig. 5 into two classes. River plains and dams are defined in this level. The plains of the Tiete and Paranapanema Rivers and other large rivers are classified as flat

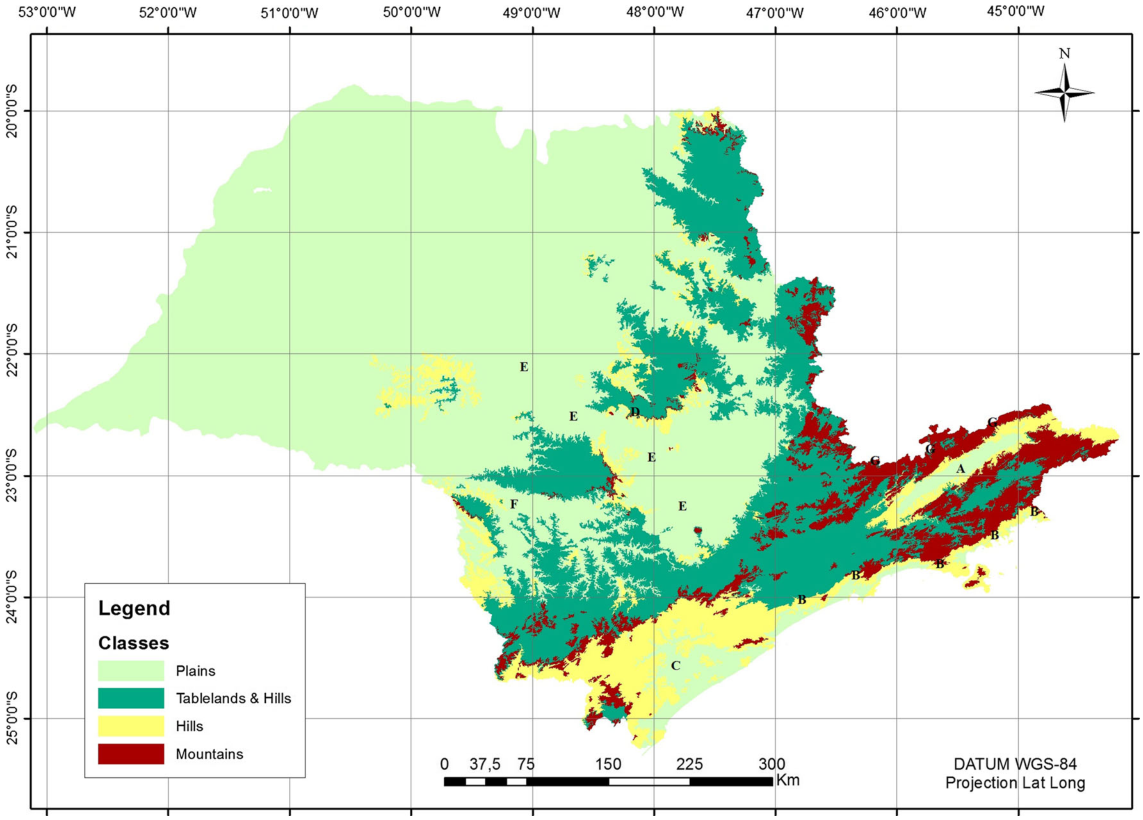


Fig. 5 Map of the relief subdivision for Sao Paulo State. The following regions are highlighted: **a** Paraiba Valley; **b** Coastal Sierra; **c** Ribeira Valley; **d** Central Custa; **e** Tiete Valley; **f** Paranapanema Valley; and **g** Mantiqueira Sierra

plains. The Paraiba River Valley is divided into irregular plains and flat plains; the Mantiqueira and Atlantic Sierras bound this valley and are subdivided into rugged hills and low and high mountains. The same approach was performed for the cuestas and other mountain formations in the south-central part of the state. The largest portion of the state is classified as irregular plains.

In general, the result of the classification provides a highly detailed landform map of Sao Paulo State. When compared with the maps of Ross and Moroz (1997) and IBGE (2000), i.e., the most recent geomorphologic maps of the region, this classification efficiently provides an accurate map with a high level of detail and refined boundaries. When compared with the results of Martinelli (2009), the map also shows several features at a very high level of detail.

Figure 7 presents the Sao Paulo City relief map, which was extracted from the map in Fig. 5. The physiography is essentially divided into tablelands and high hills, hills and mountains. The edges of the Cantareira (north) and Atlantic Sierras (south) are the only natural discontinuities shown in the map. Figure 8 presents the Sao Paulo City landform map, which was extracted from the map in Fig. 6. The predominant landform in the city is tablelands, although their edges in this map are more refined than those in Fig. 7.

The results of the local approach using the method of Dragut and Eisank (2012) are presented in Figs. 9 and 10. Figure 9 presents the Sao Paulo City relief subdivision map, and Fig. 10 presents the Sao Paulo City landform map. In Fig. 9, four classes are represented within the Sao Paulo City boundaries. The Cantareira Sierra (north) is classified as mountains, and prominent river plains are delineated. The map in Fig. 10 shows seven classes within the Sao Paulo City boundaries. The edges of the Cantareira Sierra are more evident, although the largest portion of the city is classified as tablelands.

Figure 11 presents a novel method in which OBIA is used to classify local relief subdivisions and landforms. Because of the potential for land development, the erosional dynamics and the high urban density of Sao Paulo City, the defined classes of the landforms were based on the topography of slopes and plains to delineate areas that are susceptible to floods, erosion, landslides, drainage problems, environmental issues and various types of land use. The defined classes were flood plains, erosional plains, tablelands, concave hill slopes, convex hill slopes, concave mountain slopes and convex mountain slopes.

The map in Fig. 12 presents the relief subdivisions in Sao Paulo City; the subdivisions were generated using the

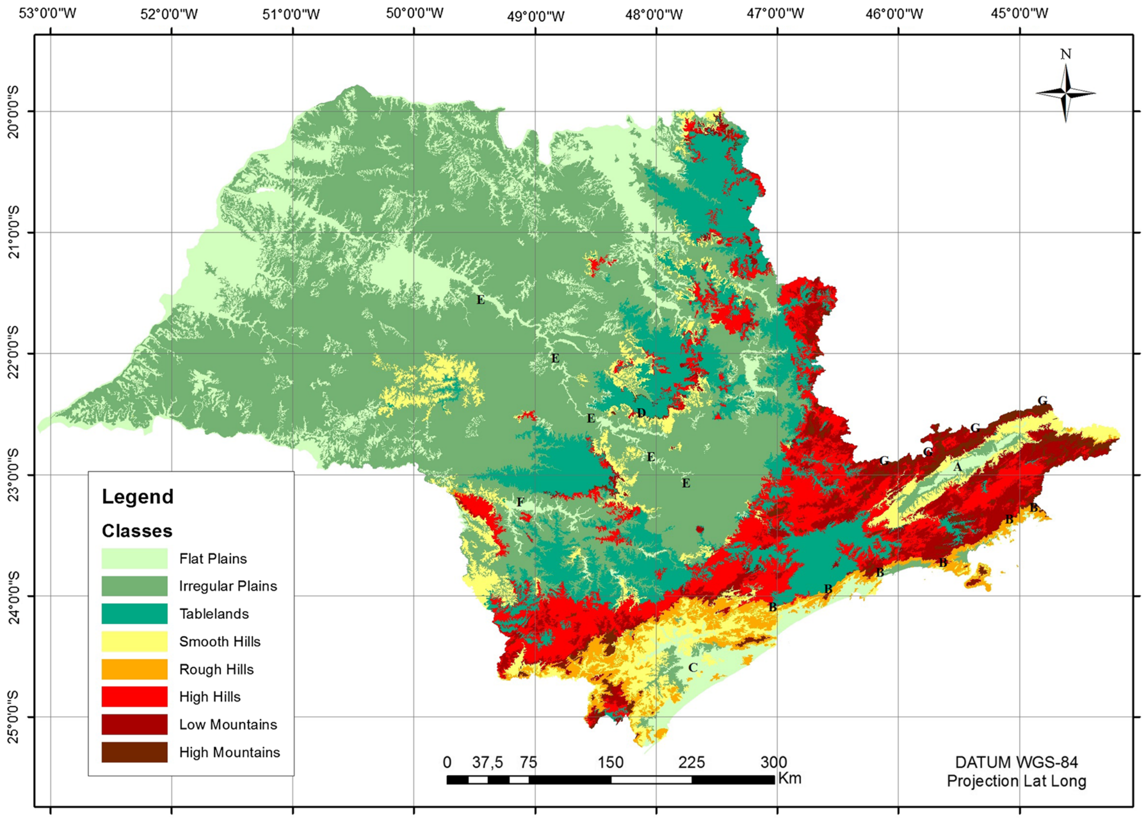


Fig. 6 Map of the landforms for Sao Paulo State. The following regions are highlighted: **a** Paraiba Valley; **b** Coastal Sierra; **c** Ribeira Valley; **d** Central Custa; **e** Tiete Valley; **f** Paranapanema Valley; and **g** Mantiqueira Sierra

new method. The defined classes were ramps, low hills, high hills, tablelands and mountains. The boundaries and shapes of the Cantareira and Atlantic Sierras and the central highlands are apparent.

The landform map of Sao Paulo City based on the new method is presented in Fig. 13. In addition to water bodies, seven classes were obtained. The relief features are subdivided, and the dams crossing the river basins are well defined. The flood plains and erosional plains along the city's principal rivers (Tiete, Pinheiros and Tamanduatei) are delineated.

Discussion

This paper presents an adaptation of the method of Dragut and Eisank (2012) for delineating subdivisions of regional and local relief and landforms. The adapted method, when applied to Sao Paulo State as a regional approach, provided reasonable results. The relief boundaries were defined, and the features similar to those described in the geomorphologic literature were delineated (Almeida 1964; IPT 1981; Ross and Moroz 1997; IBGE 2000; Martinelli 2009). The local approach proposed in this paper uses data derived from DEMs for segmentation and classification. This approach provided a refined map that shows, in substantial detail, the topographic features described in the literature.

The satisfactory results achieved for the Sao Paulo State analysis may be attributed to the state's political limits, which correspond to natural boundaries. This characteristic facilitates the analysis because the assessment is based on image object statistics of the total analyzed area, and there are few misclassifications due to the lack of diversity. In addition, Sao Paulo State has a heterogeneous geomorphology that is classified in terms of elevation and slope gradients and is well represented by the eight proposed classes.

Therefore, the proposed method can be applied on a regional scale to yield reasonable results. This favorable performance is most likely due to the size of the region, which contains a highly diverse set of objects that enhance the classification criteria because they may be based on the object statistics. Thus, the mean elevation and standard deviation are useful for the classification of landforms.

The analysis could be refined further to produce a more enhanced landform map. The refined criteria definitions would depend on the purpose of the analysis. The importance of the case study of the regional approach is to

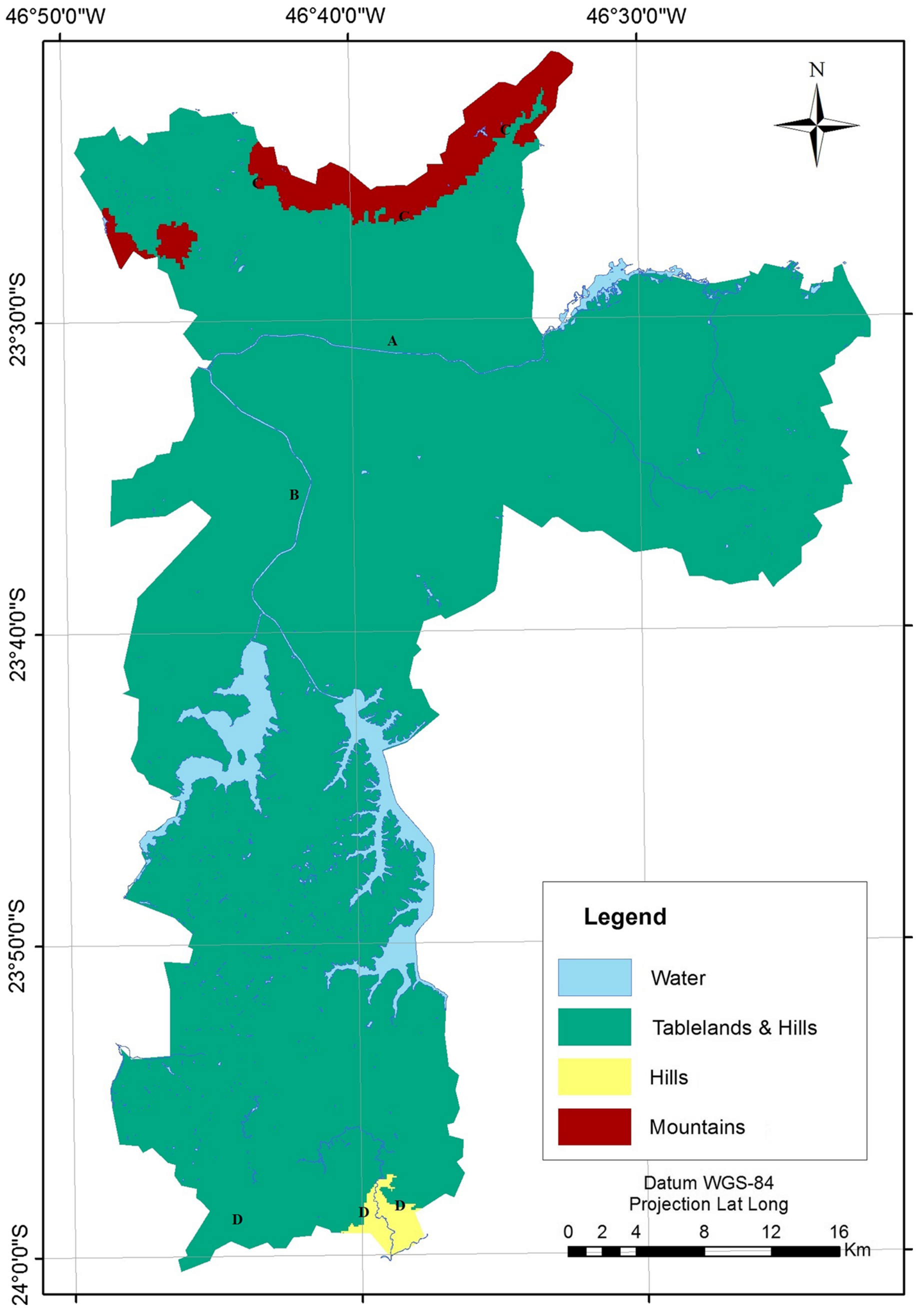


Fig. 7 Map of the relief subdivision in Sao Paulo City using a subset of the state map. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra

demonstrate the potential and suitability of this method for regional analysis.

The relief taxonomy is not the best method for delineating the features of Sao Paulo State. Adjustments could be made to improve this work and to develop an adequate nomenclature for the landform map. However, the presented results and the real nomenclature correspond well.

When used in a local context, the proposed method generally delineates the local landforms and relief, as shown in Figs. 6 and 7. A few physiographic features are delineated in Fig. 7. However, the city was essentially classified as tablelands and high hills, which neglect the natural heterogeneous topography of the city. This deficiency is clearly due to the scale of the analysis, which would be suitable for a much larger area with greater elevation and slope variations.

A similar lack of detail is present in Fig. 8, although new edges appear in this map. High hills are delineated in the southeastern and western parts of the city. The result does not represent the diverse relief in Sao Paulo City, particularly in the central and southern parts of the city (Ab'Saber 1957, 1969; Silveira 2008; PMSP and IPT 1991).

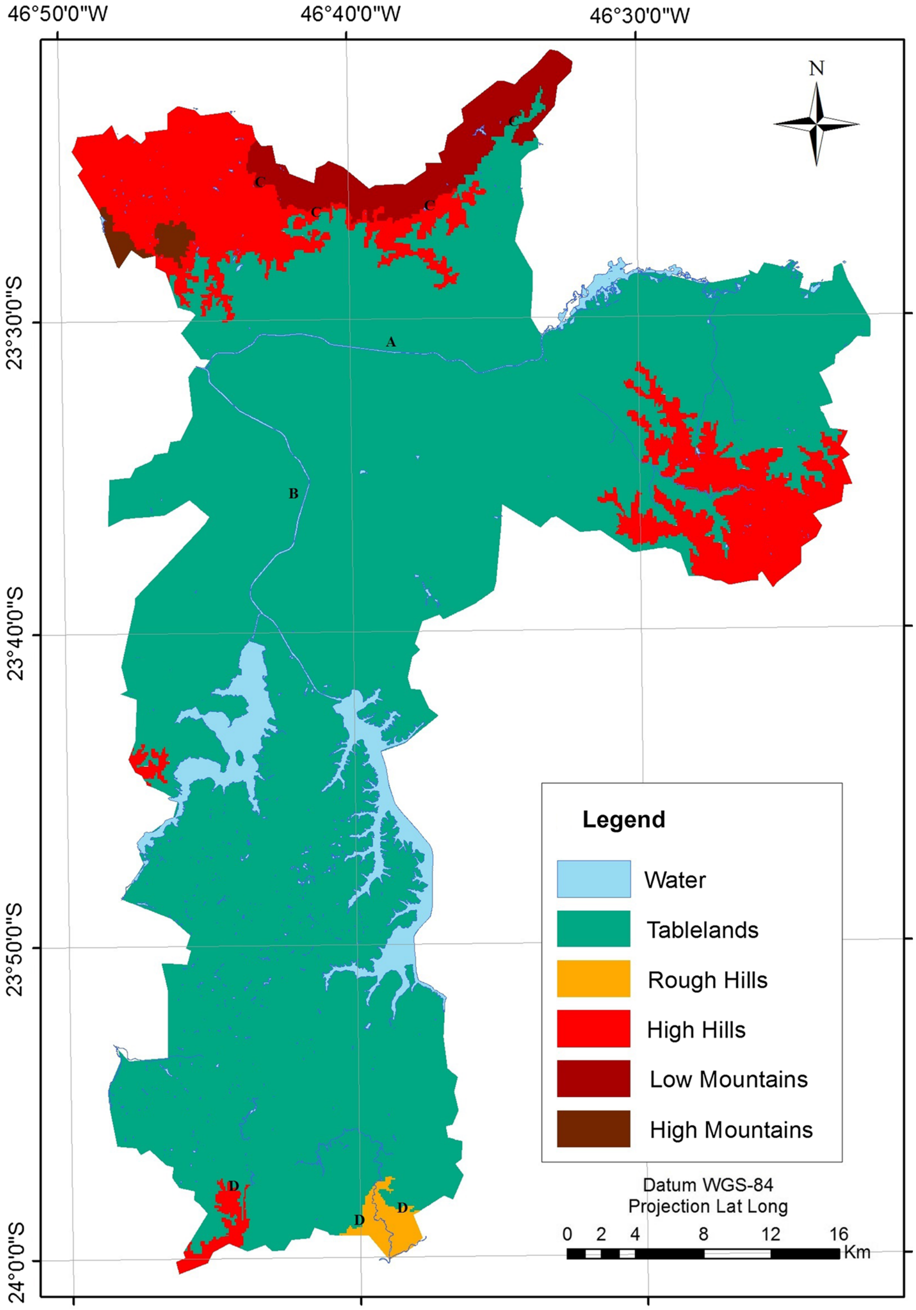


Fig. 8 Map of the landforms in Sao Paulo City using a subset of the state map. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra

These findings indicate that the method provides good results on a regional scale and can be used with particular restrictions on a local, detailed scale. An extraction of this regional analysis must be carefully analyzed; the method could be used depending on the size of the extraction and the purpose of the analysis.

Therefore, this approach is efficient for supporting the planning of land use, river basins and transportation networks, among other uses. The approach can be replicated in any regional analysis and demands only verification and perhaps particular adjustments (scale factors, classification rules and size of the area), depending on the geomorphological specifications.

The map in Fig. 9 presents an area classified as plains, and the boundaries of the main Sierras do not match the published descriptions or the geotechnical map (Ab'Saber 1957, 1969; PMSP and IPT 1991). This area is transected by the Atlantic Sierra, which was delineated well in Figs. 6 and 7. This misclassification may be attributed to the size of the analysis area or to the classification criteria (the mean standard deviation of the objects was low).

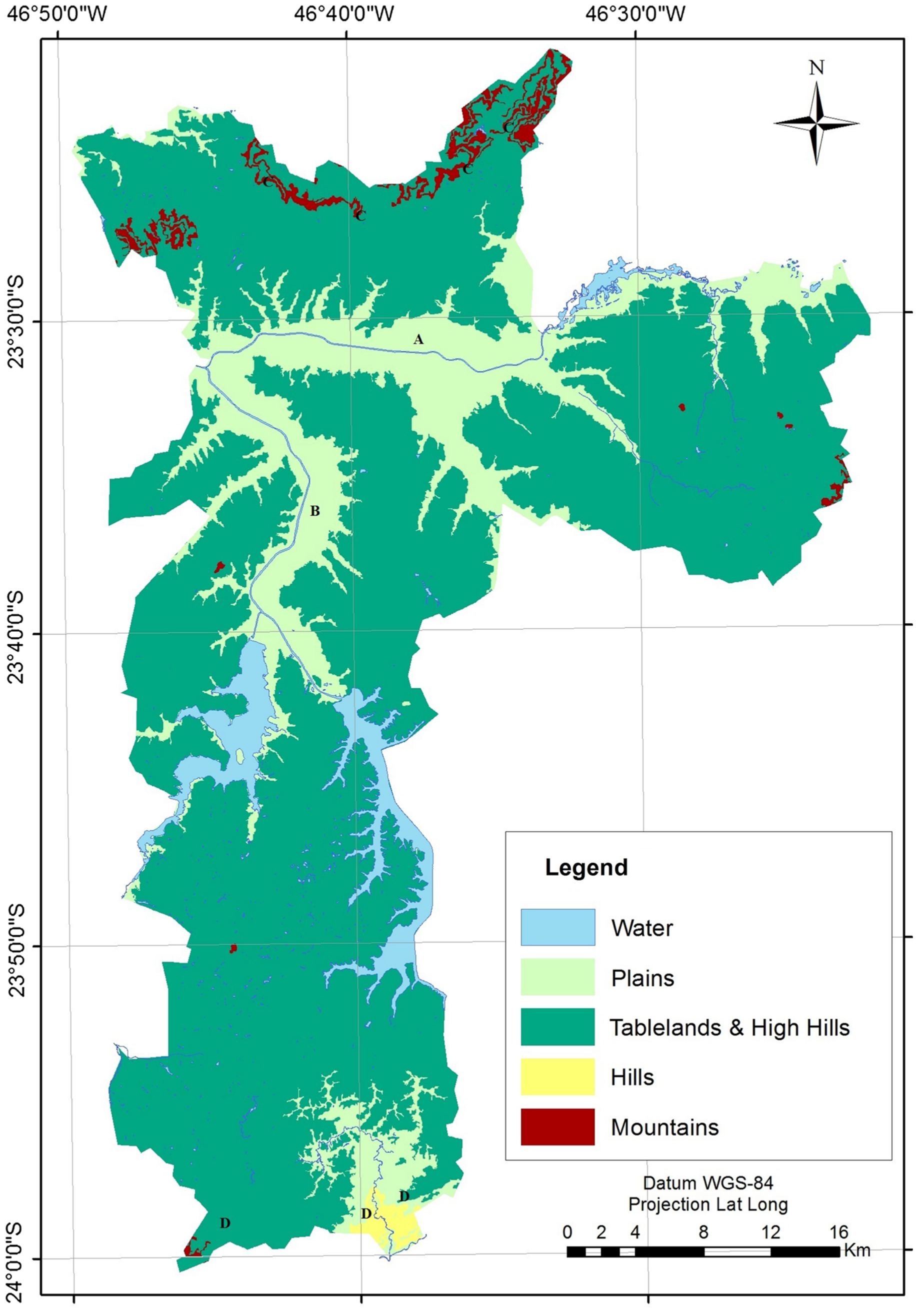


Fig. 9 Map of the relief subdivision in Sao Paulo City using a local approach. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra

However, the analysis spanned an area that extended far beyond the Sao Paulo City boundaries, i.e., the four classes are represented within the city limits. This situation indicates that the area has a very heterogeneous geomorphology. Therefore, the use of high-resolution data may be a better approach for this region.

The landform map in Fig. 10, which was derived from the map in Fig. 9, does not provide a superior characterization of Sao Paulo City when compared with the data of Ab'Saber (1957), Silveira (2008) and PMSP and IPT (1991). The only refinement represented by this map versus that in Fig. 8 is the delineation of the principal river plains.

The use of the interpolated data was not justified as it did not yield a considerable improvement over the use of the original data. The direct application of the method to a local analysis did not provide the expected results. This performance should not be attributed to the data, as it is primarily related to the method in which the entire analyzed subset of statistics is used to define the classification thresholds. This analysis is relative; thus, the classification varies depending on the subset. Therefore, the regional application of the proposed global method is reasonable and yields good results, but its local application is limited and must be carefully analyzed beforehand.

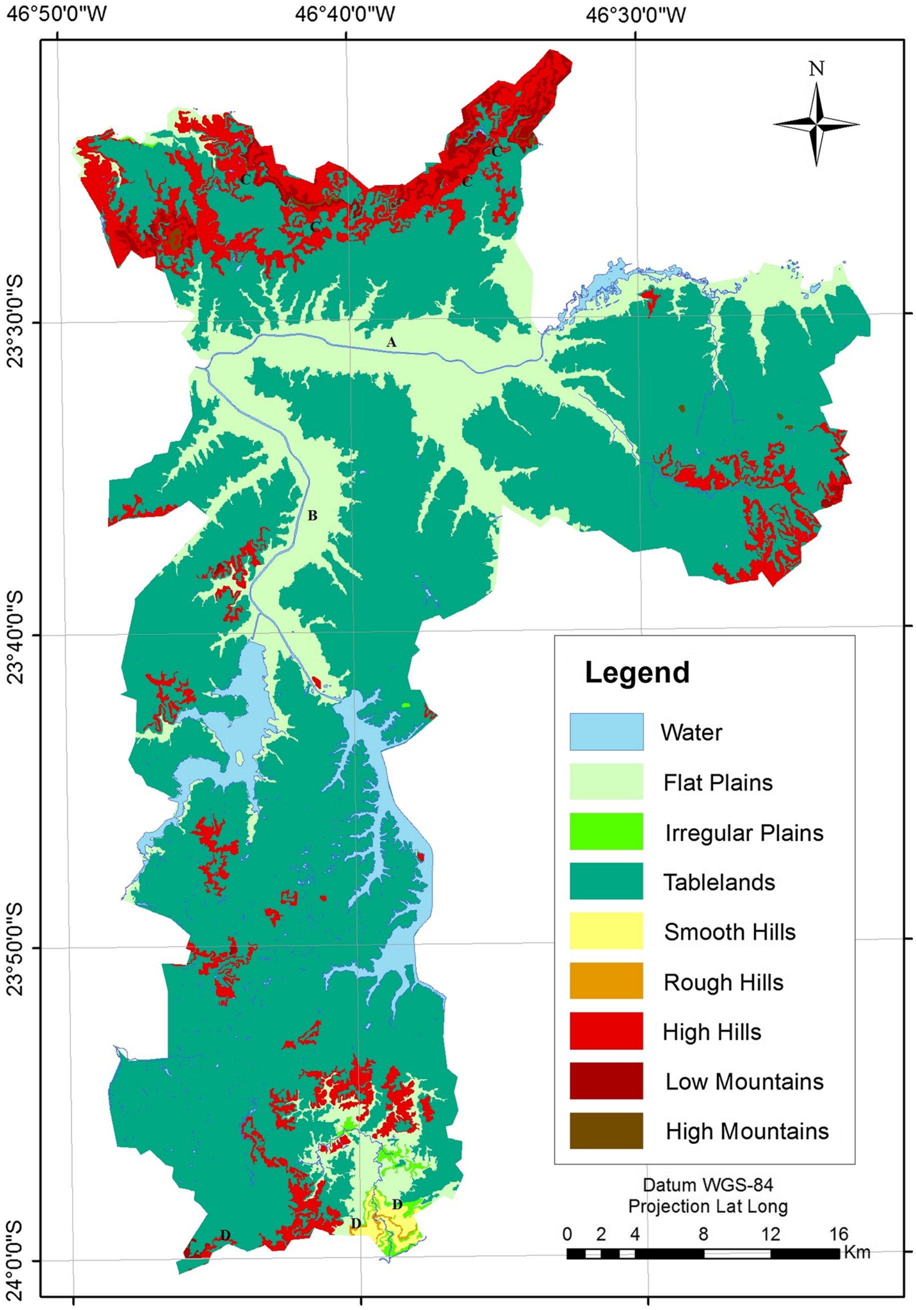


Fig. 10 Map of the landforms in Sao Paulo City using a local approach. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra

The drainage density and horizontal and vertical curvature variables were based on their ranges, which are highly dependent on the shapes of the topographic features; these variables enhanced the segmentation and provided much more homogenous objects, considering the landform and relief homogeneity. The horizontal and vertical curvatures and the numerical slope similarly affected the landform classification results once topographic shapes were added to the analysis. These enhancements were preconized by the literature (Valeriano 2003a; Tucker et al. 2001; Spörl and Ross 2004; Crepani et al. 1996).

The new approach provides a map that is very similar to the geotechnical map (PMSP and IPT 1991) and to the descriptions by Ab'Saber (1957) and Silveira (2008). Even the meteorite impact crater in the southern part of the city is delineated. The Cantareira Sierra and Jaraguá Mountain are delineated in Fig. 12, as are the mountain features in the eastern, western and southern parts of the city. In addition, the elevated area in the central part of the city between the two principal river plains is delineated and is classified as mountains. However, the most important difference of this product is the classification of tablelands,

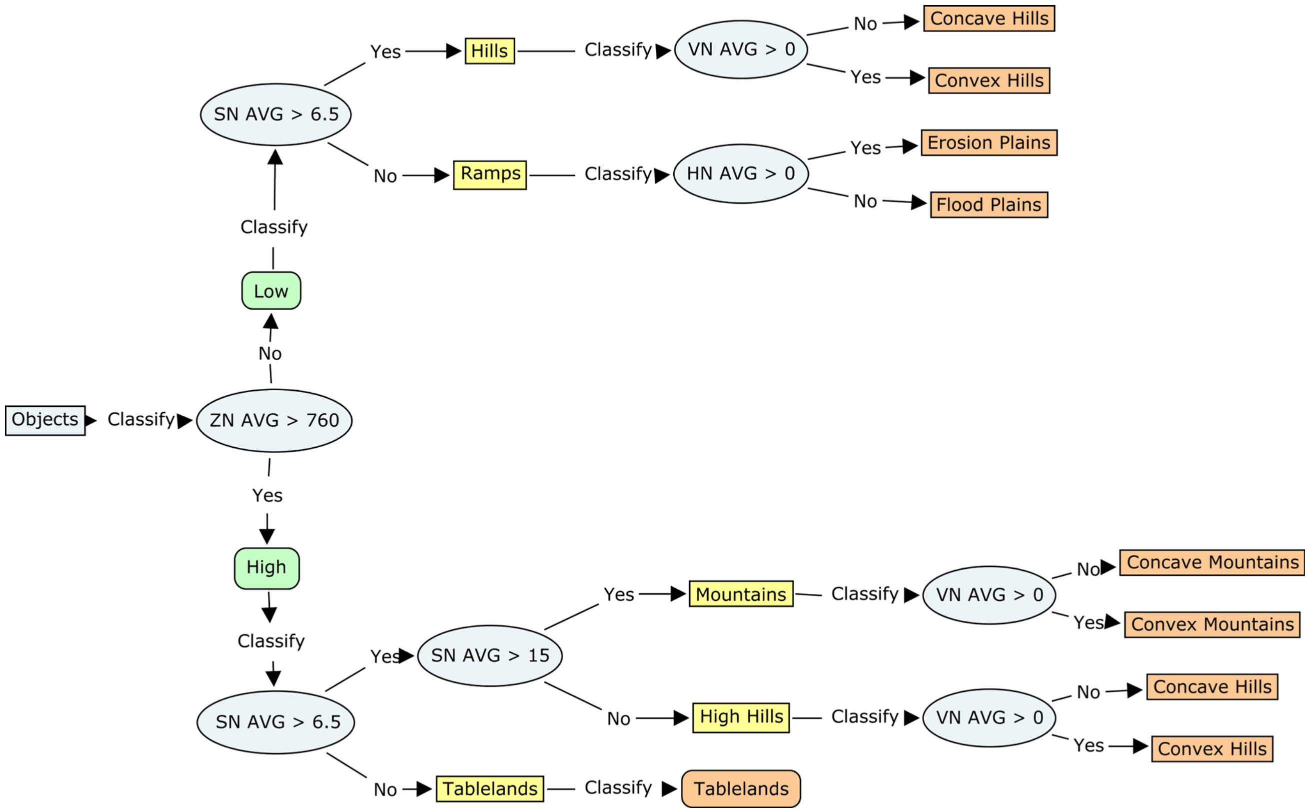


Fig. 11 Proposed methodology for relief subdivisions and landform maps. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra

which are restricted to very small areas. The map is also consistent with the geotechnical map by PMSP and IPT (1991) and the descriptions by Ab'Saber (1957).

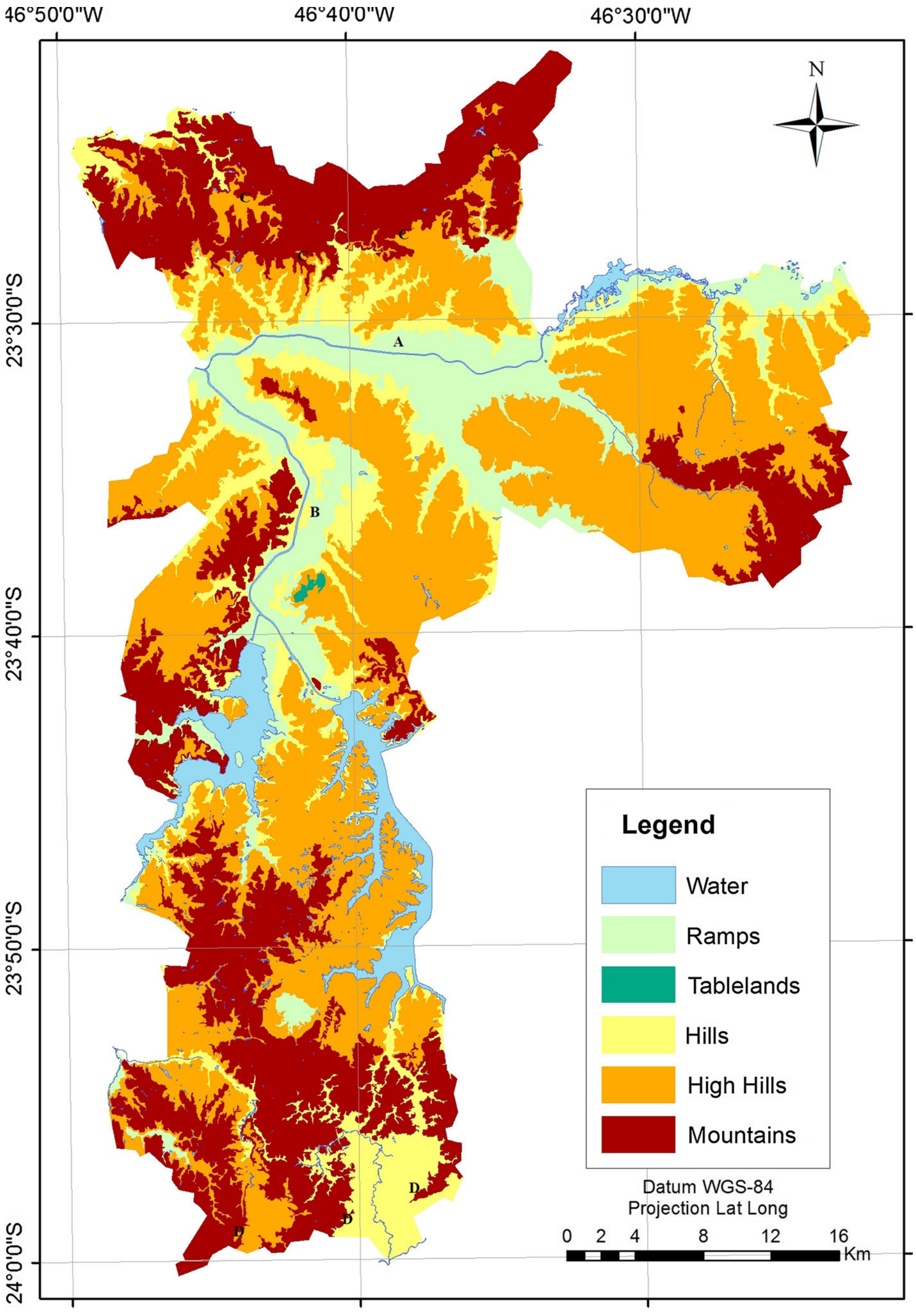
The map in Fig. 13 represents the application of the new approach to landform classification and is a much more refined product than the other maps presented in this paper. Separate erosional plains and flood plains were delineated in the ramp areas. This subdivision allows for the analysis of urban drainage concerns, which are important when considering the high population density of Sao Paulo City. Pluvial water flows, erosion and flood dynamics can thus be analyzed, and priority plans can be developed. In addition, development on erosional plains should be analyzed because such land use can produce severe changes in the erosional dynamics and negatively impact the river ecosystem. This same caution should be exercised in any intervention on flood plains.

High and low hills were both delineated among the concave and convex slopes. The same criterion was adopted for the mountains. This approach allows for the identification of areas most susceptible to erosion, landslides and drainage problems. The approach may also be useful in land use planning in urban plains in other regions because it indicates areas where intervention should proceed with caution. Notably, the concave slope classes characterize the continuity of the drainage, which is an important parameter in addressing environmental issues, particularly those associated with erosion and water ecosystem preservation. The conservation of vegetation is vital to several processes, including soil conservation and hydrological cycle maintenance (Corominas 2005).

However, a better urban drainage study may result from the use of high-resolution topographic information, as shown by Sreedevi et al. (2013). According to these authors, SRTM DEM- and GIS-based analyses of urban drainage are more appropriate than conventional methods. These analyses can be very useful for implementing rainwater harvesting and watershed management.

An example of erosion in concave areas is the large landslide scar near Anchieta Highway in Sao Paulo City. The landslide occurred in 2000 during the rainy season, and the scar is still visible. Figure 14 shows the scar's location and the overlay of the relief subdivision map on a high-resolution satellite image. The landslide scar exactly corresponds to an area classified as a concave slope. Thus, the new approach can help map landslide susceptibility and perform preliminary geotechnical investigations.

Fig. 12 Map of the relief subdivisions in Sao Paulo City using the proposed approach. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra

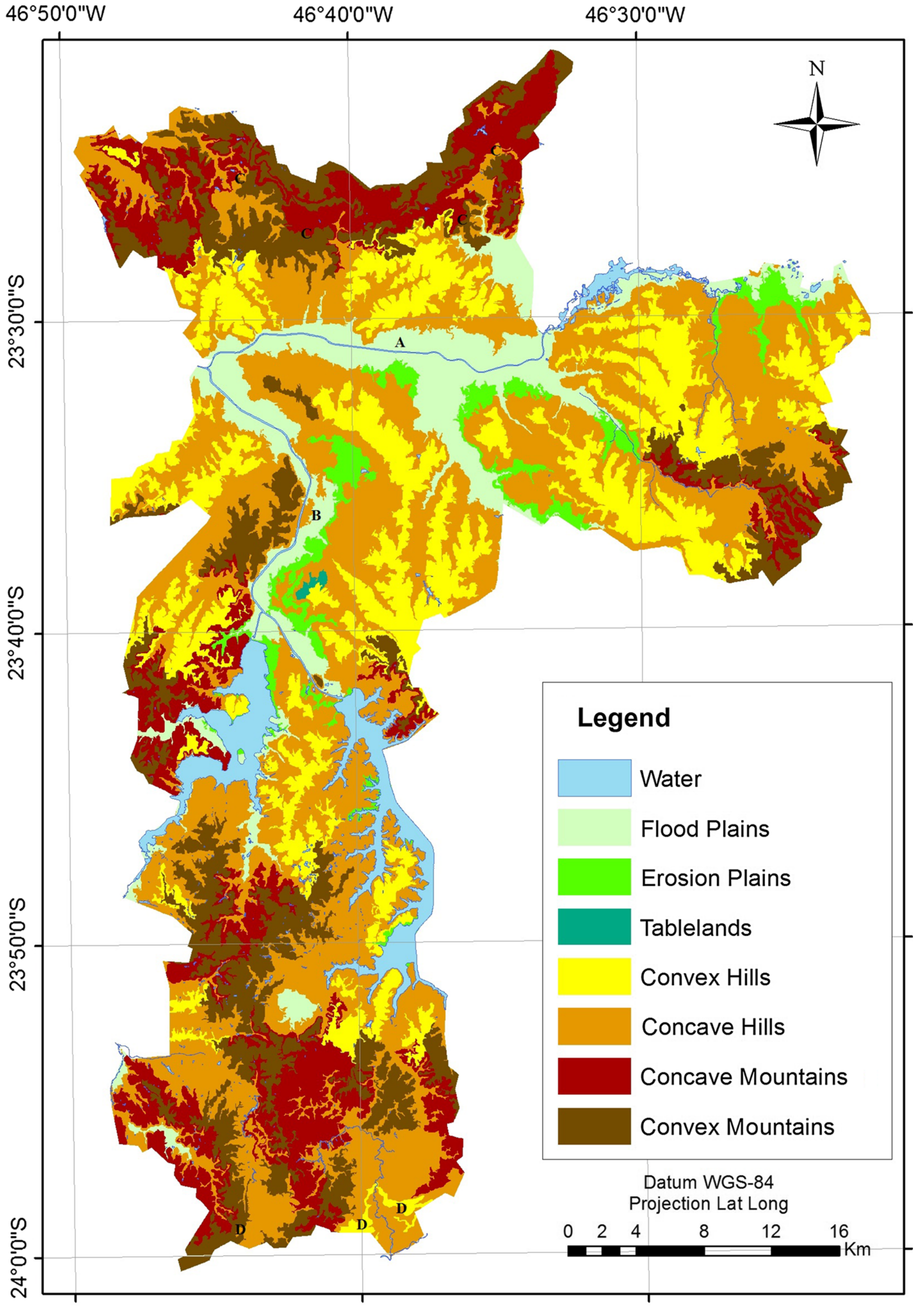


The convex features primarily represent the tops of mountains and hills, which are important in river basin planning. These features correspond to several topographic features described by Ab'Saber (1957, 1969) and Silveira (2008). The feature outlines also match those shown in the geotechnical map (PMSP and IPT 1991).

Based on a comparison with the method of Nobre et al. (2011), which is based on the HAND (height above the nearest drainage) approach, the map in Fig. 13 indicates that the new approach yields good results. Nobre et al. (2011) mapped hazard areas in the Sao Paulo metropolitan region, and their map shows boundaries and areas that match those shown in Fig. 13. The main hazard areas are located in the areas classified as concave slopes. In addition, the flood plains match those mapped in this study, and the erosional plains match particular highly eroded areas mapped in this study.

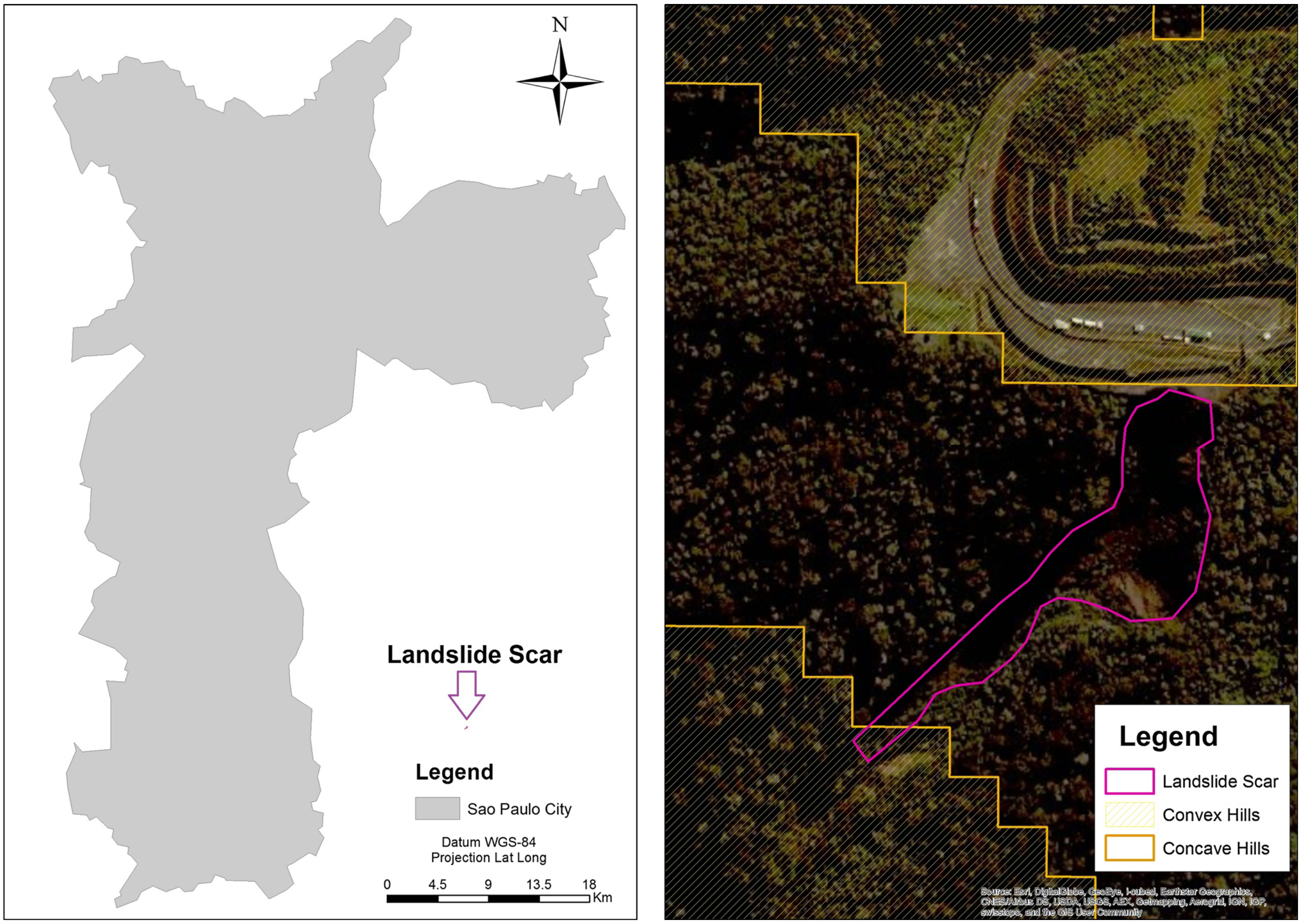
This product is superior because SRTM derivatives are used for the segmentation and theoretical thresholds are used in the classification. In addition, elements related to the topography were used to delineate new boundaries. These steps resulted in a multi-purpose map that can be subdivided into classes that aggregate other relief information.

Fig. 13 Map of the landforms in Sao Paulo City using the proposed approach. The specific regions are the **a** Tiete River; **b** Pinheiros River; **c** Cantareira Sierra; and **d** Coastal Sierra



The urban areas display altered relief due to drainage, transportation and housing development. A highly detailed analysis using SRTM-derived data might not be highly accurate or up-to-date. The adopted scale factor does not affect these aspects of the analysis, except where there are large alterations in the drainage basins, as evident in the Tiete and Pinheiros River plains; these features were rectified and caused substantial changes in the topography (Silveira 2008).

The information provided by the maps in this study is very important for defining areas of homogeneous relief for general land management. In this case study of Sao Paulo City, which is a highly urbanized megacity, such mapping is important not only for undeveloped areas and urban planning but also for drainage projects, hazard mitigation, housing projects, emergency management services mapping, environmental issues and transportation planning. Recently, authors have used geomorphologic information to delineate areas of severe erosion (Furlan et al. 2011; Beskow et al. 2009; Jorge 2009), flooding (Gao et al. 2007) and landslide hazards (Nicoll 2010). This last author assessed the landslide hazards for recent residential developments in the USA based on geomorphic variables.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Fig. 14 Landslide scar overlay with the new relief subdivision approach

Several principal roads and streets of the city are located in the area classified as flood plains. In addition, particular railways are located on the same plain (throughout the Sao Paulo metropolitan area) and are drastically affected by floods during the rainy season. Notably, the maps presented in this paper may provide guidelines for areas that deserve special attention for mitigation. Similarly, several housing projects have been built in hazard areas, and adequate geotechnical and hydrologic input to future housing projects should avoid such errors.

Moreover, a combination of landform maps with satellite imagery, geological information and field data can provide the basis for an analysis of areas susceptible to flash floods, floods and landslides. Youssef et al. (2011) used SRTM data to develop morphometric parameters and evaluate the areas susceptible to flash floods in Egypt. A similar study was performed in Turkey by Demerkisen (2012) to identify areas of flood hazards using SRTM imagery. Oh and Lee (2011) used SRTM imagery to obtain parameters that indicate landslide susceptibility. Morphometric parameters were used in a similar way in this study to classify landforms, although the set of parameters can be adjusted to suit a specific objective, such as the identification of potential flash flood areas.

Considering the current expansion of railways, roads and other transportation facilities in Sao Paulo City and the implementation of urban mobility plans, these products may become essential to urban planners and decision makers. The landform information is fundamental in urban mobility and transportation planning, and the delineation of homogeneous topographic areas is important for the optimization of urban mobility.

The maps can be used to understand urban sprawl because the geomorphology naturally shapes urban development. It is important to understand urban sprawl, as demonstrated by Jacquin et al. (2008), who developed prediction maps to improve urban plans. Land use dynamics based on homogeneous units, or territorial basic units (TBUs) according to Crepani et al. (1996) and Manfré et al. (2013), are important to consider.

TBUs are the elementary cells of environmental information and analysis. These units possess attributes that permit differentiation within a neighborhood (Spörl and Ross 2004). Each of these units is dynamically linked with others, thereby permitting their articulation in a complex net of units (Lucena 1998). TBUs allow for the integration of various attributes or environmental variables, depending on the processes that are being assessed (Ferreira and Rossini-Penteado 2011). Physiographic units define the fundamental boundaries in the analysis of land use dynamics.

Conclusions

The proposed method provides an adequate approach for computing relief subdivisions. Any of the products of the method may be used, depending on the final objective of the analysis. The method of Dragut and Eisank (2012) served as a guideline, though the classes of interest and their classification criteria must be better defined when performing local analyses.

The primary contribution of this paper is the development of a method for local analyses, and erosion was the primary issue addressed in delineating the relief subdivisions and landforms. The selection of the classes and method may vary, depending on the objectives of the study. The physiographic method and its threshold criteria may be widely replicated in a wide range of cases because it is based on theoretical assumptions and physiographic feature definitions.

The result is a product that can be used for general purposes, such as urban planning, river basin planning and ecological-economic zoning. The product can be obtained quickly using simple analytical tools and provides detailed delineation of areas that are geomorphologically homogeneous.

In the context of Sao Paulo City, the product provides basic information relevant to housing development and relocation planning, hazard area planning, transportation network expansion, preservation areas, waste disposal, waste treatment centers, and similar infrastructure and environmental issues. Because of its megacity status, vacant space within and near Sao Paulo City is rare and valuable. The relationships between land values and landforms are not closely correlated because many variables within a megacity must be taken into account. However, the topographic subdivisions are important physiographic characteristics in defining hazard areas and in allocating land uses, which directly impact land values. These subdivisions are key information for public policy.

This study proposes a method for topographic subdivision and landform mapping using SRTM-derived data, and other criteria may be used for other purposes. Every region has its own set of characteristics and classes that may be included in the analysis. Perhaps the most important contribution of this method is that it is replicable and is based on data that are available worldwide.

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