https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 26, nº 1 (2025)

http://dx.doi.org/10.20502/rbgeomorfologia.v26i1.2561

Research Article

Geomorphological mapping of the state of Paraná with digital classification method of landform patterns

Mapeamento geomorfológico do estado do Paraná com método de classificação digital de padrões de formas de relevo

Claudinei Taborda da Silveira [1], Ricardo Michael Pinheiro Silveira [2], Willian Bortolini [3], Victor Pierobom de Almeida [4]

[1] Universidade Federal do Paraná, Departamento de Geografia, Curitiba, Brasil. E-mail: claudineits@ufpr.br ORCID: https://orcid.org/0000-0001-6289-6306
[2] Universidade Federal do Paraná, Departamento de Geologia, Curitiba, Brasil. E-mail: ricardomichael@ufpr.br ORCID: https://orcid.org/0000-0002-5664-7079
[3] Universidade Estadual do Centro-Oeste, Departamento de Geografia, Guarapuava, Brasil. E-mail: willianbortolini@gmail.com ORCID: https://orcid.org/0000-0002-1164-1239
[4] Universidade Federal do Paraná, Departamento de Geografia, Curitiba, Brasil. E-mail: pierobomvictor@gmail.com ORCID: https://orcid.org/0009-0000-7615-9323

Received: 21/03/2024; Accepted: 17/02/2024; Published: 20/03/2025

Abstract: The digital classification method of landform patterns that was applied in the geomorphological mapping of the State of Paraná is presented. A Digital Terrain Model (MDT) was used to obtain three variables: 1) altimetric amplitude (AA), 2) average slope (AS) and 3) topographic position index (TPI), which were combined for classification compatible with the fourth geomorphological taxon, at a scale of 1:100,000. Sixteen classes of landform patterns were obtained: Flat Low Hills; Low Hills; Steep Low Hills; Terrain dissected between hills; Hills; High Hills; Dissected Hills; Steep High Hills; Elongated Structural Hills; Low Mountains; High Mountains; Plateau Edges; Strucutural Plateaus and Canyons; Fluviomarine Plain; Fluvial Plain and Colluvial Ramps. The method was consistent with the scale, the geomorphological characteristics and the intended representation and, after undergoing field verification with the collection of 225 points over 8,000km, it proved to be reliable at the desired level of representation, with overall mapping accuracy of 89.71%, with a slight predominance of overestimated areas (5.76%) compared to underestimated areas (4.53%), denoting the replicability of the method.

Keywords: geomorphological cartography; digital classification; landform patterns; geomorphometry; geomorphological mapping of Paraná.

Resumo: É apresentado o método de classificação digital de padrões de formas do relevo que foi aplicado no mapeamento geomorfológico do Estado do Paraná. Foi utilizado um Modelo Digital do Terreno (MDT) para a obtenção de três variáveis: 1) amplitude altimétrica (AA), 2) média da declividade (MD) e 3) índice de posição topográfica (IPT), que foram combinadas para a classificação compatível com o quarto táxon geomorfológico, na escala 1:100.000. Foram obtidas 16 classes de padrões de formas do relevo: Colinas Suaves; Colinas; Colinas Onduladas; Feições dissecadas entre colinas; Morrotes; Morros; Morros Dissecados; Morros Elevados; Morros Alongados Estruturais; Serras Montanhosas Baixas; Serras Montanhosas Altas; Serras de Bordas de Planaltos; Patamares Estruturais e Cânions; Planície Fluviomarinha; Planície Fluvial e Rampas Coluvionares, que resultaram na distinção de 226 unidades de padrões de formas de relevo no Paraná. O método foi condizente à escala, às características geomorfológicas, à representação pretendida e, depois de submetido à verificação de campo com a coleta de 225 pontos em 8.000km percorridos, demonstrou fidedignidade com o nível de representação desejado, cuja exatidão global do mapeamento foi de 89,71%, com ligeiro predomínio de áreas superestimadas (5,76%) se comparadas às áreas subestimadas (4,53%), denotando a exequibilidade do método.

Palavras-chave: cartografia geomorfológica; classificação digital; padrões de formas do relevo; geomorfometria; mapeamento geomorfológico do Paraná.

1. Introduction

Despite the legacy left by the RadamBrasil Project (BARBOSA *et al*., 1984), in the context of systematic geomorphological mapping work, which mapped the Brazilian relief on the millionth scale, there is still a large gap in the country, both from the perspective of surveys on medium and large scales, as well as methods composed of techniques compatible with current advances in computational tools using geotechnologies.

It is worth noting that the discussions on geomorphological cartography in the country, which have been taking place over the last few decades, have led to the formulation of a Brazilian Landform Classification System (Sistema Brasileiro de Classificação de Relevo - SBCR), formally instituted after the first workshop held in the city of Rio de Janeiro in 2019 (IBGE, 2020), which is under construction and which brings together the collaborative work of the community of geomorphologists represented by the Brazilian Geomorphology Union (União da Geografia Brasileira - UGB) and also specialists from the IBGE institutions and the Geological Service of Brazil (Serviço Geológico do Brasil - SGB/CPRM). The first results released were the reformulation of the first geomorphological taxon, made up of five landform classes, on a regional scale for Brazil (COMITÊ EXECUTIVO NACIONAL - CEN/SBCR, 2022).

In parallel with the development of the SBCR, the current scenario is that the most widely used methods in the country are those of Ross (1992) and IBGE (2009), both influenced by the Radam Brasil Project. However, the techniques used to represent their taxon still require further improvement.

The use of digital terrain analysis techniques, with a quantitative and computational approach, used in the classification of terrain at different scales, which has given geomorphological cartography a prominent identity in the 21st century, should be highlighted. The use of digital terrain analysis is greatly favored by advances in computer science and the availability of *hardware* and *software* with increasing storage and processing capacity; by progress in geotechnologies, especially Geographic Information Systems (GIS) and Digital Image Processing (DIP) techniques aimed at digital terrain analysis; and due to the dissemination of Digital Elevation Models (DEM) with global coverage.

The potential of digital terrain classification is recognized, especially due to the minimization of subjectivity, which makes a great contribution to geomorphological mapping work, especially in greater detail (SILVEIRA; SILVEIRA, 2017; SILVEIRA *et al*., 2018). It is also worth noting that several authors in the literature corroborate the advantages of digital terrain classification (WOOD, 1996; MACMILLAN *et al*, 2000; WILSON; GALLANT, 2000; ROMSTAD, 2001; VALERIANO, 2004; DRAGUT; BLASCHKE, 2006; IWAHASHI; PIKE *et al*, 2009; KLINGSEISEN *et al*, 2007; GROHMANN *et al*, 2008; SAADAT *et al*, 2008; WILSON, 2012).

In this context, this work focused on the development of digital terrain classification techniques for application in geomorphological mapping, with a view to representing the 1:100,000 scale. The units that make up the patterns of landforms are understood in terms of Ross's (1992) fourth geomorphological taxon, which was discussed from a multiscale perspective by Dantas *et al*. (2023). Four methods with potential use in the scope of the proposal were initially tested and refuted in an attempt to meet the established objectives: i) the topographic position index (TPI) by Weiss (2001), used in the central region of the Paraná's Sea Mountain Range by Silveira and Silveira (2016) and in the state of Paraná by Silveira and Silveira (2017); ii) the classification by Iwahashi and Pike (2007), which uses a decision tree based on three geomorphometric variables, applied by Silveira *et al*. (2014) in the state of Paraná; iii) the Dikau method (1991; 1995), automated by Reuter (2009), used in the state of Paraná by Silveira and Silveira (2015) in the central region of the Paraná's Sea Mountain Range by Silveira and Silveira (2016); and iv) the proposal by Jasiewicz and Stepinski (2013), which classifies landform elements using *geomorphons*, applied in the state of Paraná by Silveira *et al*. (2018).

It was found that the reported experiments did not satisfactorily meet the desired level of representation for landform patterns, which required the development of a method, which, after undergoing extensive field evaluations, met the expectations. The method proved to be more reliable in terms of scale and level of representation. It combines the geomorphometric variables altimetric amplitude, average slope and topographic position index, using mobile windows on a Digital Terrain Model.

Its first applications were used at an experimental level by Bortolini *et al*. (2017) on the topographic maps of Pato Branco (MI 2682) and Clevelândia (MI 2683), located in the southwest region of Paraná; by Gomes *et al*. (2018) on the Campo Largo map (MI 2841-4); by Bortolini *et al.* (2018) on the Curitiba (MI 2842) and Cerro Azul (MI 2826) maps; by Bortolini and Silveira (2021) using multiresolution segmentation in the digital mapping of landforms on the Curitiba (MI 2842) map and by Silveira *et al.* (2023) on the new geomorphological map of Paraná. This work confirmed the feasibility of the proposal.

In view of the above, the aim of this paper is to present the method for the digital classification of landform patterns in the state of Paraná and to present the classes that were obtained, making up a geomorphological map that meets the fourth taxon, at a scale of 1:100,000.

2. Study Area

The state of Paraná is located in the Southern Region of Brazil, whose territorial limits are: to the north with the state of São Paulo, to the east the Atlantic Ocean, to the south the state of Santa Catarina, to the southwest and west successively the Republics of Argentina and Paraguay and to the northwest the state of Mato Grosso do Sul. Its area is 199,575 km².

Its configuration is predominantly plateaus landforms, with five distinct geomorphological compartments (Figure 1): 1) Coastal Plain (Planície Litorânea), 2) Paraná's Mountain Range (Serra do Mar), 3) First Paraná's Plateau (Primeiro Planalto), 4) Second Paraná's Plateau (Segundo Planalto) and 5) Third Paraná's Plateau (Terceiro Planalto), named by Maack (1968) as natural landscape units and described with morpho sculptural units, dealt with in the second geomorphological taxon, by Santos *et al*. (2006) and Oka-Fiori *et al*. (2006).

The Paraná's Sea Mountain Range is a marginal mountain range to the east of the First Paraná's Plateau, separating it from the Coastal Plain, with high summits of up to 1800m (MAACK, op. cit.), whose highest elevations are supported by a Coastal Granitoid Belt (ALMEIDA; CARNEIRO, 1998), surrounded by other diverse lithological units, mostly high-grade metamorphic, associated with intrusive lithotypes (OKA-FIORI, op. cit.).

The First Paraná's Plateau stretches from the front of the *Serra do Purunã* escarpment, which borders the Second Paraná's Plateau, to the western face of the Paraná's Mountain Range (Serra do Mar). To the north there are the rocks of the Açungui Group (FIORI; GASPAR, 1993), with strongly dissected terrain, with altimetry values between 400 and 1200m, developed on the metamorphic rocks of the Açungui Group, the metavolcanics of the Castro Group, granitic intrusions and diabase dykes (SANTOS, op. cit.). In the portion above the rocks of the crystalline basement, cut by pegmatite and diabase dykes, the average elevations vary between 850 and 950m, with gently undulating terrain and the presence of flat areas along the main rivers, associated with the formation of alluvial plains (OKA-FIORI, op. cit.).

The Second and Third Paraná's Plateaus are on the Paraná Sedimentary Basin, a large sedimentary region of the South American continent covered in the central region by thick lavas resulting from intense fissure volcanism, associated with an intricate network of dykes cutting the sedimentary section and multiple dykes and sills, whose sedimentary and magmatic record is organized by Milani *et al*. (2007) into six supersequences: Rio Ivaí, Paraná, Gondwana I, Gondwana II, Gondwana III and Bauru, the first three of which are represented by sedimentary successions that define transgressive-regressive cycles linked to relative sea level oscillations in the Paleozoic, while the others correspond to packages of continental sediments with associated igneous rocks (MILANI *et al*., 2007).

The Second Paraná's Plateau, built on sedimentary rocks, is a plateau modeled on monoclinal, sub-horizontal structures, dipping to the west (OKA-FIORI, op. cit.). This unit is characterized by Costa *et al*. (2005) as a plateau modelled on sedimentary lithologies from the Paraná Basin, whose layers slope gently to the west, dissected by the drainage network which runs in the same direction. The SE-NW dykes form the nuclei of elongated elevations. This unit extends from the reverse of the *Purunã* (or Devonian) escarpment, over the sandstones of the Furnas Formation, where the average summit altitudes are between 1100 and 1200 m, to its western limit, at the foot of the front of the Triassic-Jurassic (or Serra Geral) escarpment, with altitudes varying between 400 and 500m.

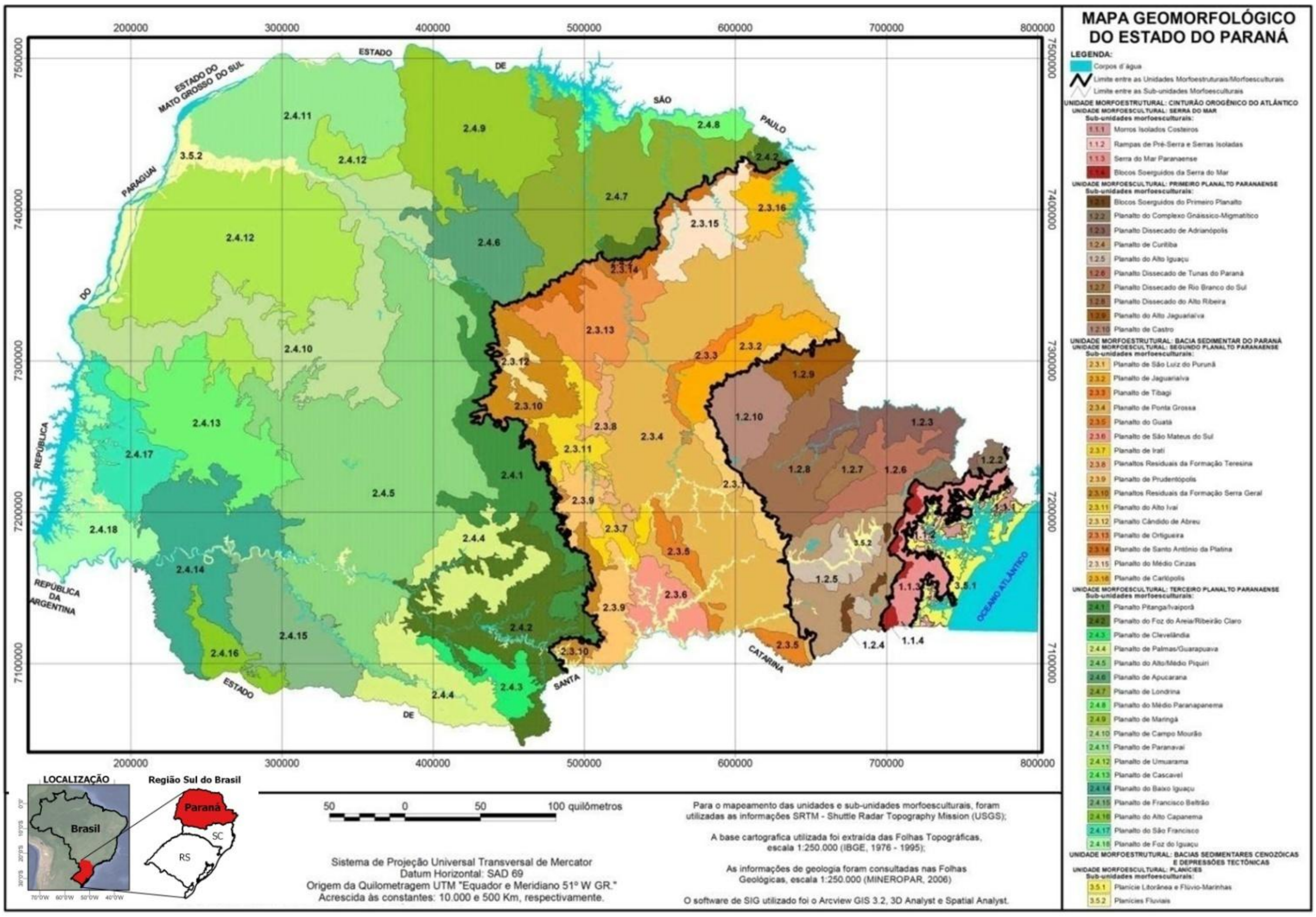

Figure 1. Geomorphological map of the state of Paraná, showing three taxonomic levels. Source: Santos *et al*. (2006).

The Third Paraná's Plateau is mainly developed on the Mesozoic volcanic rocks of the Serra Geral Group and the sandstone rocks of the Caiuá Group (Besser *et al*., 2021). The terrain of the Third Paraná's Plateau predominates in Paraná, with average summit elevations of between 1100 and 1250 m, on the reverse side of the *Serra da Esperança* escarpment, dropping to altitudes of between 220 and 300 m near the Paraná river channel (SANTOS, op. cit.).

3. Materials and Methods

The research was carried out in seven stages, described below and summarized in the flowchart (Figure 2).

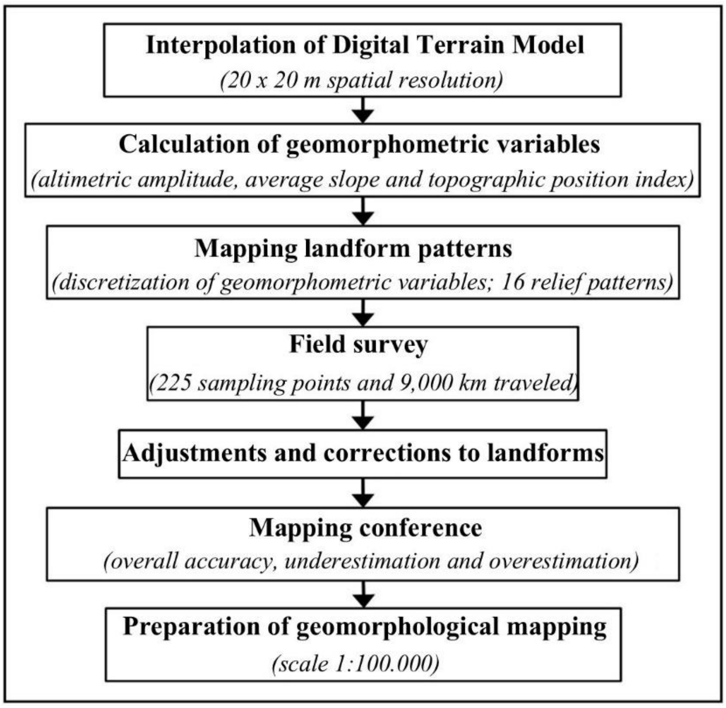

Figure 2. Flowchart of the method's stages.

Stage 1 - Interpolation of the Digital Terrain Model (DTM): This was interpolated using the Topogrid method (HUTCHINSON, 1988), available in ArcMap 10.1 software, using contour lines, elevation points and stream lines as input vector data, from the digitization of topographic maps on a scale of 1:50,000 and 1:25,000. The pixel size adopted for the grid was 20 meters, based on the proposal by Hengl (2006) and experiments carried out to assess the compatibility of the representation of the cartographic base.

Stage 2 - Calculation of the geomorphometric variables: The slope (in percentage), the Topographic Position Index (TPI), the altimetric amplitude and the average slope were calculated from the DTM.

The slope was calculated in percentage values from a 3x3 pixel moving window, according to the directional variables of Horn's theoretical model (1981).

The altimetric amplitude, treated by Aili (2008) as local relief (LR), is characterized as the difference between the maximum and minimum altimetry of a determined area (Equation 1), given by a circular radius of a size determined from the analysis of a series of slope profiles, as illustrated by an individual profile in Figure 3, calculated manually using the line measurement tool. Although the length of the slope in profile includes the slope, the length of the slope in plan was taken into account in the analysis of the DTM. The value considered for the circular radius was the length of the slopes in plan for each geomorphological context, using the geomorphological subunits as a reference:

$$Altimetric\ amplitude = A_{max} - A_{min} \quad (1)$$

where A_{max} is the maximum altitude present in the radius area and A_{min} is the minimum altitude.

The average slope is characterized as the average of the slope values of a determined area (Equation 2), which, like the altimetric amplitude, was calculated from a predefined radius.

$$Average\ slope = \sum Dn \quad (2)$$

where $\sum D$ is the sum of the slopes of each pixel covered by the analysis radius and n the number of pixels covered by the radius.

The Topographic Position Index (TPI), proposed by Wilson and Gallant (2000), is characterized as the difference between the elevation of a central pixel (Z_0) and the average neighborhood elevation (Z) (Equation 3). A circular radius of 1 km was used to calculate the average elevation.

$$TPI = Z_0 - Z \quad (3)$$

The procedure for determining the size of the radius for calculating the geomorphometric variables was carried out for each of the geomorphological subunits, according to Santos et at. (2006), mapped as the 3rd geomorphological taxon. It is considered that these subunits were used as landform units representative of morphological and morphometric characteristics, in which the trend value of the slope lengths was taken into account. The slope lengths were calculated in plan, sample and manually (Figure 3). The dimensions of the neighborhood radii determined for each geomorphological subunit are shown in Chart 1.

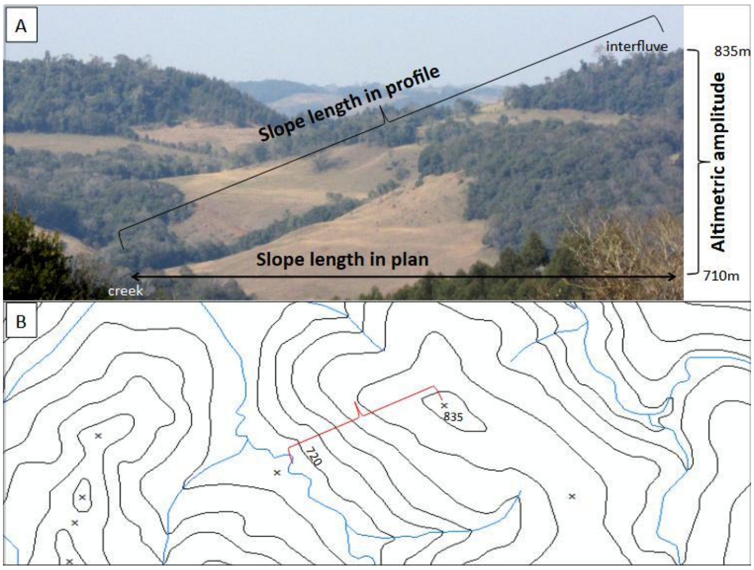

Figure 3. A) photograph showing the altimetric amplitude of a slope, the length of the slope in profile and the length of the slope, the latter being used to determine the size of the radius used to calculate the geomorphometric variables; B) representation of the slope with contour lines.

Stage 3 - Application of geomorphometric variables for mapping landform patterns: initially, the landform patterns to be mapped were defined (conceptual model), categorized based on heuristic models of the occurrence of such objects in the landscape. The expression of the morphometric dimensions of the landform patterns was measured by altimetric amplitude, average slope and topographic position index. The classification was based on the parameters applied in previous experiments, in sample areas, published by Bortolini *et al*. (2017; 2018) and Gomes *et al*. (2018). The concept of “geometric signature” (PIKE, 1988) was also considered for the quantitative representation of each individualized pattern.

Next, the geomorphometric variables were discretized according to the predefined geomorphological categories. Combining the variables using map algebra resulted in the identification of mapping units, according to the parameters set out in Chart 2 (First Plateau), Chart 3 (Second Plateau), Chart 4 (Third Plateau) and Chart 5 (Paraná’s Mountain Range and Coastal Plain).

Chart 1. Size of the radius per geomorphological subunit according to the average length of the slopes.

Units of the 3rd taxon	**Radius (m)**	**Units of the 3rd taxon**	**Radius (m)**
1.1.1 Serras Isoladas Costeiras	1200	2.3.11 Planalto do Alto Ivaí	600
1.1.2 Morros Isolados	500	2.3.12 Planalto de Cândido Abreu	600
1.1.3 Serra do Mar Paranaense	1200	2.3.13 Planalto de Ortigueira	540
1.1.4 Blocos Soerguidos da Serra do Mar	1200	2.3.14 Planalto de Santo Antônio da Platina	600
1.1.5 Rampas de Pré-Serra	-	2.3.15 Planalto do Médio Cinzas	500
1.2.1 Blocos Soerguidos do Primeiro Planalto	500	2.3.16 Planalto de Carlópolis	540
1.2.2 Planalto do Complexo Gnáissico-Migmatítico	400	2.4.1 Planalto de Pitanga/Ivaiporã	700
1.2.3 Planalto Dissecado de Adrianópolis	600	2.4.2 Planalto do Foz do Areia/Ribeirão Claro	600
1.2.4 Planalto de Curitiba	400	2.4.3 Planalto de Clevelândia	500
1.2.5 Planalto do Alto Iguaçu	450	2.4.4 Planalto de Palmas/Guarapuava	900
1.2.6 Planalto Dissecado de Tunas do Paraná	400	2.4.5 Planalto do Alto/Médio Piquiri	700
1.2.7 Planalto Dissecado de Rio Branco do Sul	550	2.4.6 Planalto de Apucarana	600
1.2.8 Planalto Dissecado do Alto Ribeira	600	2.4.7 Planalto de Londrina	600
1.2.9 Planalto do Alto Jaguariaíva	700	2.4.8 Planalto do Médio Paranapanema	800
1.2.10 Planalto de Castro	450	2.4.9 Planalto de Maringá	1500
2.3.1 Planalto de São Luís do Purunã	700	2.4.10 Planalto de Campo Mourão	1500
2.3.2 Planalto de Jaguariaíva	600	2.4.11 Planalto de Paranavaí *	3000 100 30
2.3.3 Planalto de Tibagi	600		
2.3.4 Planalto de Ponta Grossa (Porção Norte)	700		
2.3.4 Planalto de Ponta Grossa (Porção Sul)	750	2.4.12 Planalto de Umuarama	1500
2.3.5 Planalto de Guatá	700	2.4.13 Planalto de Cascavel	1400
2.3.6 Planalto de São Mateus do Sul	450	2.4.14 Planalto do Baixo Iguaçu	800
2.3.7 Planalto de Irati	540	2.4.15 Planalto de Francisco Beltrão	900
2.3.8 Planalto Residuais da Formação Teresina	600	2.4.16 Planalto do Alto Capenema	500
2.3.9 Planalto de Prudentópolis	600	2.4.17 Planalto do São Francisco	700
2.3.10 Planaltos Residuais da Formação Serra Geral	500	2.4.18 Planalto de Foz do Iguaçu	1000

* In unit 2.4.11, three neighborhood analysis radius sizes were used: 3000 m (for calculating the average slope), 100 m (for calculating the average slope that delimited the dissected features between hills); and 30 m (for calculating the altimetric amplitude).

Chart 2. Parameters for mapping landform patterns (4th taxon) in the geomorphological subunits (3rd taxon) of the First Paraná's Plateau (2nd taxon).

Units of the 3rd taxon	Landform pattern (4th taxon)							
	Low Hills (COL)	Steep Low Hills (CON)	Hills (MRT)	High Hills (MOR)	Dissected Hills (MOD)	Steep High Hills (MOE)	Plateau Edges (SBP)	Fluvial Plain (PFV)
1.2.1	AA<120 and AS<8	AA<60 and AS>8 or AA>60 and <80 and AS>8 and <30	AA>60 and <80 and AS>30 or AA>80 and <120 and AS>8	AA>120 and <200 and AS<30		AA>200		
1.2.2	AA<100 and AS<8	AA<50 and AS>8 or AA>50 and <70 and AS>8 and <30	AA>50 and <70 and AS>30 or AA>70 and <100 and AS>8	AA>100 and <200 and AS<30	AA>100 and <200 and AS>30	AA>200		
1.2.3			AA>60 and <80 and AS>30 or AA>80 and <120 and AS>8	AA>120 and <200 and AS<30	AA>120 and <200 and AS>30	AA>200		
1.2.4	AA<100 and AS<8	AA<50 and AS>8 or AA>50 and <70 and AS>8 and <30	AA>50 and <70 and AS>30 or AA>70 and <100 and AS>8	AA>100 and <200 and AS<30				S<3 and TPI>0
1.2.5	AA<100 and AS<8	AA<50 and AS>8 or AA>50 and <70 and AS>8 and <30						
1.2.6	AA<100 and AS<8	AA<50 and AS>8 or AA>50 and <70 and AS>8 and <30	AA>50 and <70 and AS>30 or AA>70 and <100 and AS>8	AA>100 and <200 and AS<30	AA>100 and <200 and AS>30	AA>200		
1.2.7			AA>60 and <80 and AS>30 or AA>80 and <120 and AS>8	AA>120 and <200 and AS<30	AA>120 and <200 and AS>30	AA>200		
1.2.8		AA<575 and AS>8 or AA>75 and <95 and AS>8 and <30	AA>75 and <95 and AS>30 or AA>95 and <130 and AS>8	AA>130 and <190 and AS<30	AA>130 and <190 and AS>30	AA>190	Visual delineation of the high hills at the contact between the First and Second Plateaus	
1.2.9		AA<80 and AS>8 or AA>80 and <120 and AS>8 and <20	AA>80 and <120 and AS>20 or AA>120 and <150 and AS>8	AA>150 and <200 and AS<30	AA>150 and <200 and AS>30	AA>200		
1.2.10	AA<130 and AS<5	AA<50 and AS>8 or AA>50 and <80 and AS>5 and <30	AA>50 and <80 and AS>30 or AA>80 and <130 and AS>8	AA>130 and <200 and AS<30				S<3 and TPI>0

Legend: AA: altimetric amplitude; AS: average slope; S: slope and TPI: topographic position index.

Chart 3. Parameters for mapping landform patterns (4th taxon) in the geomorphological subunits (3rd taxon) of the Second Paraná's Plateau (2nd taxon).

Units of the 3rd taxon	Landform pattern (4th taxon)								
	Low Hills (COL)	Steep Low Hills (CON)	Hills (MRT)	High Hills (MOR)	Dissected Hills (MOD)	Elongated Structural Hills (MAE)	Plateau Edges (SBP)	Dissected Plateaus and Canyons (PEC)	Fluvial Plain (PFV)
2.3.1	AA<120 and S<8	AA<80 and S>8 or AA>80 and <120 and S>8	AA>120 and <160	AA>160 and <200					D<3 e IPT>0
2.3.2	AA<100 and S<8	AA<100 and S>8 or AA>100 and <150 and S<13 or AA>150 and <220 and S<13						AA>100 and <150 and S>13 or AA>150 and <220 and S>13 or AA>220	
2.3.3	AA<60 and S<30 or AA>60 and <90 and S<10	AA<60 and S>30 or AA>60 and <90 and S>10 and <30	AA>60 and <90 and S>30 or AA>90 and <120						D<3 e IPT>0
2.3.4 S	AA<120 and S<8	AA<120 and S>8 and <20	AA<120 and S>20 or AA>120 and <160	AA>160 and <220	AA>220				
2.3.4 N	AA<150 and S<8	AA<150 and S>8		AA>150 and <220	AA>220				
2.3.5	AA<120 and S<8	AA<120 and S>8	AA>120 and <160						
2.3.6	AA<110 and S<7	AA<110 and S>7							
2.3.7	AA<110 and S<8	AA<80 and S>8 or AA>80 and <110 and S>8 and <20	AA>80 and <110 and S>20 or AA>110 and <150	AA>150 and <210					
2.3.8	AA<90 and S<20 or AA>90 and <120 and S<8		AA<90 and S>20 or AA>90 and <120 and S>8 or AA>120 and <160	AA>120 and <210	AA>210				
2.3.9	AA<130 and S<8	AA>90 and <130 and S>8	AA>90 and <130 and S>8 or AA>130 and <150 and S<8	AA>130 and <150 and S>8 or AA>150 and <210	AA>210				
2.3.10	AA<120 and S<20		AA<120 and S>20 or AA>120 and <160		AA>160 and <210 and S>20 or AA>210		Visual delineation of the high hills at the contact between the First and Second Plateaus		
2.3.11	AA<110 and S<20		AA<110 and S>20 or AA>110 and <160		AA>160 and <210 and S>20 or AA>210				
2.3.12	AA<110 and S<8 or AA<70 and S<20		AA<70 and S>20 or AA>70 and <110 and S>8 or AA>110 and <160	AA>160 and <210	AA>210				D<3 e IPT>0
2.3.13	AA<80 and S<8	AA<60 and S>8 or AA>60 and <80 and S>20 and <80				AA>130 and <200 and S>20			
2.3.14	AA<110 and S<8 or AA<80 and S>8 and <20		AA<80 and S>20 or AA>80 and <110 and S>8 or AA>110 and <155	AA>155 and <240	AA>140		Visual delineation of the high hills at the contact between the First and Second Plateaus		D<3 e IPT>0
2.3.15	AA<110 and S<8	AA<90 and S>8	AA>90 and <110 and S>8 or AA>110 and <160	AA>160 and <200					
2.3.16	AA<70 or AA>70 and <100 and S<8		AA>70 and <110 and S>8 or AA>110 and <150		AA>150 and <210 and S>20 or AA>210				

Legend: AA: altimetric amplitude; AS: average slope; S: slope and TPI: topographic position index.

Chart 4. Parameters for mapping landform patterns (4th taxon) in the geomorphological subunits (3rd taxon) of the Third Paraná's Plateau (2nd taxon).

Units of the 3rd taxon	Landform pattern (4th taxon)								
	Flat Low Hills (COS)	Low Hills (COL)	Steep Low Hills (CON)	Terrain dissected between hills (FDC)	Hills (MRT)	High Hills (MOR)	Dissected Hills (MOD)	Steep High Hills (MOE)	Fluvial Plain (PFV)
2.4.1		AA<120 and AS<8	AA<80 and AS>8 or AA>80 and <120 and AS>8 and <14		AA>80 and <120 and AS>14	AA>120 and <250 and AS<20	AA>120 and <250 and AS>20		S<3 and TPI>0
2.4.2		AA<115 and AS<8	AA<75 and AS>8 or AA>75 and <115 and AS>8 and <12		AA>75 and <115 and AS>12	AA>115 and <245 and AS<20	AA>115 and <245 and AS>20	AA>245	
2.4.3		AA<110 and AS<8	AA<70 and AS>8 or AA>70 and <110 and AS>8 and <12		AA>70 and <110 and AS>12	AA>110 and <240 and AS<20	AA>110 and <240 and AS>20	AA>240	S<3 and TPI>0
2.4.4		AA<130 and AS<8	AA<90 and AS>8 or AA>90 and <130 and AS>8 and <12		AA>90 and <130 and AS>12	AA>130 and <250 and AS<20	AA>130 and <250 and AS>20		
2.4.5		AA<120 and AS<8	AA<80 and AS>8 or AA>80 and <120 and AS>8 and <12		AA>80 and <120 and AS>12	AA>120 and <250 and AS<20	AA>120 and <250 and AS>20		
2.4.6		AA<115 and AS<8	AA<75 and AS>8 or AA>75 and <115 and AS>8 and <14		AA>75 and <115 and AS>14	AA>115 and <245 and AS<20	AA>115 and <245 and AS>20		
2.4.7		AA<115 and AS<8	AA<75 and AS>8 or AA>75 and <115 and AS>8 and <14		AA>75 and <115 and AS>14	AA>115 and <245 and AS<20	AA>115 and <245 and AS>20		S<3 and TPI>0
2.4.8		AA<125 and AS<9	AA<85 and AS>9 or AA>85 and <125 and AS>9 and <14						
2.4.9	AS<5	AS>5 and <8	AS>8						
2.4.10		AS<8	AS>8						
2.4.11	AA<90 and AS*<8,5 and AS**<4,5	AA<90 and AS*<8,5 and AS**>4,5		AA<90 and AS*>8,5					
2.4.12		AS<7,5	AS>7,5						
2.4.13		AA<160 and AS<8	AA<160 and AS>8 and <12		AA<160 and AS>12	AA>160 and AS<20	AA>160 and AS>20		
2.4.14		AA<125 and AS<8	AA<85 and AS>8 or AA>85 and <125 and AS>8 and <12		AA>85 and <125 and AS>12	AA>125 and <255 and AS<20	AA>125 and <255 and AS>20		
2.4.15		AA<130 and AS<8	AA<90 and AS>8 or AA>90 and <130 and AS>8 and <12		AA>90 and <130 and AS>12	AA>130 and <260 and AS<20	AA>130 and <260 and AS>20		
2.4.16			AA<70 and AS>8 or AA>70 and <110 and AS>8 and <14		AA>70 and <110 and AS>14	AA>110 and <240 and AS<20	AA>110 and <240 and AS>20		
2.4.17		AA<120 and AS<8	AA<80 and AS>8 or AA>80 and <120 and AS>8 and <14		AA>80 and <120 and AS>14	AA>120 and <250 and AS<20	AA>120 and <250 and AS>20		
2.4.18		AA<135 and AS<8	AA<95 and AS>8 or AA>95 and <135 and AS>8 and <12		AA>95 and <135 and AS>12	AA>135 and <265 and AS<20			S<3 and TPI>0

Legend: AA: altimetric amplitude; AS: average slope; S: slope and TPI: topographic position index.

Chart 5. Parameters for mapping landform patterns (4th taxon) in the geomorphological subunits (3rd taxon) of the Coastal Plain and Paraná's Mountain Range (Serra do Mar) (2nd taxon).

Units of the 3rd taxon	Landform pattern (4th taxon)							
	Steep Low Hills (CON)	Hills; (MRT)	High Hills (MOR)	Low Mountains (SMB)	High Mountains (SMA)	Fluviomarine Plain (PFM)	Fluvial Plain (PFV)	Colluvial Ramps (RCV)
3.5.1						Z<15	S<3 e TPI>0	
3.5.2								
1.1.1				AA<380	AA>380	Z<15		Z<120 e S<16
1.1.2	Z>15 e AA<60 e S>6	Z>15 e AA>60 e <90 e S>6	Z>15 e AA>90 e S>6			Z<15	S<3 e TPI>0	
1.1.3				AA<380	AA>380			
1.1.4				AA<380	AA>380			
1.1.5				AA<380	AA>380		S<3 e TPI>0	Z<120 e S<16

Legend: Z: Altimetry; AA: altimetric amplitude; S: slope; TPI: topographic position index.

After integrating and combining the geomorphometric variables, a filter was applied that removed clusters ranging from 0.25 km² (or 625 pixels) to 30 km² (or 75,000 pixels), with the value of 1 km² (or 2500 pixels) as the predominant generalization parameter. The removed areas were reclassified as belonging to the landform pattern of the neighboring areas. The application of the filter (generalization) is linked to the taxonomic hierarchy intended by the mapping, and the value of the filter is defined based on the size of the categorized landform units proposed by Dikau (1989).

Stage 4 - Survey and field checking: Field expeditions were carried out to check the preliminary results and subsequently correct the landform patterns, totaling approximately 9,000 km over land. These activities were carried out in order to evaluate the classifications obtained from the geomorphometric parameters defined for each landform pattern.

During the field expeditions, georeferenced photos representing the terrain were collected from 225 sample points in different geomorphological compartments, described and illustrated by ground-level photos, and complemented by 25 flights made with a DJI Phantom 3 drone. The field points were used to check the landform patterns that had previously been defined and mapped based on prior knowledge of the terrain of the different regions.

Stage 5 - Implementing adjustments to the mapped landform patterns: Manual edits were made to the mapping obtained, with the support of the field sample points, in order to: incorporate small portions of the landform pattern into the surrounding pattern, as they have similar characteristics; adjust areas of contact between landform patterns, which had boundaries that cut across the slopes; and adjust areas classified as a particular landform pattern that only covers one slope face. These adjustments were made based on visual interpretation of the hillshade, as shown in Figure 4.

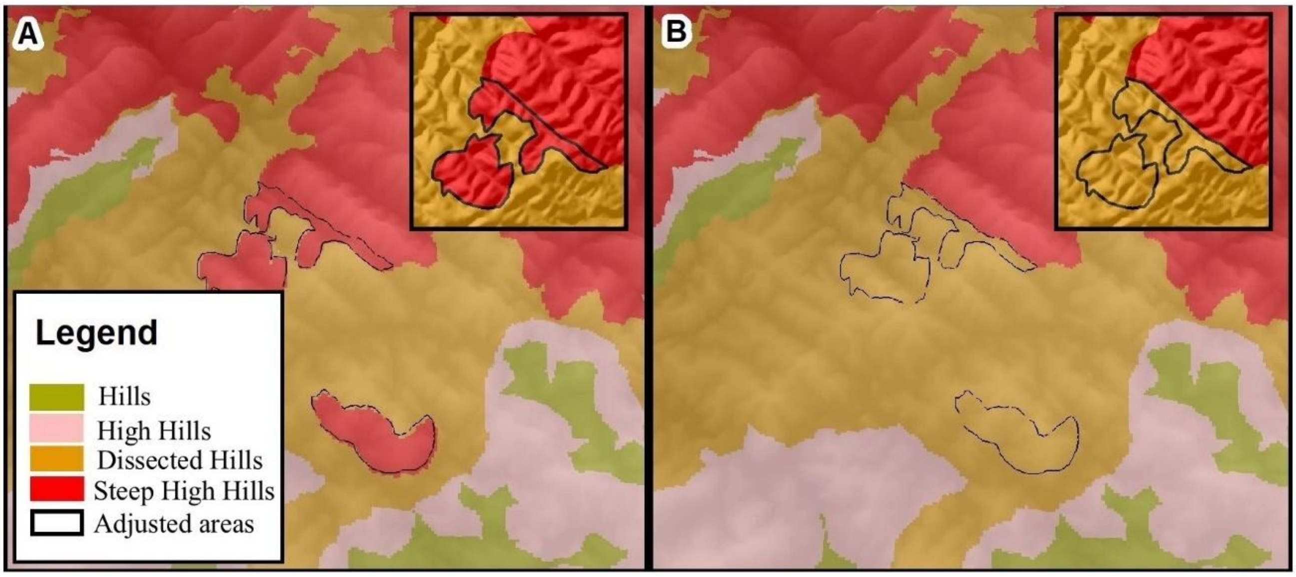

Figure 4. A: example of the area before adjustment; B: example of the area after adjustment.

Stage 6 - Checking the mapping: This was done by calculating the overall accuracy obtained through a confusion matrix, comparing the result of the classification of landform patterns before and after the adjustments made in Stage 5.

Quantitative evaluation was carried out using the accuracy of the corrected mapping. The calculations took into account: i) global accuracy, which measures the areas in agreement between the mapped classes (equation 4); ii) inclusion errors, which are the areas overestimated by the mapping; iii) omission errors, which refer to the areas underestimated by the mapping.

Stage 7 - landform pattern map: corresponds to the preparation of the cartographic product appropriate to the 1:100,000 scale and the construction of the representative geomorphological legend, where each landform pattern was represented by polygons, differentiated by color and intensity.

4. Results

Sixteen classes of landform patterns were identified: 1) Flat Low Hills (COS); 2) Low Hills (COL); 3) Steep Low Hills (CON); 4) Terrain dissected between hills (FDC); 5) Hills (MRT); 6) High Hills (MOR); 7) Dissected Hills (MOD); 8) Steep High Hills (MOE); 9) Elongated Structural Hills (MAE); 10) Low Mountains (SMB); 11) High Mountains (SMA); 12) Plateau Edges (SBP); 13) Dissected Plateaus and Canyons (PEC); 14) Fluviomarine Plain (PFM); 15) Fluvial Plain (PFV) and 16) Colluvial Ramps (RCV). The combination of these 16 classes with the 50 pre-existing geomorphological units of the third taxon proposed by Santos *et al*. (2006) resulted in the individualization of 226 distinct units of landform patterns in Paraná, which make up a new geomorphological map of the state (Figure 5).

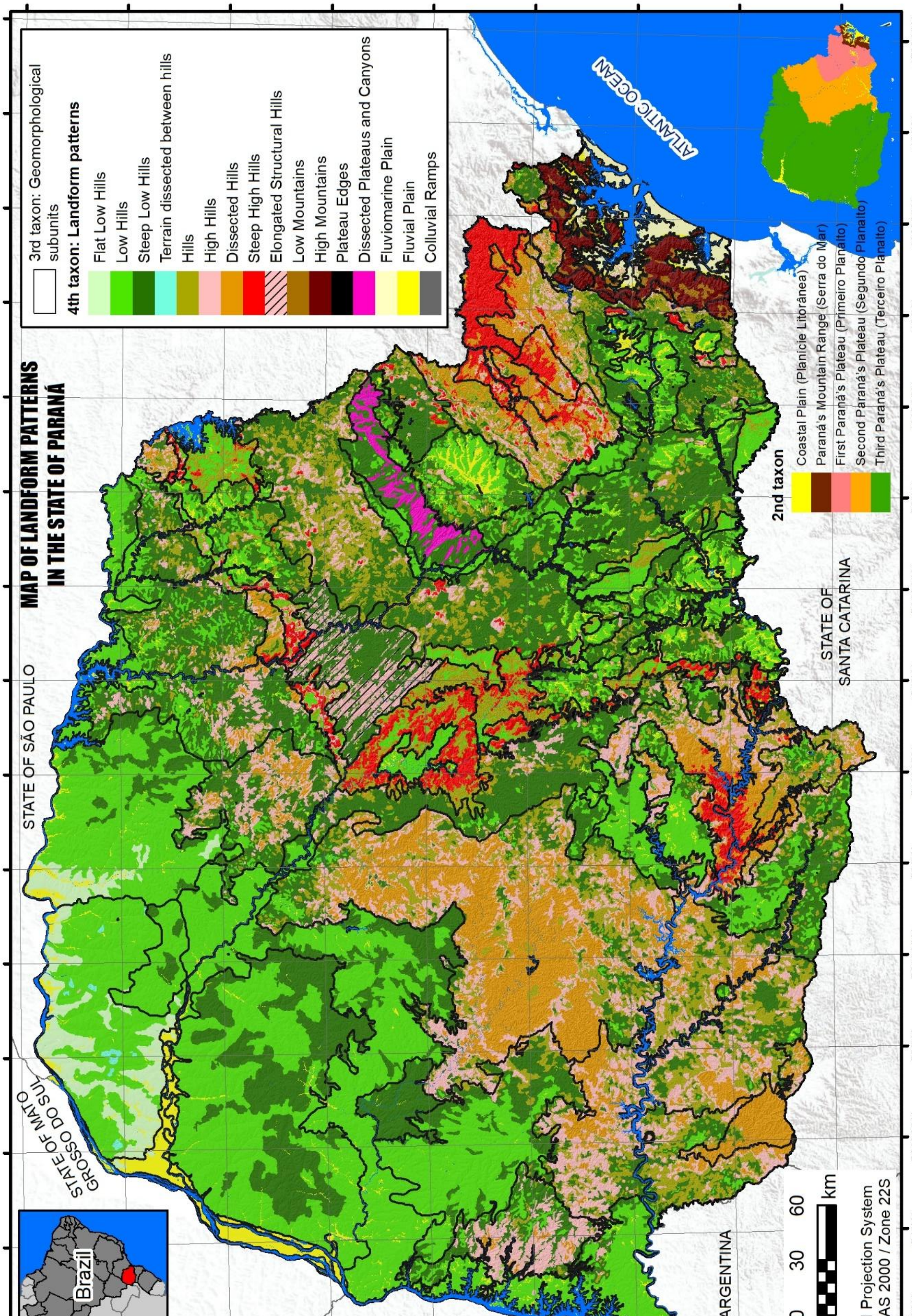

Figure 5. Geomorphological map of Paraná with landform patterns

The distribution of landform patterns in Paraná's geomorphological units is shown in Figure 6. Figure 6A represents the Plains units, Figure 6B the Paraná's Mountain Range (Serra do Mar) units, Figure 6C the First Plateau units, Figure 6D the Second Plateau and Figure 6E the Third Plateau.

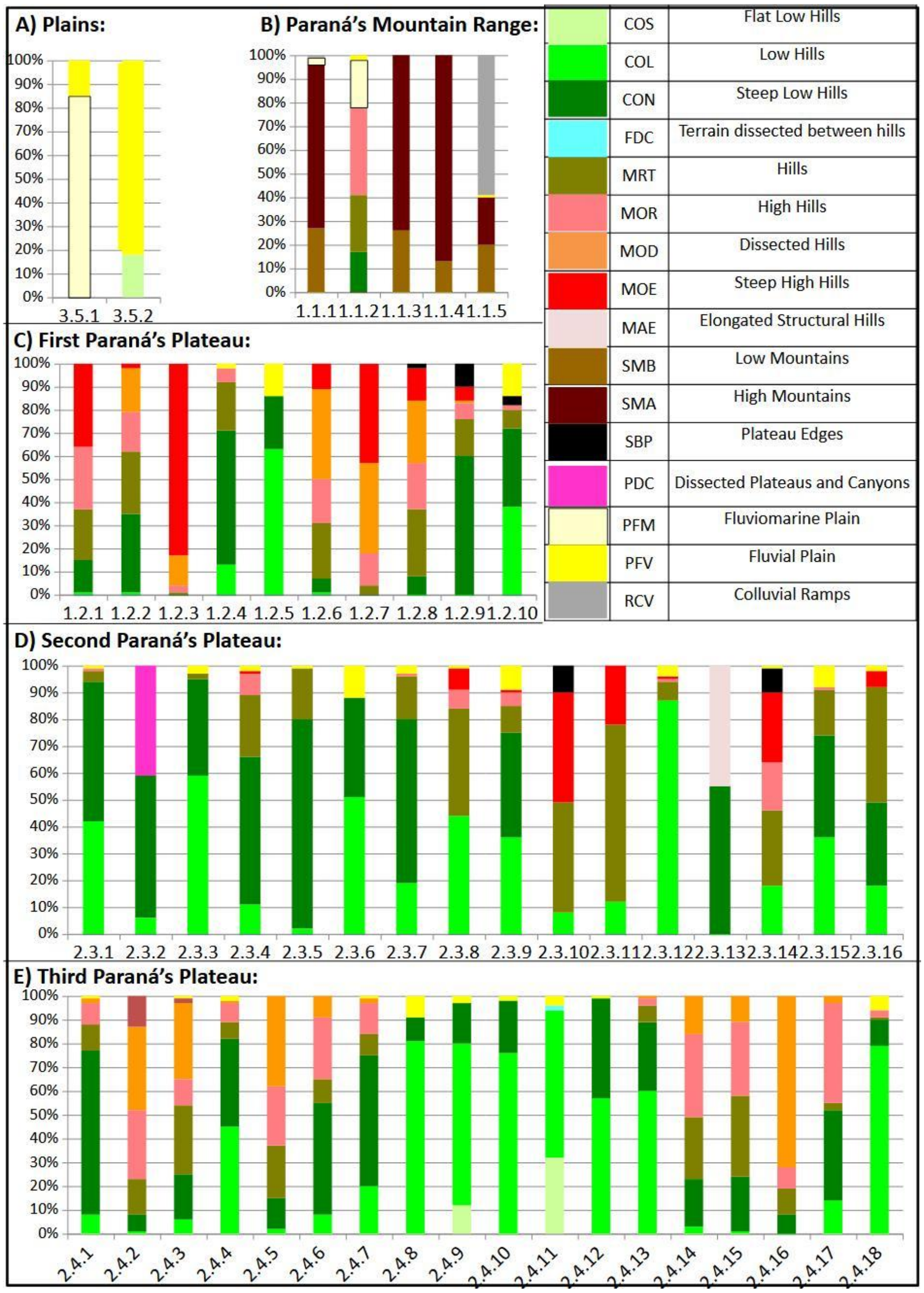

Figure 6. Graphs showing the proportional distribution of landform patterns in Paraná's geomorphological units.

Regarding the confusion matrix, the results showed that the overall accuracy of the mapping (Chart 6) was 89.71%, with a slight predominance of overestimated areas (5.76%) compared to underestimated areas (4.53%), with reference to the modeling carried out without manual adjustments and corrections. The most underestimated landform patterns were High Hills (16.9%), Hills (16%), Low Mountains (14.5%) and Plateau Edges, which were 100% included after manual adjustments, since it was not possible to use the moving windows technique in the semi-automatic delimitation, as the criteria coincide with those used for High Hills, while the most overestimated patterns were Elongated Structural Hills (50.2%) and Fluvial Plains (40%). The highest accuracy values were recorded for High Mountains (94.7%) and Low Hills (88.3%).

Chart 6. Results of the confusion matrix by landform pattern.

Landform pattern (Map WITH manual corrections and adjustments)	Map WITHOUT manual corrections and adjustments (area in km²)																
	PFM	PFV	COS	COL	CON	MRT	MOR	MOD	MOE	MAE	SMB	SMA	SBP	RCV	PEC	FDC	Under.
PFM	1754,5 **80,4%**	5,1	0	0	35,7	40,5	27,0	0	0	0	9,3	0,7	0	2,7	0	0	**14,0%**
PFV	293,9	5182,5 **54.8%**	382,7	2675,8	304,6	39,6	66,0	7,7	1,0	0	5,8	1,0	0	1,3	0	0	**5,2%**
COS	0	65,5	3138,0 **82,8%**	4,6	0	0,0	0,0	0	0	0	0	0	0	0	0	0	**15,4%**
COL	0	358,6	199,1	52079,6 **88,3%**	1611,6	185,7	66,5	0,2	14,8	0	0	0	0	0	0	15,4	**7,5%**
CON	1,7	22,8	0	973,4	50915,3 **86,9%**	1815,3	460,2	35,4	81,3	41,7	0	0	0	0	82,5	0	**7,1%**
MRT	0,6	10,8	0	767,5	1816,3	21289,2 **71,2%**	988,2	36,0	188,3	1,9	0,1	0	0	0	1,5	0	**16,0%**
MOR	4,1	10,9	0	11,9	179,8	1510,9	17697,8 **76,5%**	630,4	56,4	0,4	0,7	0,3	0	0,2	0,4	0	**13,1%**
MOD	0	4,7	0	2,0	11,7	153,9	963,9	15993,1 **86,9%**	288,4	0	0	0	0	0	0	0	**5,3%**
MOE	0	4,4	0	4,5	8,5	382,9	344,5	260,2	6152,2 **71,5%**	0,4	0	0	0	0	0	0	**16,9%**
MAE	0	0,4	0	0	0	599,3	2,8	0	238,7	790 **47,1%**	0	0	0	0	0	0	**2,7%**
SMB	3,1	0,5	0	0	0	0,2	0,8	0	0	0	698,5 **83,9%**	3,9	0	4,7	0	0	**14,5%**
SMA	1,1	0,7	0	0	0	0,1	0,8	0,1	1,3	0	99,1	2057,3 **94,7%**	0	3,1	0	0	**0,4%**
SBP	0	2,3	0	1,3	0,7	54,6	100,0	8,9	581,0	0	0	0	0 **0,0%**	0	1,1	0	**100,0%**
RCV	1,9	0,1	0	0	0	0,1	0,3	0	0,0	0	5,7	2,1	0	92,7 **80,8%**	0	0	**10,4%**
PEC	0	0,3	0	1,3	189,4	0,7	1,6	0,2	0,3	0	0	0	0	0	786,0 **73,8%**	0	**8,0%**
FDC	0	0	0	0,7	0	0	0	0	0	0	0	0	0	0	0	128,7 **88,8%**	**10,7%**
Over.	**5,5%**	**40,0%**	**1,9%**	**4,2%**	**6,0%**	**12,8%**	**10,4%**	**7,7%**	**11,7%**	**50,2%**	**1,65**	**4,9%**	**0%**	**8,8%**	**18,2%**	**0,5%**	**TOTAL Under. 4,53% TOTAL Over. 5,76%**
Accuracy	**80,4%**	**54,8%**	**82,8%**	**88,3%**	**86,9%**	**71,2%**	**76,5%**	**86,9%**	**71,5%**	**47,1%**	**83,9%**	**94,7%**	**0,0%**	**80,8%**	**73,8%**	**88,8%**	**89,7%**

Legend: Under: underestimation; Over. : overestimation; COS: Flat Low Hills; COL: Low Hills; CON: Steep Low Hills; FDC: Terrain dissected between hills; MRT: Hills; MOR: High Hills; MOD: Dissected Hills; MOE: Steep High Hills; MAE: Elongated Structural Hills; SMB: Low Mountains; SMA: High Mountains; SBP: Plateau Edges; PEC: Dissected Plateaus and Canyons; PFM: Fluviomarine Plain; PFV: Fluvial Plain and RCV: Colluvial Ramps.

5. Discussion

The landform patterns mapped represent an advance in geomorphological mapping in Paraná, the results of which have the potential to support derived socio-environmental analyses and establish morphometric criteria for detailing subsequent geomorphological maps. According to Botelho *et al.* (2024), the different morphologies of Paraná, which have a complex genesis associated with lithostructural and climatic factors, interfere in the formation and distribution of soils and can condition or limit land use and occupation, especially in the current agricultural model, morphodynamic processes and urban environmental problems.

4.1. Low Hills and Terrain dissected between hills (colinas)

The term hill (*colina*, in Brazil) is widely used in geomorphology. Some designations found in the literature conceptualize it as a "term used in the description of the physical landscape, by geomorphologists, to indicate small elevations of land with gentle slopes, some of which may have an accumulation genesis, as is the case with moraines and dunes, however the vast majority are forms of erosion" (GUERRA; GUERRA, 2008, p. 146). 146), or that a hill "is an elevation of land that has gentle slopes, with a gradient of less than 15% and an altitude of less than 100m" (IBGE, 2004, p. 78). A hill is also treated as a landform pattern whose parameters for detection are: predominant amplitude between 40m and 70m with a slope of less than 20% (IPT; CPRM, 2014, p. 12).

In this study, hills are a set of landform patterns. It was adopted in order to identify morphological patterns, whose distinction has morphometric characteristics established in intervals of altimetric amplitude and average slope. Thus, their detection in the proposed method had no genetic and/or processual relationship, although in the landforms of the state of Paraná their presence is associated with denudational morphogenesis.

Four different classes of hill were identified: i) Flat Low Hills (COS), whose slopes are more extensive, with low declivity and small altimetric amplitude; ii) Low Hills (strictu sensu) (COL), with declivity varying from low to moderate and with small altimetric amplitude; iii) Steep Low Hills (CON), with a higher slope and greater altimetric amplitude than the other hill classes; and a fourth class, iv) Terrain dissected between hills (FDC), which are associated with paleovolcano features, so called by Goulart and Santos (2014) and Marcolin *et al*. (2023), which are imbricated between flat low hills, the pattern of which was detectable exclusively in the landscape of the northwestern region of Paraná, over the Caiuá Group, in geomorphological unit 2.4.11-Planalto de Paranavaí (SANTOS *et al*., 2006), which represents 0.1% of the state of Paraná (Table 1).

Table 1. Total area of landform patterns in the state of Paraná.

Landform patterns	Total area in Paraná's geomorphological compartments					Total area in Paraná km²
	Coastal Plain km²	Paraná's Mountain Range (Serra do Mar) km²	First Paraná's Plateau km²	Second Paraná's Plateau km²	Third Paraná's Plateau km²	
Flat Low Hills	-------	-------	-------	-------	3314 **(3%)**	3314 **(1,7%)**
Low Hills	-------	-------	2276 **(12%)**	7459 **(17%)**	41781 **(35%)**	51516 **(25,9%)**
Steep Low Hills	-------	77**(2%)**	4800**(26%)**	17974 **(42%)**	29561 **(25%)**	52411 **(26,3%)**
Terrain dissected between hills	-------	-------	-------	-------	149 **(0%)**	149 **(0,1%)**
Hills	-------	108 **(3%)**	3109**(17%)**	8878 **(20%)**	12142 **(10%)**	24237 **(12,2%)**
High Hills	-------	167 **(5%)**	1886**(10%)**	1839 **(4%)**	16093 **(13%)**	19986 **(10,0%)**
Dissected Hills	-------	-------	2547**(14%)**	0 **(0%)**	14732 **(12%)**	17279 **(8,7%)**
Steep High Hills	-------	-------	3055**(16%)**	2851 **(7%)**	962 **(1%)**	6868 **(3,5%)**
Elongated Structural Hills	-------	-------	-------	1633 **(4%)**	-------	1633 **(0,8%)**
Low Mountains	-------	706 **(21%)**	-------	-------	-------	706 **(0,4%)**
High Mountains	-------	2179 **(63%)**	-------	-------	-------	2179 **(1,1%)**
Plateau Edges	-------	-------	307**(2%)**	587 **(1%)**	-------	894 **(0,4%)**
Dissected Plateaus and Canyons	-------	-------	-------	977 **(2%)**	-------	977 **(0,5%)**
Fluviomarine Plain	1668 **(22%)**	99**(3%)**	-------	-------	-------	1767 **(0,9%)**
Fluvial Plain	5897 **(78%)**	11**(0%)**	602**(3%)**	1108 **(3%)**	1520 **(1%)**	9138 **(4,6%)**
Colluvial Ramps	-------	93**(3%)**	-------	-------	-------	93 **(0,0%)**

Flat Low Hills and Low Hillsare the most common landform patterns found in the territory of Paraná, accounting for more than half of the state's area, occupying 25.9% and 26.3% respectively (Table 1). Flat Low Hills occur to a limited extent only in the Third Plateau compartment, present exclusively in units 2.4.9 - Maringá Plateau and 2.4.11 - Paranavaí Plateau (SANTOS *et al*., 2006), in the northern and northwestern regions of Paraná (Figure 6D), representing 1.7% of the state's area (Table 1).

It should be noted, however, that although Low Hills and/or Steep Low Hills occur widely in the state, when viewed as a group, each landform pattern distributed over the different geomorphological units differs from the other, depending on the unit in which it is inserted, which gives it individual morphogenetic and morphodynamic characteristics. For example, hills in the northwestern region of Paraná and those around the capital, Curitiba. Although both are represented as a pattern of hills, those located in the northwest are susceptible to gullying processes, due to the type of material and soil, which participate in their evolutionary and dynamic process, while those located in Curitiba are not predisposed to the development of the same processes and have different genesis, as well as being inserted in different geomorphological compartments.

Therefore, the classes of: i) Flat Low Hills (COS), ii) Low Hills (COL), iii) Steep Low Hills (CON) and iv) Terrain dissected between hills (FDC) comprise 54% of Paraná's territory, the first and last being restricted to the Third Plateau, with an area of 3. 314km² and 149km², respectively (Table 1); the second predominates on the Third Plateau (Table 1) with a total area of 41,781km² and the third class on the First and Second Plateaus (Table 1), with a total area of 4,800km² and 17,974km², respectively, as well as a significant area on the Third Plateau totaling 29,561km².

4.2. Hills and High Hills (morros)

The term hill (*morro*, in Brazil) is often used in morphographic terms. It aims to express the geometry of landform in a qualitative way, such as the definition that it is a low hill with an altitude of approximately 100 to 200m (GUERRA; GUERRA, 2008, p. 440), or Florenzano's (2008) definition that they are medium elevations of the land, with rounded tops, amplitudes between 100 and 200m and high slopes. Morphometric intervals are often used to distinguish them, such as IBGE (2004), which uses a slope class of more than 15% and an altimetric amplitude of between 100 and 300m.

It is also common to subcategorize hills, as in IPT and CPRM (2014), which distinguishes them into low hills with a predominant slope of 30% and an altimetric range of between 90 and 110m and high hills with a slope of more than 30% and an altimetric range of between 140 and 200m. Another separation is presented in IPT (1981), whose classes are hills and hills with smoothed slopes, both with an altimetric range between 100 and 300m and the former with a slope of more than 30% and the latter with lower values.

In Paraná, four different classes of hills (*morros*) were classified, representing 23% of the state's territory (Table 1): a) Hills (MOR), which represent 10% and are characterized by great altimetric amplitude and moderate slope, b) Dissected Hills (MOD), with 8.7%, and which are characterized by great altimetric amplitude and high slope, c) Steep High Hills (MOE), with 3.5%, characterized by a greater altimetric range than the other hill classes and d) Elongated Structural Hills (MAE), with 0.8%, which have the same morphometric characteristics as the hills, but are characterized by elongated crests controlled by linear geological structures in a NW-SE direction located on the central axis of the Ponta Grossa Arch.

The regions made up of highly dissected and complex landforms were the ones that required the segregation of hills into classes that separated them into dissected and elevated. A similar distinction between hills was made by Bortolini and Silveira (2021), when they used a multiresolution segmentation method and identified different classes of landform patterns of hills, elevated hills and sloping hills, the latter equivalent to what is referred to here as Dissected Hills (MOD).

High Hills were identified on all of Paraná's plateaus, mostly on the First Plateau with an area of 3,055km², on the Second Plateau with an area of 2,851km² and on the Third Plateau with 962km². The Dissected Hills occurred on the First Plateau with an area of 2,547km² and most prominently on the Third Plateau with an area of 14,732km². The Steep High Hills pattern was the most widespread, classified in the plateaus and the Serra do Mar, with the greatest representation in the Third Plateau with 16,093km², in the First and Second Plateaus with equivalent areas, 1,886km² and 1,839km², and the least in the Serra do Mar with 167km² (Table 1).

On the other hand, the Elongated Structural Hills, restricted to the Second Plateau (Figure 14-C), with an area of 1,633km², form the positive lineaments along the structures of the Ponta Grossa Arch dyke swarm, in areas where the underlying rocks have less denudational resistance than the dyke rock. These dykes, predominantly basaltic, constitute a remarkable geological feature with structural alignments in a preferential direction between

N50W and N60W, whose length can vary from a few meters to tens of kilometers, and are intruded into the Paleozoic rocks of the Paraná basin, as well as rocks belonging to its crystalline basement (RENNE *et al.*, 1996).

The hills (MRT) class (*morrotes* in Brazil) was identified as a set of landform patterns with morphometric values intermediate between High Hills and Low Hills. From a morphological point of view, it is the transition between High Hills and Low Hills, differing from the latter in that it expresses intermediate values of slope and altimetric amplitude. According to IBGE (2004, p. 221) and IPT (1981), hills (*morrotes*) have a slope of more than 15% and altitudes of more than 100m; for Florenzano (2008) they have a predominant slope of 20% and an altimetric amplitude of 60 to 90m and for IPT and CPRM (2014) they have a high slope with low altimetric range values, varying between 20 and 60m.

In this study, despite the fact that the values used to determine them were close to those established in the literature, with variations depending on the geomorphological subunits, it was found that the majority of them are found in a consortium and neighboring situation with the hill classes, often in a transitional way with the Steep Low Hills. As with the Low Hills and High Hills, the Hills (*morrotes*) also differed according to the geomorphological unit to which they belonged. For example, in parts of the First Plateau, the hills have elongated crests supported by dykes of diabase, quartzite or phyllite, which are more resistant than the surrounding rocks, which are predominantly carbonate (ROSA FILHO; GUARDA, 2008). Meanwhile, in other portions where they developed over the Gneissic-Migmatitic Complex, the hills have rounded tops and dissecated valleys.

Thus, the Hill class was identified mostly in the plateaus, and to a lesser extent in the mountainous region. This class is most representative in the Second Plateau, where it covers approximately 20.5% (8,878km2) of its area. In the First Plateau and Third Plateau it covers 16.7% (3,109km2) and 10.1% (12,142km2) of their areas, respectively, while in the Paraná's Mountain Range (Serra do Mar) it only covers 3.1% (108km2) of its area (Table 1).

4.3 Mountains and Plateau Edges

According to Guerra and Guerra (2008), *serra* is a term used to describe the physical landscape of rugged terrain with steep slopes. It is therefore used to describe landforms, disregarding their origin and evolution. Thus, for these authors, the concept of *ierra* is very general.

In part, this perspective is true, since in Brazil *serras* are widely used to designate geomorphological units with high declivity and altimetric amplitude, which often appear in the designation of regional toponyms. An example of this is the Serra do Mar, a term used with remarkable consensus to designate the escarpments of fault blocks that surround the eastern border between the plateau and the coast in the south and southeast of the country.

In the state of Paraná, the name of the *Serra do Mar Paranaense* (Paraná's Mountain Range) geomorphological unit is historical and has already been used in established literature, such as in Maack (1968), who highlighted it as one of the state's five physiographic units, corroborated by Bigarella (1978) and, more recently, adopted by Santos *et al.* (2006) in the designation of one of Paraná's five geomorphological units.

For Maack (1968) and Bigarella (1978), the *Serra do Mar* (Paraná's Mountain Range) is not just a step between the coast and the First Plateau, but a typical marginal mountain range that rises between 500 and 1,000m above the average level of the plateau that surrounds it to the west. Similarly, its morphology is not exclusively a plateau edge mountain range, as it has sectors originating from regressive differential erosion, where the highest elevations, with high summits, are supported by the Coastal Granitoid Belt of the State of Paraná (ALMEIDA; CARNEIRO, 1998), also influenced by systems of faults, fractures and dykes which, together, control the drainage network and the scarp of the mountain front of the Serra (SANTOS *et al.*, 2006).

Therefore, in classifying the patterns of landforms, the terminology of mountain was used exclusively for the landform units that comprise the prominent feature on the eastern edge, between the First Paraná's Plateau and the Coastal Plain, whose landform has already been treated as a typical marginal mountain range in Maack (1968) and Bigarella (1978), as it has a high gradient on both sides, east and west. The mountains were distinguished into two different shape patterns: Low Mountains (SMB) and High Mountains (SMA), the first class with an area of 706km² and the second with 2,179km² (Table 1).

The addition of the term mountain, complementing the designation serra, used in this work exclusively for the landscape of the Serra do Mar, was intended to assume this geomorphological compartment as a set of mountains in accordance with the current interpretation of the Brazilian Landform Classification System (COMITÊ EXECUTIVO NACIONAL - CEN/SBCR, 2022) and Botelho *et al.* (2023), which express the Serra do Mar as a landscape of mountains.

These mountains, from the point of view of genesis, differ from mountains in modern fold structures, along the lines of typical orogenic chains of young terrain (GUERRA; GUERRA, 2008), such as the obvious great mountain ranges that exist on the planet, such as the Andes, the Himalayas and the Alps, among other cases. The Serra do Mar was categorized by Ab'Saber (1985; 2006) as failed block mountains, when dealing with the origins of the geomorphological complexity of southeastern Brazil. According to Guerra and Guerra (2008), the old worn-out mountains of Atlantic Brazil contrast in South America with the young mountains of the Andean chain.

The term *serra* has been used here to designate the mountains landform patterns, because it is understood that a mountain can be designated as a *serra*, but it should be noted that not every *serra* is a mountain. In this sense, another set of *serras* has been treated here as Plateau Edges.

The landforms on the Plateau Edges found in Paraná often has the toponyms of *serras*. It is accepted in the literature that a *serra* is the name given to the plateau edges (GUERRA; GUERRA, 2008, p. 570), as is the case with *Serra do Purunã*, at the transition from the First to the Second Plateau, and *Serra da Esperança*, which represents the transition from the Second to the Third Plateau. We therefore opted to use the term "Plateau Edges" instead.

This pattern forms the erosion front of the two *cuestas* present in Paraná (AB'SABER, 1949): the front of the Devonian *cuesta*, whose genesis is associated with the process of post-Cretaceous circumnudation, which forms a line of *cuestas* of relative morphological expression in Paraná, regionally called the Devonian Escarpment, with association to the age of its geological framework, or even as the Purunã Escarpment or Serrinha (AB'SABER, 1964); and another, located at the transition from the Second to the Third Plateau of Paraná, whose boundary is marked by the topographic prominence of the so-called Triassic-Jurassic Escarpment, with the names of Mezosoic Escarpment, Sandstone-Basalt Escarpment, Serra Geral Escarpment or, as it is commonly called in Paraná, Serra da Esperança Escarpment, or Boa Esperança Escarpment. According to Ab'Saber (1949), the Serra Geral escarpment constitutes, over almost its entire length, a system of circumnudation escarpments, one of the most typical and gigantic on record.

4.4 Dissected Plateaus and Canyons

Structural plateaus are defined by the IBGE Geological-Geomorphological Dictionary as "a flat surface that interrupts the continuity of the slope of a slope", and are generated by the resumption of erosion due to the presence of geological structures (GUERRA, 1993, p. 314). Adapted to the general slope of the sedimentary layers, this landforms in the state of Paraná was modeled as a response to Tertiary-age epirogenesis (currently equivalent to the Paleogene period), where drainage was superimposed, presenting itself as cataclinal (consequent), thus running westwards and opening up deep epigenetic bokeh or superimposed valleys on the *cuesta* (COSTA *et al.*, 2005). The rivers penetrate this geomorphological unit following structural alignments and grooves that exist in the reverse area of the *cuesta*, resulting in deep and narrow canyons (COSTA *et al.*, 2005). This is the case of the valleys of the Iapó (Guartelá Canyon), Jaguariaíva (Codó Valley Canyon) and Itararé rivers, which have their sources in the First Paraná's Plateau and break through the *cuesta*, thus draining towards the interior of the continent (MELO *et al.*, 2007). Between the Iapó and Jaguariaíva rivers there is a very large sequence of these structural valleys (COSTA *et al.*, 2005).

An important uplift megastructure that marks this geomorphological context is the Ponta Grossa Arch. During the Lower Cretaceous there was intense volcanism that filled a large part of the Paraná Basin and then the swarms of dykes exposed at the edges of the sedimentary basin were established, including the swarm associated with the Ponta Grossa Arch (RAPOSO, 1995). According to Ferreira (1982), the northern limit of the Ponta Grossa Arch, marked by the Guapiara Alignment, is 600 km long and varies in width from 20 to 100 km. The southern limit of the Arch is characterized by the Piquiri River Alignment, which is oriented N60-65W, 115 km long and has a maximum width of 20 km. The central region is defined by the São Jerônimo-Curiúva and Rio Alonzo Alignments and is characterized by intense fracturing and small faults.

The establishment of the arc, by means of tectonic inversion mechanisms (FERREIRA, 1982), was responsible for developing a series of faults and fractures on the metasedimentary cover rocks from the reactivation of old lines of weakness in the basement (FASSBINDER, 1990). With the intense volcanic event that occurred in the Lower

Cretaceous and which was responsible for filling a significant part of the Paraná Basin, a swarm of large, NW-directed mafic dykes were established which are associated with the Ponta Grossa Arc (RAPOSO, 1995). Melo *et al*. (2007) state that the Ponta Grossa Arc is responsible for the growing shape that the geological units and escarpments that delimit the plateaus have taken over the course of their evolution, in addition to the fact that their rupile structures, such as faults and fractures, are characterized as important factors controlling the drainage of the area.

4.5 Plains and Colluvial Ramps

The plains, defined as a set of flat or undulating forms in which the processes of sedimentation are greater than those of erosion (IBGE, 2009), have been subdivided into two categories in this mapping: Fluviomarine Plain and Fluvial Plain. In the coastal context, the formation of the Fluviomarine Plain is associated with Quaternary transgressive/regressive cycles in the last two glacial periods (ANGULO, 2004) and with the drainage system linked to the Paranaguá and Guaratuba estuarine complex, which receive eroded material from the Serra do Mar mountains. This landform pattern includes terraces, river channels susceptible to flooding, mangroves, sandy ridges and small dunes.

The Fluvial Plain, in turn, diverge from the conceptualization that classifies them as "generally positioned at low altitude" (IBGE, 2009, p. 30) in the state of Paraná. The First and Second Plateaus contain plains that exceed 1000 m in altitude. The plains of the Iguaçu (especially in the middle and upper third), Tibagi, Ivaí and Paraná rivers and the smaller fluvial plains that show the aggradational processes in the interplanaltic context stand out.

The genesis of the river plains is directly related to the geomorphological units in Paraná, since the accumulation processes originate in the denudation of features that support the highest elevations in the region. Examples are the granite massifs of the Paraná's Mountain Range (Serra do Mar), which condition the fluvial plains at the foot of the mountains (to the east) and the Curitiba Sedimentary Basin (to the west) with the river plain of the Alto Iguaçu; the sedimentary escarpment and the Ponta Grossa Arch on the Second Plateau, with the formation of the Tibagi River plain; the residual plateaus of the Serra Geral Formation, the deepening of the base level of the Paraná River and the differential erosion of volcanic phases (effusions, volcanoclasts and pyroclasts) on the Third Plateau, which exemplify the origin of the Ivaí River plain.

With regard to Colluvial Ramps, proposed by Bigarella and Mousinho (1965), the importance of this landform pattern in understanding local morphodynamics should be emphasized. They are defined as "gently sloping valley bottom forms, associated with the coalescence of colluvial deposits coming from the slopes that interdigitate and/or cover the alluvial deposits. It occurs in low slope sectors, in concave segments that characterize the hollows or depressions of the terrain in the amphitheatres" (IBGE, 2009, p. 36). The colluvial ridge complexes, highlighted in this mapping around the Paraná's Mountain Range (Serra do Mar), are formed by reworking due to the recurrence of erosive and depositional processes during the Quaternary (GUERRA; GUERRA, 2008).

The presence of colluvial deposits is favored by the break in slope and the transport of weathered material upstream by gravitational processes. This is a current characteristic, since mass movements control morphodynamics in this mountainous environment, and at the same time it is a feature that highlights the morphogenesis of the eastern region of Paraná. Many of the flood plains in the transition between the Paraná's Mountain Range (Serra do Mar) and the Coastal Plain are associated with debris cone systems. On the geomorphological map of Sheet SG.22 Curitiba (COSTA *et al*., 2005) of the RADAMBRASIL Project (BARBOSA *et al*., 1984), for example, all the plains confined to the great valleys of the Serra do Mar were mapped as "Alluvial-Colluvial Plains", in the "Colluvial Ramps" category, characterizing them as an accumulation model, in flat or embayed areas, resulting from the convergence of colluvial fans, dejection cones or the concentration of flood deposits.

6. Conclusion

The method proved to be feasible and compatible with the proposed requirements, making use of current technological resources to obtain a geomorphological mapping product on an intermediate scale. It had some limitations, requiring adjustments through visual interpretation. Field work is essential for its implementation.

The sixteen classes that made up the landform patterns in Paraná were established with the support of the literature and proved to be compatible with the scale and configure units suitable for adoption in the fourth geomorphological taxon.

Application of the method led to the creation of a new geomorphological map of the state of Paraná at a scale of 1:100,000, proposed here as an advance in scale and taxon, with the distinction of 226 units of landform patterns. The main limitations of the method were the border effect on geomorphometric attributes with regional calculation and the need for operators to be clear about the landform distribution model of the area in order to determine the parameters and verify the classifications obtained.

The method, the hierarchical designation and the composition of the classes aim to offer their contribution to the advancement of geomorphological cartography in Brazil, especially at the current time of debate and formulation of the Brazilian Landform Classification System. This is an open methodological proposal, whose inclusion of additional geomorphometric variables or other parameterization methods can detail the classes in the composition of the geomorphological map obtained.

Authors' Contributions: Conception, C. T. S., R. M. P. S. and W. B.; methodology, C. T. S., R. M. P. S., W. B. and V. A. P.; software, C. T. S., R. M. P. S., W. B and V. A. P.; validation, C. T. S., R. M. P. S., W. B. and V. A. P.; research, C. T. S., R. M. P. S., W. B. and V. A. P.; resources, C. T. S.; data preparation, C. T. S., R. M. P. S., W. B. and V. A. P.; article writing, C. T. S., R. M. P. S., W. B.; revision, C. T. S., R. M. P. S., W. B. and V. A. P.; acquisition of funding, C. T. S. All authors have read and agreed with the published version of the manuscript.

Data linking: The vector files of the geomorphological map for this study are available at https://doi.org/10.5281/zenodo.14884572.

Funding: Research funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq (434343/2018-8 and 305670/2020-4).

Acknowledgements: To the Instituto Água e Terra (IAT-PR), at the time ITCG/Mineropar, for the internship grants granted during the development of the project.

Conflict of Interest: The authors declare no conflict of interest.

References

1. AB'SABER, A.N. **O relevo brasileiro e seus problemas**. *In*: *Brasil - a terra e o homem*, Org.: Aroldo de Azevedo. São Paulo: Companhia Editora Nacional. 1964.
2. AB'SABER, A.N. Regiões de circundesnudação pós-cretácea, no Planalto Brasileiro. **Boletim Paulista de Geografia, São Paulo**, v. 1, p.1-21, 1949.
3. AB'SABER, A. N. O Ribeira de Iguape: uma setorização endereçada ao planejamento regional. **Boletim Técnico Sudelpa**, São Paulo, n. 1, p. 1-35, 1985.
4. AB'SABER, A. N. Montanhas de blocos falhados. **Scientific American Brasil**, n. 47, p. 98, 2006. Tradução. Disponível em: <biblio.fflch.usp.br/AbSaber_AN_1667445_MontanhasDeBlocosFalhados.pdf>.
5. AILI, L. DEM-based Analysis of Local Relief. In: Zhou, Q., Lees, B., Tang, Ga. (eds) Advances in Digital Terrain Analysis. Lecture Notes in Geoinformation and Cartography. Springer, Berlin, Heidelberg. 2008. https://doi.org/10.1007/978-3-540-77800-4_10
6. ALMEIDA, F.F.M.; CARNEIRO, C.D.R. Origem e evolução da Serra do Mar. **Revista Brasileira de Geociências**, n.28, v.2, p.135-150, 1998.
7. ANGULO, R. J. Mapa do Cenozoico do litoral do Estado do Paraná. **Boletim Paranaense de geociências**, v. 55, p. 25-42, 2004.
8. BARBOSA, G. V.; SILVA, T. C.; NATALI FILHO, T.; DEL'ARCO, D. M.; COSTA, R. C. R. Evolução da metodologia para mapeamento geomorfológico do Projeto Radambrasil. **Boletim Técnico, Série Geomorfologia**. Salvador n. 1, 187 p., 1984.
9. BESSER, M.L; BRUMATTI, M; SPISILA, A.L. Mapa Geológico e de Recusos Naturais do Estado do Paraná. Programa Geologia, Mineração e Transformação Mineral, Curitiba: SGB-CPRM, 2021, 1 mapa colorido, 235 x 90 cm. Escala 1:600.000, disponível em: https://rigeo.cprm.gov.br/jspui/handle/doc/22492
10. BIGARELLA, J. J.; MOUSINHO, M. R. Considerações a respeito dos terraços fluviais, rampas de colúvio e várzeas. **Boletim Paranaense de Geografia**, Curitiba-PR, 16/71:153-198, 1965.
11. BIGARELLA, J. J; BECKER, R.D; MATOS, D.J.; WERNER, A. **A Serra do Mar e a porção oriental do Estado do Paraná: Um problema de segurança ambiental e nacional**. Secretaria do Estado do Planejamento do Paraná: Curitiba. 1978.
12. BORTOLINI, W.; SILVEIRA, C. T.; SILVEIRA, R. M. P.; SILVA, J. M. F. Técnicas geomorfométricas para o mapeamento de padrões de relevo: aplicação nas cartas Curitiba e Cerro Azul, estado do Paraná. **Revista do Departamento de Geografia da USP,** v. 36,p. 15-32, 2018. DOI: 10.11606/rdg.v36i0.144285

13. BORTOLINI, W; SILVEIRA, C. T. Emprego de segmentação multiresolucional no mapeamento digital de formas de relevo. **Revista Brasileira de Geomorfologia**, v. 24, 2021. DOI: 10.20502/rbg.v22i4.1987
14. BORTOLINI, W; SILVEIRA, C. T.; SILVEIRA, R. M. P. Emprego de técnicas geomorfométricas na identificação de padrões de relevo. **Revista Ra'e Ga**, v. 41, p. 131-150, 2017. DOI: 10.5380/raega.v41i0.51724
15. BOTELHO, R.G.M.; DANTAS, M.E.; SILVEIRA, C.T. Excursões técnicas : pelas montanhas do Rio de Janeiro. Rio de Janeiro : IBGE, 2023. 58p.
16. BOTELHO, R. M. G.; SILVEIRA, C. T.; SILVEIRA, R. M. P. **Excursões técnicas: guia de campo da I Reunião de Classificação do Relevo Planaltos do Estado do Paraná**. IBGE, Coordenação de Meio Ambiente. Rio de Janeiro: IBGE, 2024.
17. COSTA, R. C.; BUSS, M. D.; ROSA, R. O. **Capítulo 2 – Geomorfologia**. In: Levantamento de Recursos Naturais, Volume 35: folha SG.22 Curitiba, parte da folha SG.21 Asunción e folha SG.23 Iguape (Relatório técnico do extinto Projeto RADAMBRASIL), Org. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, 2005.
18. COMITÊ EXECUTIVO NACIONAL – CEN/SBCR.Breve estado da arte do Sistema Brasileiro de Classificação de Relevo (SCBR): contribuições de e para a sociedade científica geomorfológica.**Revista Brasileira de Geografia**, Rio de Janeiro, v. 67, n. 2, p. 212-227, 2022.
19. DANTAS, M. E.; LACERDA, A.; MAIA, M. A. M. **Cartas de padrão de relevo multiescala**. Guia de procedimentos técnicos do Departamento de Gestão Territorial: volume 7 – versão 1.. SGB-CPRM, 2023.
20. DIKAU, R. The application of a digital relief model to landform analysis. In: RAPER, J. F. (Ed.), **Three Dimensional Applications in Geographical Information Systems.** Taylor & Francis, London, p.51-77, 1989.
21. DIKAU, R.; BRABB, E. E.; MARK, R. M. **Landform Classification of New Mexico by Computer.** Open File report 91-634. U.S. Geological Survey, 1991.
22. DIKAU, R.; BRABB, E. E.; MARK, R. K.; PIKE, R. J. Morphometric landform analysis of New Mexico. **Zeitschrift fur Geomorphologie Supplementband**. v. 101, p. 109-126, 1995.
23. DRAGUT, L; BLASCHKE, T. Automated classification of landform elements using object-based image analysis. **Geomorphology**, v. 81, p. 330-344, 2006. DOI: 10.1016/j.geomorph.2006.04.013.
24. FASSBINDER, E. **Análise estrutural da Falha da Lancinha: estado do Paraná.** 1990. Dissertação (Mestrado em Geologia) - Programa de Pós-Graduação em Geoquímica e Geotectônica, Universidade de São Paulo, São Paulo.
25. FERREIRA, F.J.F. **Integração de dados aeromagnéticos e geológicos: configuração e evolução tectônica do Arco de Ponta Grossa.** Dissertação (Mestrado) – Universidade de São Paulo, São Paulo, 1983.
26. FIORI, A. P.; GASPAR, L. A. Considerações sobre a estratigrafia do Grupo Açungui (Proterozóico Superior), Paraná, sul do Brasil. **Boletim IG-USP. Série Científica**, v. 24, p. 1-19, 1993. DOI: 10.11606/issn.2316-8986.v24i0p1-19.
27. FLORENZANO, T. G. Introdução à geomorfologia. In: ______ (org.). **Geomorfologia conceitos e tecnologias atuais.** São Paulo: Oficina de Textos, 2008.
28. GOMES, S. M. A; SILVEIRA, R. M. P.; SILVEIRA, C. T. Aplicação de técnicas geomorfométricas para classificação de formas do relevo em Campo Largo, estado do Paraná - Brasil. **Revista Geografar**, v. 13, n. 1., p. 75-97, 2018. DOI: 10.5380/geografar.v13i1.56463.
29. GOULART, A. Á.; SANTOS, L. J. C. Evolução temporal e espacial das paleovoçorocas presentes no município de Loanda/PR. **Revista Geonorte**, Edição Especial, v. 10, p. 81-86, 2014.
30. GROHMANN, C. H.; RICCOMINI, C.; STEINER, S. S. Aplicações dos modelos de elevação SRTM em geomorfologia. **Revista Geográfica Acadêmica**, v. 2, n. 2, p. 73-83, 2008. DOI: 10.31223/osf.io/amn2t
31. HENGL, T. Finding the right pixel size. **Computers & Geosciences**. 32, p. 1283-1298, 2006. DOI: 10.1016/j.cageo.2005.11.008
32. HORN, B. K. P. Hill shading and the reflectance map. Proceedings of the IEEE, n. 69, v.01, p. 14-47, 1981.
33. HUTCHINSON, M. F. Calculation of hydrologically sound digital elevation models. **Paper presented at Third International Symposium on Spatial Data Handling at Sydney,** Australia, 1988.
34. GUERRA, A. T. **Dicionário Geológico-Geomorfológico.** 8ª ed. Rio de Janeiro: IBGE, 446 p. 1993.
35. GUERRA, A. T.; GUERRA, A. J. T. **Novo dicionário Geológico-Geomorfológico**. 6ª ed. Rio de Janeiro: Bertrand Brasil, 2008.
36. IBGE – Instituto Brasileiro de Geografia e Estatística. **Manual Técnico de Geomorfologia**. 2ª ed. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística, 175 p., 2009.
37. IBGE. **Vocabulário Básico de Recursos Naturais e Meio Ambiente.** Rio de Janeiro: IBGE, 2004.
38. IBGE. **Relatório Técnico 1º Workshop sobre o Sistema Brasileiro de Classificação de Relevo**. Rio de Janeiro: IBGE, 2020. 77p. Disponível em: https://biblioteca.ibge.gov.br/visualizacao/livros/liv101731.pdf.

39. IPT. Mapa Geomorfológico do Estado de São Paulo, citado em: cap. 4 – cartografia in: geomorfologia conceitos e tecnologias atuais. 1981.
40. IPT; CPRM. **Cartas de suscetibilidade a movimentos gravitacionais de massa e inundações - 1:25.000** - Nota técnica explicativa. 2014.
41. IWAHASHI, J. ; PIKE, R. J. Automated classification of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature. **Geomorphology.**v. 86, p. 409-440, 2007. DOI: 10.1016/j.geomorph.2006.09.012
42. JASIEWICZ, J.; STEPINSKI, T. F. Geomorphons a Pattern Recognition Approach to Classification and Mapping of Landforms. **Geomorphology**, v. 182, p. 147-156, 2013. DOI: 10.1016/j.geomorph.2012.11.005
43. KLINGSEISEN, B.; METTERNICHT, G.; PAULUS, G. Geomorphometric landscape analysis using a semi-automated GIS–approach, Environmental Modeling and Software Vol. XX, pag. 1–13. **Science Direct**, 2007.
44. MAACK, R. **Geografia Física do Estado do Paraná**. Curitiba: Banco de Desenvolvimento do Estado do Paraná, Universidade Federal do Paraná e Instituto de Geologia e Pesquisas Tecnológicas, 1968.
45. MACMILLAN, R. A.; PETTAPIECE, W. W.; NOLAN, S. C.; GODDARD, T. W. A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic**. Fuzzy Sets and Systems,** v. 113, 81–109, 2000. DOI: 10.1016/S0165-0114(99)00014-7
46. MARCOLIN, L.; CALEGARI, M. R.; SANTOS, L. J. C.; CAMARGO, P. B. de . Phytoliths, $\delta^{13}C$ and Charcoal: holocene environmental memories from a paleogully in northwestern Paraná State . **Revista Brasileira de Geomorfologia**, *[S. l.]*, v. 24, n. 00, 2023. DOI: 10.20502/rbg.v24i00.2328. Disponível em: https://rbgeomorfologia.org.br/rbg/article/view/2328. Acesso em: 3 set. 2024.
47. MELO, M. S.; GUIMARÃES, G. B.; RAMOS, A. F.; PRIETO, C. C. Relevo e hidrografia dos Campos Gerais. IN: MELO, K. S.; MORO, R. S.; GUIMARÃES, G. B. **Patrimônio natural dos Campos Gerais do Paraná.** Ponta Grossa: Editora UEPG, 2007. p. 49-58.
48. MILANI, E. J.; RANGEL, H. D.; BUENO, G. V.; STICA, J. M.; WINTER, W. R.; CAIXETA, J. M.; NETO, O. P. Bacias sedimentares brasileiras: cartas estratigráficas. **Boletim de Geociencias da PETROBRAS**, v. 15, n. 2, p. 183-205, 2007.
49. OKA-FIORI, C., SANTOS, L.J.C., CANALI, N.E., FIORI, A.P., SILVEIRA, C.T., SILVA, J.M.F., ROSS, J.L.S. **Atlas geomorfológico do estado do Paraná: Escala base 1:250.000 modelos reduzidos 1:500.000.** Curitiba, Minerais do Paraná SA. - MINEROPAR; Universidade Federal do Paraná. Curitiba, 2006. 59p.
50. PIKE, R. J. The geometric signature: quantifying landslide-terrain types from digital elevation models. **Mathematical Geology**, v. 20, p. 491–511, 1988.
51. PIKE, R. J.; EVANS, I., HENGL, T. Geomorphometry: A Brief Guide. In: HENGL, T.; REUTER, H. I. (eds.) **Geomorphometry - Concepts, Software, Applications.** Series Developments in Soil Science vol. 33, Amsterdam: Elsevier, pp. 3-30, 2009.
52. RAPOSO, M. I. B. Episódios intrusivos no Arco de Ponta Grossa, determinados através de estudos paleomagnéticos. **Revista Brasileira de Geociências**, v. 25, n. 1, p. 3-19, 1995.
53. RENNE, P. R.; DECKART, K.; ERNESTO, M.; Fe, G.; PICCIRILLO, E. M. Age of the Ponta Grossa dike swarm (Brazil), and implications to Paraná flood volcanism. **Earth and Planetary Science Letters**, v. 144, n. 1-2, p. 199-211, 1996. DOI: 10.1016/0012-821X(96)00155-0
54. REUTER, H. I. (eds.) **Geomorphometry - Concepts, Software, Applications**, Series Developments in Soil Science, Amsterdam: Elsevier, v. 33, p. 3-30, 2009.
55. ROSA FILHO, E. F.; GUARDA, M. J. Compartimentação hidrogeológica da Formação Capiru na região norte de Curitiba-PR, Brasil. **Águas Subterrâneas**. , v. 22, n. 01, p. 67-74, 2008. DOI: 10.14295/ras.v22i1.17024
56. ROMSTAD, B. Improving relief classification with contextual merging. **Proceedings of ScanGIS'2001** — The 8th Scandinavian Research Conference on Geographical Information Science. Ås, Norway, p. 3-13, 2001.
57. ROSS, J. S. Registro cartográfico dos fatos geomorfológicos e a questão da taxonomia do relevo. **Rev. Geografia**. São Paulo, IG-USP, p. 17-29, 1992.
58. SAADAT, H.; BONNELL, R.; SHARIFI, F.; MEHUYS, G.; NAMDAR, M.; ALE-EBRAHIM, S. Landform classification from a digital elevation model and satellite imagery. **Geomorphology.** v. 100, p. 453-464, 2008. DOI: 10.1016/j.geomorph.2008.01.011
59. SANTOS, L. J. C. ; OKA-FIORI, C.; CANALI, N.E.; FIORI, A.P.; SILVEIRA, C.T.; SILVA, J.M.F.; ROSS, J.L.S; Mapeamento Geomorfológico do Estado do Paraná. **Revista Brasileira de Geomorfologia.** Ano 7, n. 2. p. 03-11. 2006. DOI: 10.20502/rbg.v7i2.74

60. SILVEIRA, C. T.; SILVEIRA, R. M. P. Índice de Posição Topográfica (IPT) para classificação geomorfométrica das formas de relevo no estado do Paraná - Brasil. **Revista Ra'e Ga**, v. 41, p. 98-130, 2017. DOI: 10.5380/raega.v41i0.51674
61. SILVEIRA, C. T.; SILVEIRA, R. M. P.; TRENTIN, R.; ROBAINA, L.E.S. Classificação automatizada de elementos de relevo no estado do Paraná (Brasil) por meio da aplicação da proposta dos *geomorphons*. **Revista Brasileira de Geomorfologia**, v. 19, n.01, p. 33-57, 2018. DOI: https://doi.org/10.20502/rbg.v19i1.1263
62. SILVEIRA, C. T.; SILVEIRA, R. M. P.; BORTOLINI, W.; ALMEIDA, V. P. Unidades de relevo do novo mapa geomorfológico do Paraná: avanço na escala e táxon. **Geo UERJ,** n. 42, 2023. DOI: 10.12957/geouerj.2023.74576
63. SILVEIRA, R. M. P.; SILVEIRA, C. T.; OKA-FIORI, C. Emprego de técnicas de inferência espacial para identificação de unidades de relevo apoiado em atributos topográficos e árvore de decisão. **Revista Brasileira de Geomorfologia**, v. 15, n. 1, 87-101, 2014. DOI: 10.20502/rbg.v15i1.433.
64. SILVEIRA, R. M. P.; SILVEIRA, C. T. Classificação hierárquica automatizada de formas do relevo no estado do Paraná apoiada na modelagem digital do terreno. **Revista Brasileira de Geografia Física,** v. 08, n. 05, p. 1509-1523, 2015.
65. SILVEIRA, R. M. P.; SILVEIRA, C. T. Análise digital do relevo aplicada à cartografia geomorfológica da porção central da Serra do Mar Paranaense. **Revista Brasileira de Geomorfologia**,v. 17, nº 4, 615-629, 2016. DOI: 10.20502/rbg.v17i4.1063
66. VALERIANO, M.M. **Modelo digital de elevação com dados SRTM disponíveis para a América do Sul**. Instituto Nacional de PesquisasEspaciais, p. 1-72, 2004.
67. WEISS, A. **Topographic Position and Landforms Analysis.** Poster presentation, ESRI User Conference, San Diego, CA, 2001.
68. WILSON, J. P. Digital terrain modelling. **Geomorphology**. v. 137, p. 107-121, 2012. DOI: 10.1016/j.geomorph.2011.03.012
69. WILSON, J. P.; GALLANT, J. C. (eds.). **Terrain analysis: principles and applications**. New York: John Wiley &Sons, p.1-27, 2000.
70. WOOD, J. **The geomorphological characterisation of digital elevation models.** Leicester, UK, 1996. 185p. PhD Thesis - University of Leicester. Disponível em: http://www.soi.city.ac.uk/~jwo/phd.