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Artigo de Pesquisa

Geomorphological mapping of the municipality of Chía, Colombia: methodological contributions and proposed classification

Mapeamento geomorfológico do município de Chía, Colômbia: contribuições metodológicas e proposta de classificação

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Abstract: This article presents the application of a geomorphological mapping methodology developed in Brazil to the municipality of Chía, located in the Colombian Andes. The research relies on the interpretation of geological maps, topographic charts, satellite images, geotechnologies, and fieldwork, enabling geomorphological characterization across various scales of analysis. The methodology employed originated in Brazil driven by the RADAMBRASIL project (1970–1985) and is currently used with modifications and adaptations specific to the regions being mapped. It integrates morphostructural, morphological, and morphometric aspects and, more recently, anthropogenic landforms within a systemic, integrated, and applied approach. The results demonstrate the feasibility of applying this methodology in Andean areas, provided that certain technical and methodological adaptations are made, adjustments that do not alter the fundamental Brazilian methodological structure. The conclusions confirm the methodology's applicability within the Andean context, highlighting its potential for environmental and territorial planning.

Keywords: Bogotá Savannah; Relief Taxonomy; Anthropogenic Landforms

Abstract: Este artigo apresenta a aplicação de uma metodologia de mapeamento geomorfológico desenvolvida no Brasil ao município de Chía, situado nos Andes colombianos. A pesquisa baseia-se na interpretação de mapas geológicos, cartas topográficas, imagens de satélite, geotecnologias e trabalho de campo, permitindo a caracterização geomorfológica em diversas escalas de análise. A metodologia empregada originou-se no Brasil impulsionada pelo projeto RADAMBRASIL (1970–1985) e é atualmente utilizada com modificações e adaptações específicas para as regiões mapeadas. Ela integra aspectos morfoestruturais, morfológicos e morfométricos e, mais recentemente, formas de relevo antropogênicas em uma abordagem sistêmica, integrada e aplicada. Os resultados demonstram a viabilidade da aplicação dessa metodologia em áreas andinas, desde que sejam realizadas certas adaptações técnicas e metodológicas ajustes estes que não alteram a estrutura metodológica brasileira fundamental. As conclusões confirmam a aplicabilidade da metodologia no contexto andino, destacando seu potencial para o planejamento ambiental e ordenamento territorial.

Palavras chaves: Savana de Bogotá; Taxonomia do Relevo; Formas de Relevo Antropogênicas

1. Introduction

Throughout history, landforms have been investigated as products of the interaction between different elements and processes, generating a wide variety of morphologies. Geomorphological maps, in addition to attempting to map landforms at various levels and scales, can constitute a synthesis of geomorphological research. The main morphogenetic factors correspond to endogenous and exogenous processes (Cholley, 1950), and it is impossible to dissociate them in geomorphological studies, since all morphosculpture is supported by a morphostructure, which is the geological basement (Ross, 1992; Ross; Moroz, 1996; Santos et al. 2006; Diniz et al. 2017). Therefore, the geomorphological map must represent the most varied hierarchical levels of landforms, including the morphostructure.

However, with technological advances, especially after the Industrial Revolution in the 18th century and more intensely after the Second World War, human action began to act as an important agent modifying landforms (Nir, 1983), equaling or even surpassing, in certain areas of the planet, the intensity of endogenous and exogenous natural processes. Anthropogenic geomorphology and the mapping of anthropogenic landforms have also been gaining prominence through a series of publications in Portuguese and English, such as those by Peloggia (1997, 1998, 2015, 2017, 2018), Miyazaki (2014), Oliveira (2014), Silva et al. (2014), Luz and Rodrigues (2015), Paschoal et al. (2015), Barbosa et al. (2018), Barbosa et al. (2019), and Barbosa and Furrier (2023a; 2023b).

Brazil has a long tradition in geomorphological mapping, initiated with the RADAMBRASIL Project in the 1970s and 1980s, and might be considered an international reference in this area. Furthermore, the country has a national executive committee composed of numerous researchers dedicated to developing a standardized system for classifying landforms (CEN/SCBR, 2022). This initiative places Brazil in a prominent position on the international stage, given that geomorphological mapping still lacks a standardization system comparable to that already established in geological mapping.

However, this is not the reality observed in Colombia. In that country, geomorphology is predominantly developed and debated by geologists, with only eight undergraduate programs in Geography and only two doctoral programs throughout the entire national territory. Discussions related to geomorphology largely take place within the framework of *Congreso Colombiano de Geología*, restricted to a single thematic section dedicated to geomorphology (CCG – ACTAS, 2025). In this context, strengthening scientific exchange between Brazilian and Colombian researchers becomes essential to enable, in the future, the expansion of geomorphological discussions and the analysis of application of Brazilian geomorphological mapping methodology in different areas of Colombia.

One of the most prominent researchers in geomorphological mapping in Brazil is Professor Jurandyr Ross, who also worked for several years on the RADAMBRASIL Project. The methodological core developed by Ross (1992), in conjunction with other geomorphologists on the project, is based on the division of landforms into six hierarchical taxa, applicable to general studies on the geomorphology of specific regions. This methodology allows the mapping of different landforms, from the large morphostructures that support the morphosculptures, to the current forms produced by natural processes, such as scars from mass movements, and anthropogenic landforms, such as dikes and artificial terraces resulting from human activity.

The methodology developed by Ross (1992) represents the result of the continuous evolution of geomorphological mapping produced within the scope of the RADAMBRASIL Project and has been widely applied in Brazil notably its use in the geomorphological mapping of the state of São Paulo (Ross; Moroz, 1996; Ross; Gouveia, 2022), the state of Paraná (Santos et al., 2006) and the state of Rio Grande do Norte (Diniz et al. 2017.

More recent works have also presented different methodological proposals aimed at the geomorphological mapping of urban areas and anthropogenic landforms, or adaptations of Ross's (1992) methodology to this type of landforms. Notable works in this approach include Rodrigues (2005), Ford et al. (2010), Peloggia et al. (2014a; 2014b), Del Monte et al. (2016), Furrier et al. (2017), Brandolini et al. (2018), Barbosa et al. (2018), Barbosa et al. (2019), Cappadonia et al. (2020), Barbosa and Furrier (2023a; 2023b) and Moura et al. (2023).

Therefore, geomorphological mapping is a constantly evolving field, in which the methodologies developed in Brazil are continuously employed and adapted to the particularities of the analyzed landforms. In Colombia, however, this methodology has only been applied on two occasions: by Furrier et al. (2017), in the urban area of Cartagena de Indias, and by Furrier and Vargas Cuervo (2018), in the Cartagena chart, which covers both the urban site of Cartagena de Indias and an extensive rural area of the Colombian Caribbean. Although applications remain

limited, this represented a scientific and methodological advance, given that the proceedings of geology symposia addressing geomorphology did not contain a single abstract on geomorphological mapping (CCG, 2015).

In this sense, this article presents a proposal for geomorphological mapping based on the Brazilian methodology, which has its precursor in Ross (1992), incorporating technical and methodological adaptations to the environmental specificities of the municipality of Chía, located in the Eastern Cordillera of the Colombian Andes. The study area was selected because it is a municipality undergoing rapid urban expansion, with a landscape constantly altered by human intervention and a lack of detailed geomorphological studies.

2. Location of the study area

Chía is a municipality located in the Department of Cundinamarca, Colombia (Figure 1) and is part of the Eastern Cordillera of the Colombian Andes, upper hydrographic basin of the Bogotá River. Steep mountainous landforms stand out on the eastern and western flanks, while in the center lies the Bogotá Altiplano, also known as the Bogotá Savannah, with relatively flat fluvial-lacustrine landforms. (Castiblanco, 2021; 2022).

According to the *Instituto Geográfico Agustín Codazzi* (IGAC, 2024a), the municipality of Chía covers an area of 79.8 km² and is located 34.1 km north of the center of Bogotá, the capital of Colombia. The municipality has altitudes between 2,545 and 3,220 meters above sea level. The hydrographic network is composed of streams that descend from the mountains and feed the Bogotá and Frío rivers, the main watercourses of the municipality. Most of the territory has a semi-arid and cold semi-humid climate, while the peaks have a cold semi-humid climate.

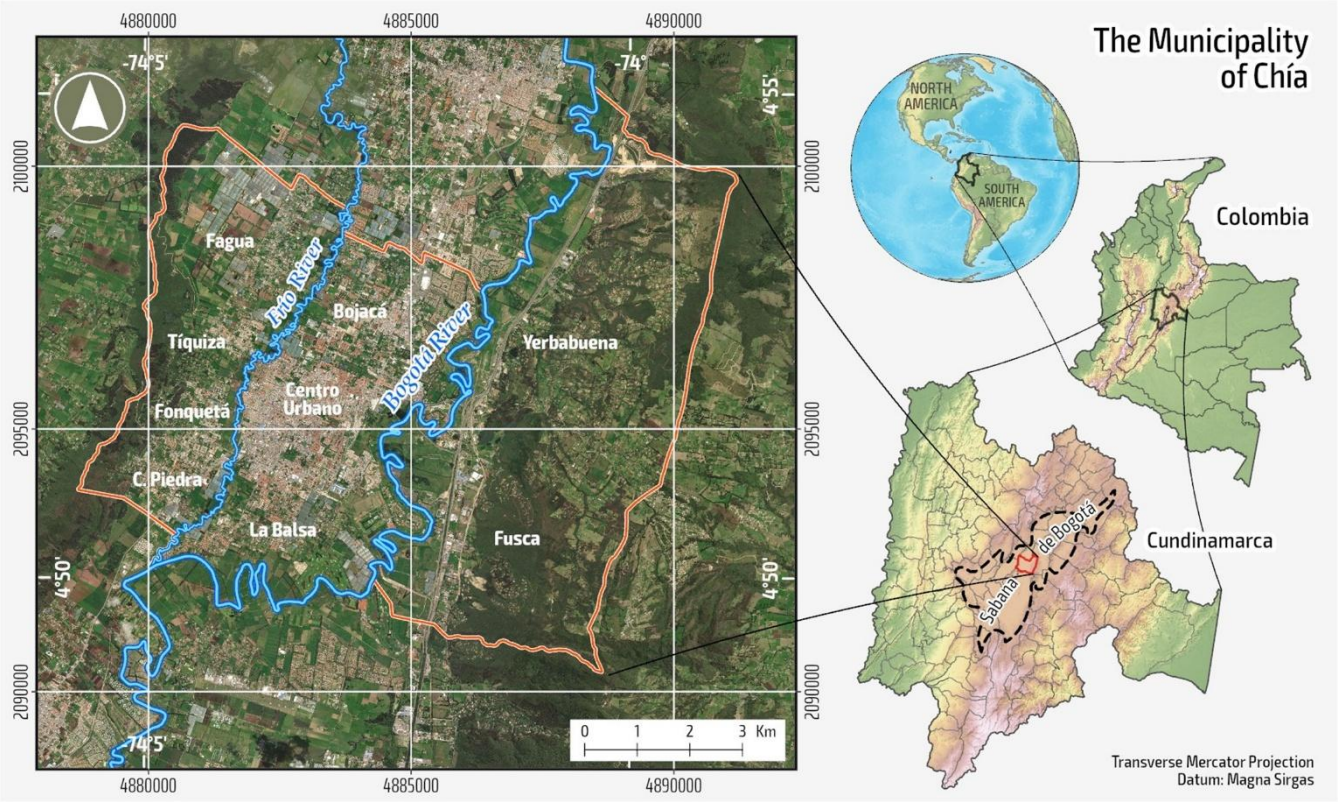


Figure 1. Study area.

The central area of the municipality, known as the Bogota Savannah, is dominated by agroecosystems and a high proportion of urbanized areas, while some areas with semi-natural vegetation are preserved in the foothills. The municipality has an important tertiary sector in its economy, with road and rail connectivity that provides a high degree of commercial and service diversification (IGAC, 2024a). The total projected population for Chía in 2026 exceeds 170,000 inhabitants (DANE, 2025).

2.1. Geological characterization of the study area

Regionally, the municipality of Chía is situated in the axial zone of the Eastern Cordillera of the Colombian Andes, between the Magdalena Valley Basin to the west and the Llanos Foreland Basin to the east; to the north and south, the mountain range is bounded by major fault systems associated with the Santander and Quetame–Garzón massifs (Barrera et al., 2019). Cenozoic evolution involved progressive shortening, exhumation, and deformation migration, culminating in the uplift of the Eastern Cordillera and the development of the Bogotá tectono-sedimentary basin (Bogotá Savannah), which was subsequently filled by fluvial and lacustrine deposits reaching up to 320 m in thickness (Barrera et al., 2019).

In the municipality of Chía, Cretaceous sedimentary rocks outcrop, exposed to varying degrees of folding, faulting, fracturing, and denudation. The oldest and most resistant consolidated rocks are in the higher mountain blocks to the east and west, while the intermediate and less resistant formations are found on the inner edges of these mountain ridges. In the central tectonic depression (Bogotá Savannah), there are extensive Quaternary deposits that vary in origin and materials that form a broad, flat area characterized by fluvial terraces, as well as fluvial and lacustrine plains (Carvajal; Navas, 2016) (Figure 2). The following lithostratigraphic and morphostructural classification is based on the work of: Helmens and Van der Hammen (1995); Acosta and Ulloa (2001); Montoya and Reyes (2005); Corredor and Melo (2015); and CAR (2018).

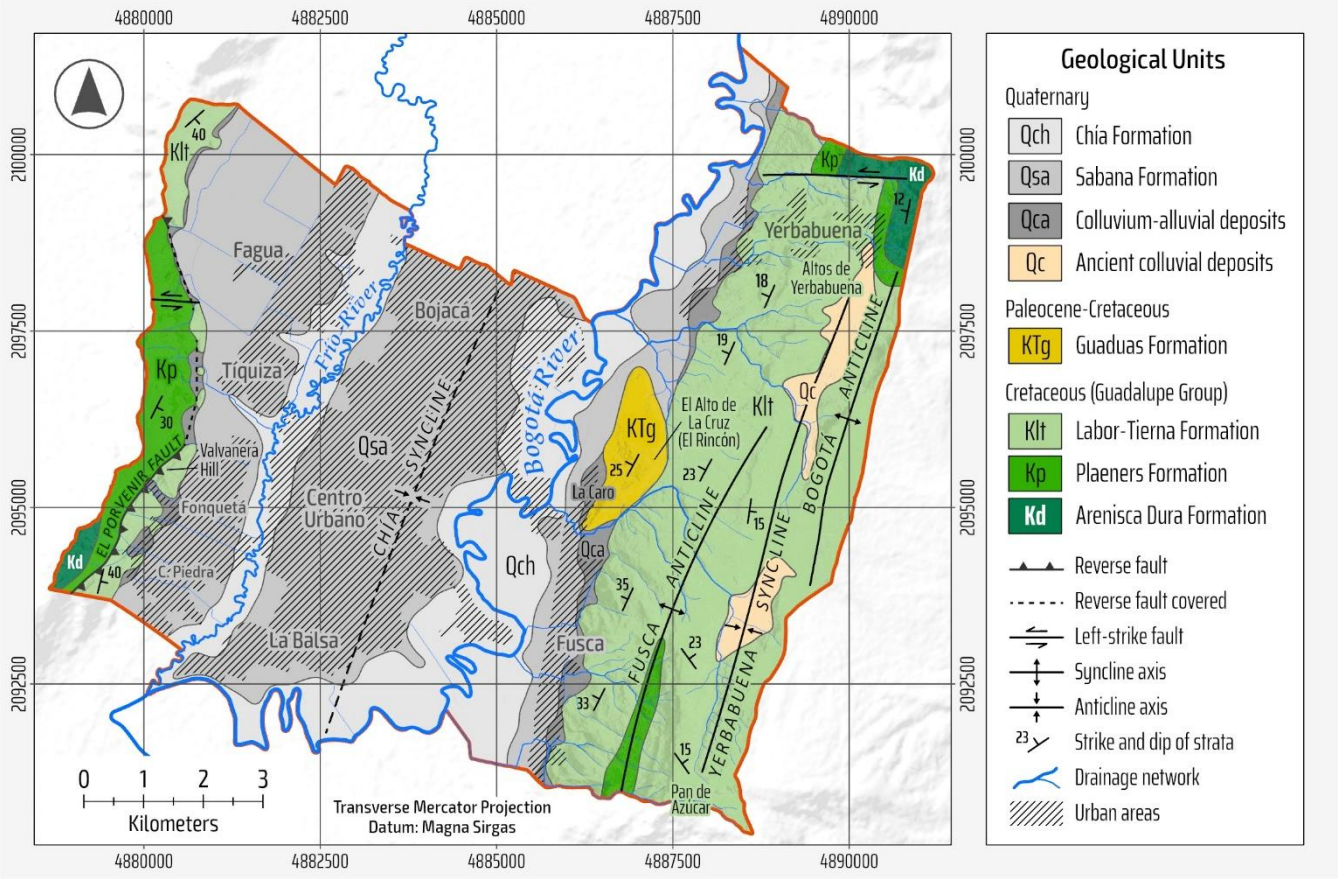


Figure 2. Geology of the municipality of Chía. Elaboration: Authors. Based on Helmens and Van der Hammen (1995); Ulloa et al. (1998) and Buitrago et al. (2008).

2.1.1. Guadalupe Group

It forms most of the landforms that border the Bogotá Savannah. It is composed of the following formations: Arenisca Dura, Plaeners, and Labor-Tierna:

Arenisca Dura Formation (Kd), a Middle Cretaceous unit that stands out for the steep and elevated morphologies of the northeastern and southwestern extremes of the municipality. It consists of light gray quartz arenites, fine to medium grained, well cemented, hard in consistency, thick to very thick stratification, weakly to moderately weathered, slightly fractured, and very resistant.

Plaeners Formation (Kp) an Upper Cretaceous unit that outcrops on the western flank of the municipality, with small units to the east. It consists of an interbedded sequence of siltstones, siliceous claystones, lydites, and fine-grained sandstones with very thin to medium stratification, hard to medium consistency, weakly to moderately weathered, highly fractured, and of intermediate strength (Figure 3a).

Labor-Tierna Formation (Klt) Upper Cretaceous unit that predominates in the eastern reliefs, with significant outcrops on the lower edges of the western flank. It consists of fine- to coarse-grained quartz arenites, poorly cemented, slightly friable, in thick stratification with thin intercalations of claystones and siltstones, moderately to highly weathered, somewhat fractured, and of intermediate strength (Figure 3b).

2.1.2. Guaduas Formation

The Guaduas Formation (KTg) is a unit dating from the transition between the Cretaceous and Paleogene periods, outcropping in a small low-lying area of the eastern mountain range. It consists mainly of laminated argillites of various colors, interbedded with friable quartzose sandstones and coal seams, moderately fractured, in highly weathered areas, with soft consistency and regular to weak resistance (Figure 3c).

2.1.3. Quaternary sedimentary deposits

In the eastern mountains, these refer to ancient colluvial deposits (Qc), developed in synclinal folds, with ancient accumulations of heterogeneous material consisting of blocks and gravel in a sandy matrix and partially associated with the periglacial dynamics of the Quaternary. In contact with the central tectonic depression, colluvial-alluvial deposits (Qca) are described, with sub-recent and recent accumulations of hydrogravitational (torrential) debris, blocks and angular and subangular clasts in a sandy-silty matrix, heterometric, mainly sandstones in a sandy-clay matrix, associated with unstable orogenic dynamics (Figure 3c).

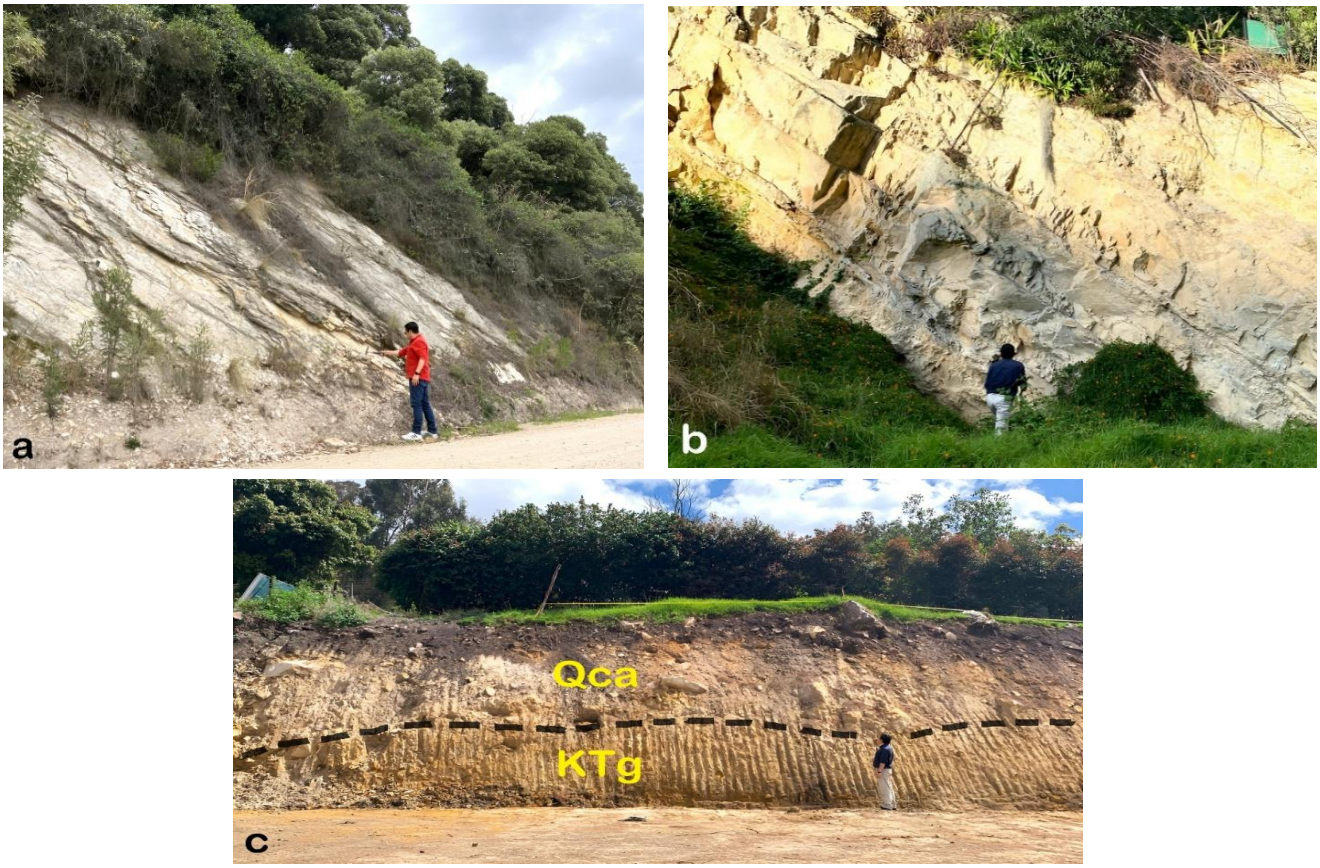


Figure 3. a) Plaeners Formation (Kp), Cerros Occidentales. b) Labor-Tierna Formation (Klt), Valvanera Hill (Fonquetá). c) Guaduas Formation (KTg) and colluvium-alluvial deposits (Qca), La Caro sector. **Photo:** Authors (2025).

Specifically, in the Bogota Savannah, lacustrine deposits of the Sabana Formation (Qsa) are delimited, filling the central synclinal structure of the municipality and corresponding to ancient and subrecent accumulations of gray clays, with some layers of silts, sands, gravel, peat, buried soils, and volcanic ash deposits. Finally, and associated with the current fluvial dynamics of the Bogotá and Frío rivers, there are fluvial flood deposits of the Chía Formation (Qch), with recent accumulations of silts and clays of light gray, yellow, dark gray, and locally organic coloration, dated from the Upper Pleistocene and Holocene.

3. Materials and Methods

For the development of this work, it was necessary to use computational tools and basic cartographic products for the processing, organization, and subsequent analysis of the data. The following section details the technical-operational and methodological processes used to create the cartographic products generated in this research and subsequently analyzed.

Cartographic material was produced using ArcGIS® PRO version 3.1.5. All cartographic products were based on contour lines derived from data from the Digital Elevation Model of the Municipality of Chía (IGAC, 2015; 2024b), with a resolution of 1 m for the study area and a scale of 1:1,000. The coordinate system used was Universal Transverse Mercator (UTM) and the datum was Magna Sirgas (GRS80 Spheroid - National Geocentric Reference System).

For the vectorization process, the same software was used, whose multifunctionality allows for the editing and storage of files in a geodatabase (gdb). A Digital Elevation Model (DEM) was generated using ArcGIS® PRO version 3.1.5, and from this, altimetry and slope maps were generated, which served as the basis for the elaboration of the geomorphological map and topographic profiles. All maps were originally produced at a scale of 1:25,000 and subsequently resized to fit the format and dimensions of this article, without, however, compromising the level of detail of the cartographic information presented.

3.1. Elaboration of altimetric and slope maps

Altimetric and slope maps provide fundamental and detailed information about the landforms, serving as a basis for the identification and quantification of slopes, terraces, and floodplains. In general, the model has proven satisfactory and useful for quantifying slope gradients, especially in areas with irregular landforms (Carvalho; Latrubesse, 2004). Several studies have used these maps to investigate recent tectonics and as support for geomorphological mapping (Furrier et al., 2006; Hartwing; Riccomini, 2010; Furrier et al., 2014; Silva; Furrier, 2021; Lima et al., 2024). The slope classes proposed by the *Instituto Geográfico Agustín Codazzi* (IGAC, 2018) were chosen for this study (Table 1).

Table 1. Slope classes.

Slope Gradient (%)	Slope Classification
> 75	Very steep
50 – 75	Steep
25 – 50	Moderately steep
12 – 25	Moderately inclined slopes
7 – 12	Moderately sloped
3 – 7	Slightly sloped
0 – 3	Flat to slightly flat

Source: IGAC (2018)

3.2. Topographic profiles

According to Fitz (2008), the topographic profile faithfully reflects the characteristics of the terrain, therefore providing a better understanding of landforms. It was decided to generate the profiles automatically using contour lines obtained from the contour lines generated by the Digital Elevation Model, drawing the profile lines with the Interpolate Line tool, which creates a 3D line interpolating the elevation from a selected functional surface. Then, with the aid of geological maps, lithological information was included.

Three segments were drawn to illustrate the slopes and their relationship to the respective geology as faithfully as possible. One SW – NE profile (A – A') and two NW – SE profiles (B – B' and C – C') were drawn. The choice of these profiles was based on the geological map produced for this study, which sought to encompass the main geological formations and geomorphological features, therefore obtaining a reliable correlation between geology and terrain morphology. For better visualization, and due to the scale used, the profiles were drawn with a vertical exaggeration of 1.5 times.

3.3. Elaboration of the geomorphological map

Geomorphological mapping is an important tool in the study of landforms, as it is in the geomorphological map that various methodologies are translated and synthesized, as well as the results of the respective research (Ross, 1992). Therefore, the geomorphological map can be considered a product of the synthesis of research. According to Ross (1992), a geomorphological map cannot simply describe landforms without including or underestimating the underlying geological structure that supports them.

Ross (1992), based on the methodological and structuralist concepts of Penck (1953) and Mescerjakov (1968), used geological basement, landforms, and the extent of each taxonomic unit as classification parameters. Therefore, Ross (1992) established six hierarchical taxonomic levels: morphostructure, morphosculpture, landform patterns, types of landforms, types of slopes, and forms of current natural and anthropic processes (Figure 4).

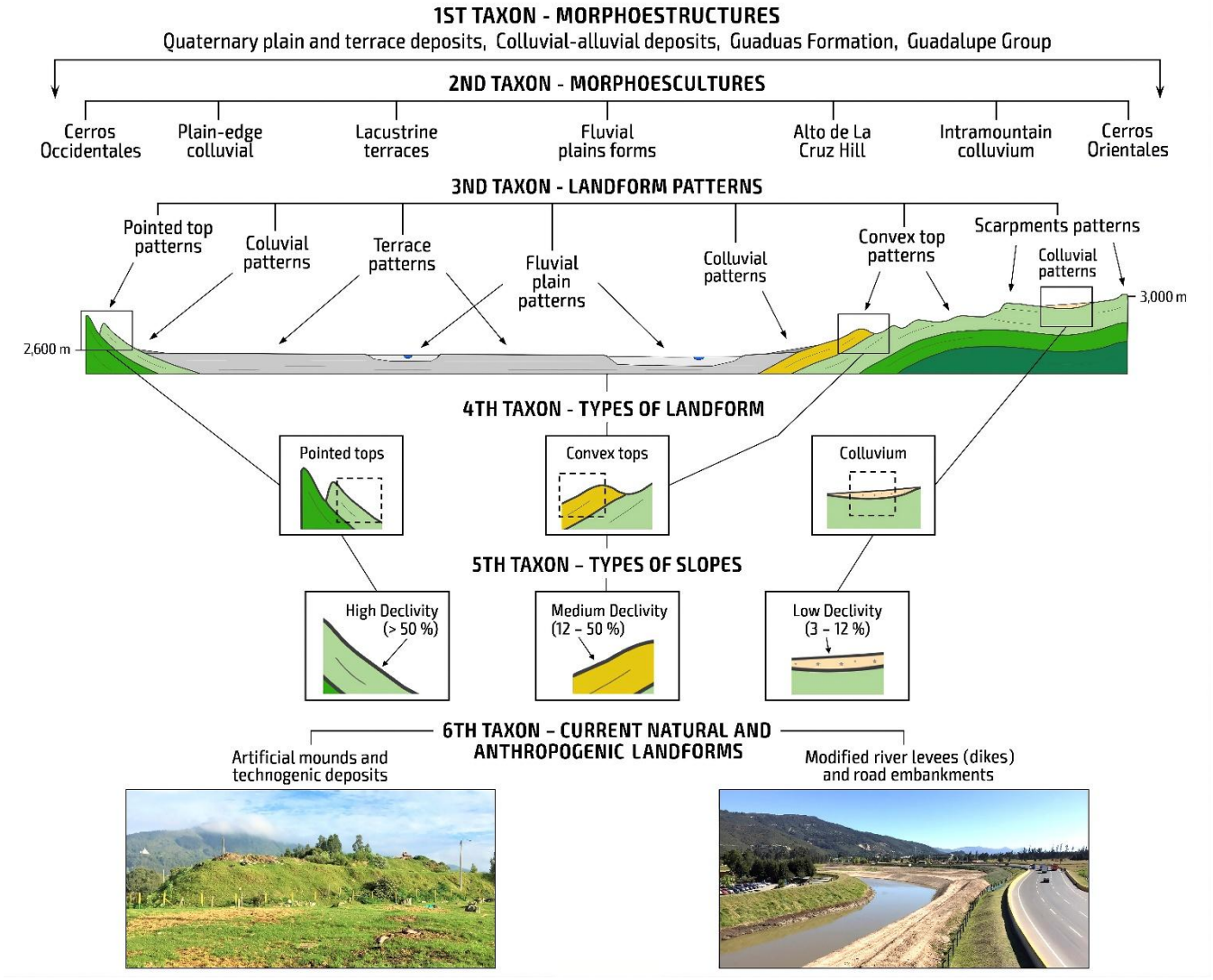


Figure 4. Relief taxonomy. Source: Modified from Ross (1992).

The 1st taxon corresponds to the definition of morphostructure, which is the geological basement, and the 2nd taxon represents the morphosculptures developed on the morphostructures. The 3rd taxon corresponds to units with similar landform patterns. These smaller units present differences among themselves, such as topographic roughness or relief dissection index. Landform patterns can be accumulation forms, such as fluvial, lacustrine or marine plains, or denudation forms, such as hills, mountain and plateaus.

The landforms related to the 3rd Taxon (landform patterns) are represented on the geomorphological map by a set of uppercase and lowercase letters. The uppercase letters indicate the patterns that were formed by denudation (letter D) or by accumulation (letter A), and the lowercase letters represent the generated forms (Table 2).

Table 2. Landforms Patterns (3rd Taxon).

Denudational landforms	Accumulative landforms
Dp - Landforms with pointed tops	Afp - Fluvial plain landforms
Dc - Landforms with convex tops	Alt - Lacustrine terrace landforms
De - Landforms with escarpment	Acpe - Plain-edge colluvial landforms
	Acim - Intramountain colluvial landform

Source: Adapted of Ross (1992).

The landform patterns are accompanied by a set of Arabic numerals according to a previously elaborated matrix, whose columns indicate the degree of valley incision; the rows, the average interfluvial dimension (Table 3). Aggradational forms do not receive Arabic numerals, as they do not represent dissection by erosive processes.

Table 3. Relief dissection index matrix.

	Interfluvial dimension (classes)				
Incising of the valleys (classes)	Very large (1) > 1,500 m	Large (2) 1,500 - 700 m	Middle (3) 700 - 300 m	Small (4) 300 - 100 m	Very small (5) < 100 m
Very low (1) < 20 m	11	12	13	14	15
Low (2) 20 - 40 m	21	22	23	24	25
Middle (3) 40 - 80 m	31	32	33	34	35
Strong (4) 80 - 160 m	41	42	43	44	45
Very strong (5) > 160 m	51	52	53	54	55

Source: Ross (1992).

In general, these landform patterns are characterized by different intensities of relief dissection due to the influence of watercourses (Ross 1992). To calculate the relief dissection index, it is necessary to consider the average valley incision and the average interfluvial dimension (Table 3). However, it should be noted that, to define a landform pattern, the order of the fluvial channel must be considered. First-order fluvial channels do not present a conspicuous landform pattern because the incision is still in its initial stage. The definition of which order would be most appropriate was not defined by Ross (1992). For tabular landforms, Souza and Furrier (2019) defined third-order fluvial courses as the most appropriate for the cartographic delimitation of the 3rd taxon.

The 4th taxon in descending order is characterized by the individual types of landforms within each landform pattern. These can be either denudation landforms, resulting from erosion processes, such as hills, mounds, and plateaus, or aggradation landforms, such as lacustrine plains, fluvial plains, and fluvial terraces. The types of landforms share similarities in both their morphology and morphometry, that is, in shape and size.

The cartographic representation of the 4th Taxon (types of landforms) is done in conjunction with the representation of the 3rd Taxon (landforms patterns). A landform pattern of type Dc 52 consists of denudational relief (letter D) with convex tops (letter c), with an incision > 160 m (number 5) and a large interfluvial dimension of 700 m to 1,500 m (number 2) (Table 3).

To calculate fluvial incisions or cuts, it is essential to consider the regional geological/geomorphological structure and the hierarchical order of the drainage network, which will determine the size of the relief to be mapped. It should be noted that the choice of the hierarchical order of watercourses is fundamental for the characterization and mapping of the required relief and is described in the methodological procedures of the RADAMBRASIL project, in which this methodology was initially developed in Brazil (Barbosa et al., 1984).

The 5th taxon, which are type of slopes, is formed by the slopes or slope sectors that make up the individual type of landform. A slope, or even a slope sector, is individualized by geometric, genetic, and dynamic characteristics (Ross 1992).

Due to the dimensions or aspects of its own sectors, the 5th taxon can only be represented cartographically at large scales, greater than or equal to 1:25,000. Therefore, an adaptation of the original methodology was chosen. In this research, the 5th taxon was analyzed through slope inclination. Three slope ranges were suggested to classify the gradient: low slope (3 – 12%), medium slope (12 – 50%), and high slope (greater than 50%). Slopes less than 3% were not considered slopes, but rather areas of aggradation, such as the floodplains and fluvial terraces mapped in the study area.

Due to the scope of this work, the 5th Taxon was also analyzed using the produced topographic profiles. The proposal to analyze the 5th Taxon through slopes and the analysis of topographic profiles also aims to avoid visual pollution of the geomorphological map with excessive information that could hinder its reading and understanding. Salomé and Van Dorsser (1982) compared six European geomorphological mapping systems applied to the same area in Europe. The geomorphological map that contained the greatest amount of information and detail, and supposedly the best from a theoretical point of view, was not considered the most practical or the most usual, precisely because of the difficulty of interpretation caused by the excess of cartographic information.

The 6th taxon represents the smallest mappable forms. These are forms produced by current erosive or depositional processes. This taxon includes forms caused by natural agents, such as gullies, ravines, current sedimentary banks, and anthropogenic landforms, such as cuts, embankments, mining, among others. Mapping the 6th taxon can be done using aerial photographs, high-resolution orbital images, and fieldwork. Its cartographic representation, when possible, is done using a specialized and detailed legend. The study of anthropogenic geomorphology and, consequently, the mapping of anthropogenic landforms has shown significant theoretical and conceptual advances, especially in recent decades, as discussed in the works cited in the introduction of this research. The cartographic representation of the sixth taxon was based on the works of Barbosa and Furrier (2023a; (2023b).

In these articles, the authors focused on mapping anthropogenic landforms and incorporated more recently developed methodologies such as those of Ford et al. (2010), Peloggia et al. (2014a, 2014b), Peloggia (2018), Del Monte et al. (2016), and Cappadonia (2020). Consequently, a new methodology was created that incorporates Ross's (1992) approach up to the fourth taxon while simultaneously utilizing other national and international methodologies for mapping urban and anthropogenic landforms.

Due to the enormous conceptual and methodological advances that anthropogenic geomorphology has experienced in recent decades, especially in Brazil, it was decided to call the 6th taxon "current natural and anthropogenic landforms" and not "current natural and anthropic forms", as originally proposed by Ross (1992).

4. Results

4.1. Geology and structural geomorphology

In the municipality of Chía, the faults and folds of the sedimentary layers stand out, with narrow anticlines and wide synclines, and the formation of a large internal subsiding synclinal depression, covered by Quaternary sediments where the Bogotá and Frío rivers form their floodplains. As a trend, the slopes exhibit extensive structural inversions and short erosional fronts, with structural control over the hydrographic network.

The mountain ranges, therefore, have a general NE – SW orientation and, in tectonic terms, the region is the result of a complex structural system that presents a system of reverse faults and folds whose predominant orientation is NNE – SSW. The extent of the Bogotá Savannah is limited in this sense and locally interrupted by mountainous and undulating structures associated with sedimentary rocks. These mountains, locally known as the Cerros Orientales and Cerros Occidentales, reach altitudes of up to 3,220 m a.s.l, representing an elevation difference of up to 600 meters relative to the urban center of Chía.

The southeastern sector of the municipality, where the Cerros Orientales exceed 3,200 m a.s.l. (Pan de Azúcar), features escarpments resulting from tectonic activity and denudation (Figure 5a). The Cerros Occidentales are affected by the reverse fault of the El Porvenir Fault (Figure 5b). This dynamic led to the elevation of the Cerros Occidentales to altitudes higher than 2,800 m above sea level. In the central sector (Bogotá Savannah), regional

morphostructural conditions determined the formation of a large syncline, covered by Quaternary sediments derived mainly from fluvial-lacustrine and fluvial morphodynamic processes.

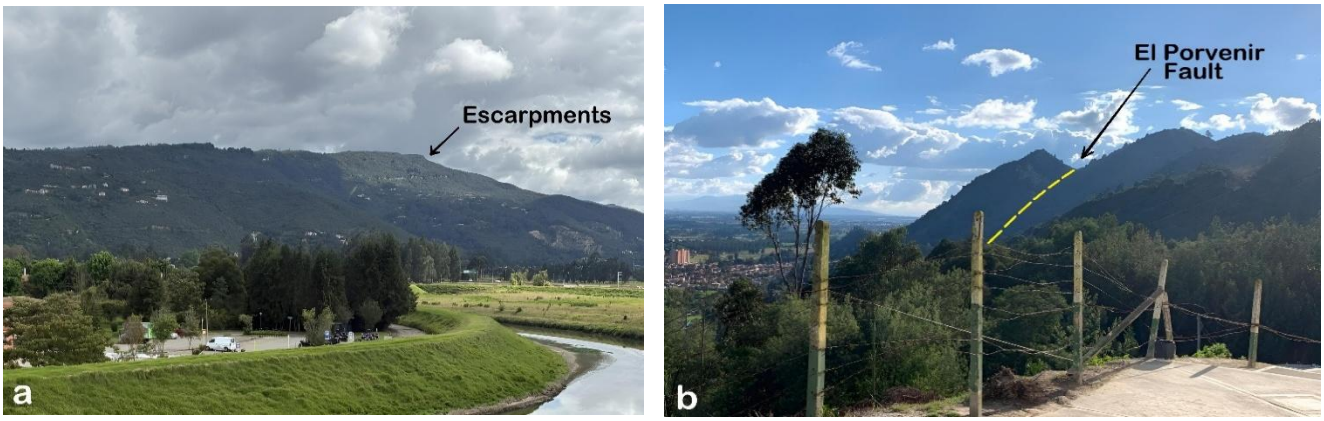


Figure 5. a) Cerros Orientales, Pan de Azucar sector view from NW to SE (Fusca). b) Cerros Occidentales and reverse fault El Porvenir between the Plaeners and Labor-Tierna formations view from N to S (Fonquetá-Cerca de Piedra, La Valvanera sector). Photos: Authors (2025).

4.2. Slope map

The slope map provides information that allows us to distinguish between different landforms, escarpments, slopes, lacustrine terraces, floodplains, and other features (Figure 6). In addition to being an extremely relevant tool for elaboration of the geomorphological map, this map provides important information about the different slopes of the area.

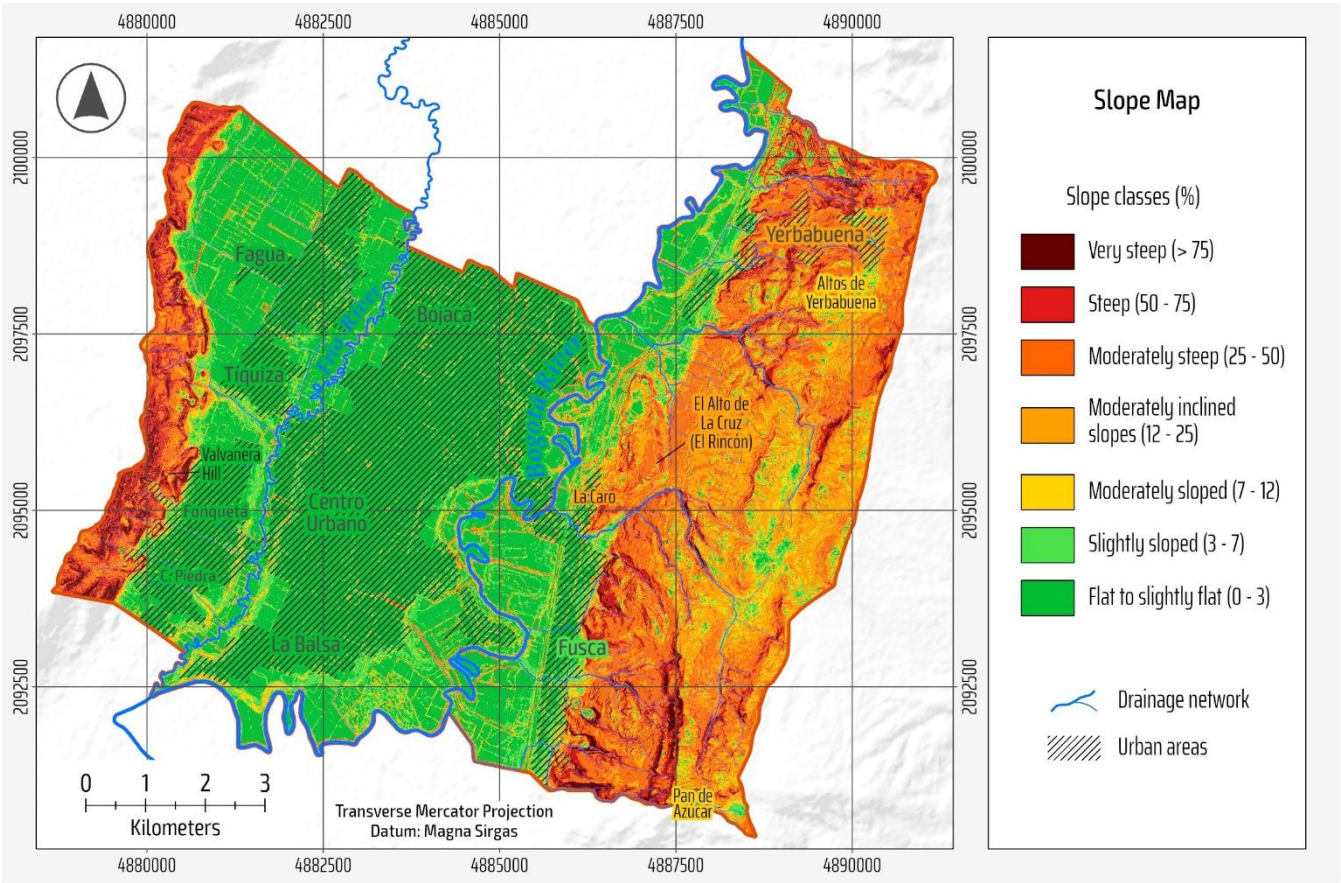


Figure 6. Slope Map.

Although the altitudes of the Cerros Orientales are higher than those of the Cerros Occidentales, the slopes do not reflect these altimetric differences. The Cerros Occidentales have steeper slopes than those found in the Cerros Orientales, with slopes predominantly between 50 and 75% (Figure 6). The slopes in the Cerros Orientales are more heterogeneous, with steep slopes visible in the Fusca Anticline, located in the southeastern sector of the area. Areas of gentle slopes can also be observed in the Cerros Orientales. These areas are synclines currently filled with colluvial deposits. In these locations, the slopes vary from 0 to 7%. However, it is possible to observe incised and relatively deep valleys in first and second-order streams, which corroborate active uplift tectonics.

The urban area of Chía is predominantly located in a flat or slightly sloped area, not exceeding 7%. However, recently, new urban areas have been established on the slopes and valleys of the Cerros Orientales, mainly in the northeastern sector of the Yerbabuena region. The slopes classes observed in the area, as well as the area in km² where each slope class occurs, can be seen in Table 4.

Table 4. Percentage spatial coverage of slope classes.

Slope classes	Area (Km²)	Area (%)
Very steep	2,1	2,8
Steep	5,6	6,9
Moderately steep	12,8	16,0
Moderately inclined slopes	9,9	12,4
Moderately sloped	5,7	7,1
Slightly sloped	8,6	10,7
Flat to slightly flat	**35,3**	**44,1**

4.3. Altimetric map

The altimetric map has proven quite useful as a tool for elaboration of the geomorphological map and also for aiding in understanding the tectonic dynamics of the area, since the altimetric differences found in the same geological formation indicate recent tectonic activity in the region (Figure 7).

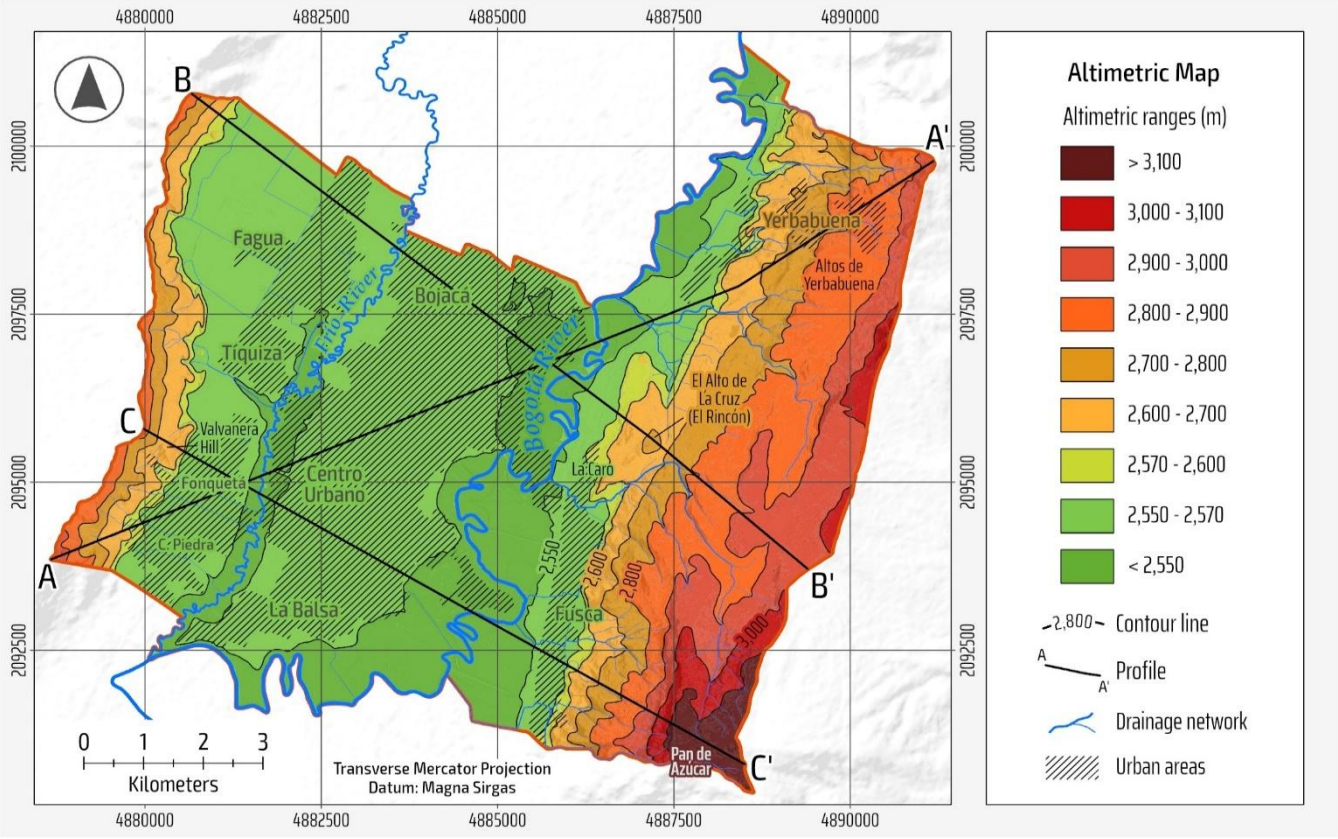


Figure 7. Altimetric map showing the lines where the topographic profiles were verified.

This map allows you to visualize the steep elevations that reach the two hills that delimit the municipality of Chía in the east and west sectors. The highest elevations are found in the Cerros Orientales, in the southeast sector, with a maximum altitude of 3,220 m a.s.l. The urbanized sector of the municipality is at an altitude between 2,550 and 2,570 m a.s.l.

The largest spatial coverage corresponds to the altitudinal range of 2,550 to 2,570 meters (Bogotá Savanna), where the urban center of Chía is located. The altimetric ranges observed in the area, as well as the area in km² where each altimetric class occurs, can be seen in Table 5.

Table 5. Percentage spatial coverage of altimetric ranges.

Hypsometric ranges	Area (Km²)	Area (%)
> 3,100	1,1	1,5
3,000 – 3,100	1,8	2,5
2,900 – 3,000	5,5	6,9
2,800 – 2,900	8,6	10,7
2,700 – 2,800	5,9	7,3
2,600 – 2,700	6,4	8,0
2,570 – 2,600	2,6	3,3
2,550 – 2,570	**33,1**	**41,2**
< 2,550	15,0	18,6

4.4. Topographic profiles with lithologies

Topographic profile A – A' (SW – NE) shows the steep slopes of the Cerros Occidentales, mainly in the Arenisca Dura Formation, as well as their rectilinear pattern. A decrease in slope is observed when the profile crosses the colluvial slopes of the Cerros Occidentales. Upon reaching the Labor-Tierna Formation in the Cerros Orientales, the slopes are predominantly convex, with moderate gradients. Upon reaching the Arenisca Dura Formation again, the slopes become rectilinear once more, with steep gradients (Figure 8).

Topographic profile B – B' (NW – SE) again shows the steep slopes of the Cerros Occidentales in the Labor-Tierna Formation and its rectilinear pattern. Crossing the Bogotá Savanna, the profile intersects Cerro El Alto de la Cruz (El Rincón), which is supported by the Guaduas Formation. The slopes are rectilinear, but with moderate gradients. The discontinuity of this formation with the Labor-Tierna Formation is notable, where the slopes are slightly convex with moderate gradients (Figure 8).

The C – C' (NW – SE) topographic profile again shows the steep slopes of the Cerros Occidentales in the Plaeners Formation and its rectilinear pattern. However, in this profile, the topographic irregularity due to the reverse fault of El Porvenir is noticeable. At the top of the Labor-Tierna Formation, there is a convex slope, followed by a rectilinear slope with a high gradient. Crossing the Bogotá Savanna, the profile intersects the Cerros Orientales in the Labor-Tierna Formation with rectilinear slopes of moderate gradient. Thanks to the Fusca Anticline, the Labor-Tierna Formation has been completely eroded, and the Plaeners Formation outcrops in this sector. At a higher altitude, the profile again intersects the Labor-Tierna Formation with a rectilinear slope and a very steep gradient, greater than 75%. At the top of the Cerros Occidentales, the slopes are convex and rectilinear with moderate gradients (Figure 8).

4.5. Geomorphological map

The geomorphological map was developed based on a literature review and a systematic analysis of data extracted from geological, altimetric, and slope maps, including direct field observations. The various elements and units described in the final geomorphological map range from the geological base, represented in the first taxon, to current natural and anthropogenic forms, represented in the sixth taxon. The comprehensive and integrated legend is noteworthy, allowing professionals from diverse fields, even those without in-depth knowledge of geomorphology, to understand and use the information contained in this map in other works such as environmental, territorial, and urban planning.

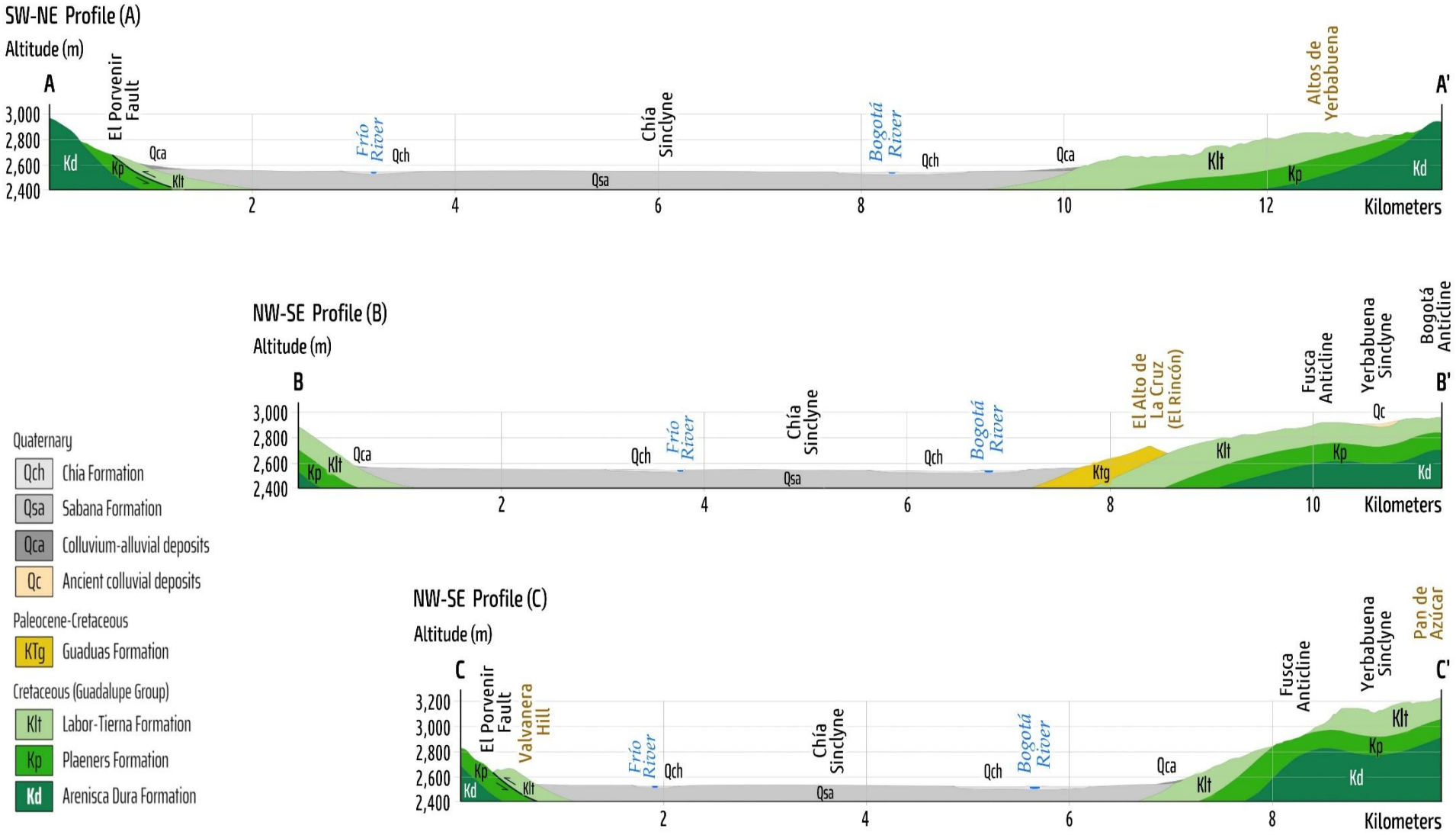


Figure 8. Topographic profiles with their respective lithologies and geological features (vertical exaggeration of 1.5)

Four morphostructures (1st Taxon) were identified in the study area: Guadalupe Group, Guaduas Formation, Colluvial-Alluvial Deposits, and Quaternary Plain and Terrace Deposits. These four morphostructures were subdivided into seven morphosculptures (2nd Taxon). The Guadalupe Group supports two distinct morphosculptures: Cerros Orientales and Cerros Occidentales. The Guaduas Formation supports the morphosculpture named in this research as El Alto de La Cruz Hill (El Rincón). The Colluvial-Alluvial Deposits present two distinct morphosculptures: Intramountain Colluvium and Plain-Edge Colluvium. The Quaternary Terrace and Plain Deposits present two morphosculptures: Lacustrine Terraces and Fluvial Plain Forms (Figure 9).

The seven morphosculptures were subdivided into ten landform patterns (3rd taxon) and ten landform types (4th taxon), since the delimitation of the 3rd and 4th taxa is done together, with the 3rd taxon being descriptive, for example: convex dissection (Dc); and the 4th taxon being morphometric, based on the relief dissection index, such as 41 (strong valley incision of 80 to 160 meters and very large interfluvial dimension > 1,500 meters).

The fifth taxon (types of slopes), as explained previously, could not be delineated on the geomorphological map due to the scale used. Therefore, the types of slopes were described in the interpretation of the topographic profiles with the lithologies. The slope gradients were included in the geomorphological map legend as the 5th taxon. Therefore, there was an adjustment to the original methodology, since, due to the scale used and the complexity of the types of slopes found, it would have been impossible to delineate them on the geomorphological map.

The sixth taxon (current natural and anthropogenic landforms) was significantly expanded in this mapping, due to methodological and conceptual developments related to anthropogenic geomorphology and addressed in this research. The sixth taxon was divided into made ground, such as road embankments, and dikes; worked ground, such as road cuts and quarries; and landscaped ground, which are urban areas (Figure 9). This division of anthropogenic landforms was based on Ford et al. (2010).

4.5.1. Denudational landforms

These denudational landforms refer to the morphosculptures developed in the sedimentary tectonic morphostructures of the Guadalupe Group and the Guaduas Formation.

Cerros Orientales: consist of sandstones, siltstones, and, to a lesser extent, claystones of the Guadalupe Group, which are moderately resistant and quite weathered, with structural control linked to regional anticline and syncline folding, at elevations ranging from approximately 2,600 to 3,200 m a.s.l. These include the unit described as **De 51** (Denudacional with escarpments), which consists of rugged terrain with stepped slopes exceeding 75% and located at altitudes above 2,900 meters, where weathered material and some evidence of erosion with small landslides are present in the Pan de Azúcar sector to the southeast in the village of Fusca (Figure 5a) and in Encenillos at the northeastern extremity. Unit **Dc 53** (Denudational with convex tops) corresponds to convex landforms with slopes between 50 and 75 percent, a highly incised drainage network, slow solifluction processes, erosion, and slope instability (isolated landslides); it is found in the Sindamanoy sector in the northeast and the Altos de Fusca sector in the southeast. Unit **Dc 41** also refers to convex landforms with gentler slopes between 25 and 50%, strong dissection by watercourses, but with a larger interfluvial dimension; it extends widely across the Altos de Yerbabuena, Altos de Hicatá, and Alto del Oso sectors.

Cerros Occidentales: They are also composed of sandstones, siltstones, and claystones of the Guadalupe Group, which are slightly more resistant and moderately weathered, with structural features resulting from reverse faulting, at an elevation range of approximately 2,600 to 2,900 m a.s.l. This defines Unit **Dp 52** (Denudational with pointed tops,) characterized by sharp denudation forms with slopes greater than 75%, small planar movements, and deep dissection by streams, primarily to the northwest in the El Retiro and Vía a Tabio sectors, and to the southwest in the Cerro de La Valvanera sector (Figure 5b). The intermediate unit defined as **Dp 43** exhibits slopes between 50 and 75%, a medium interfluvial dimension, and is in the upper part of the Tíquiza Gully sub-basin.

El Alto de La Cruz Hill (El Rincón): Unit **Dc 42** consists primarily of claystones from the Guaduas Formation, with elevations ranging from 2,570 to 2,740 m a.s.l. It features convex landforms with moderate slopes between 25 and 50% and deep incisions with a long interfluvial dimension; evidence is also observed of slow

mass movement such as solifluction, small landslides, signs of water erosion, and human intervention with terraces and "cow's foot" soil degradation.

4.5.2. Accumulative landforms

It encompasses some sectors of intramontane colluvial deposits in the Cerros Orientales and the central area of the municipality of Chía that is bordered by the Cerros Orientales and the Cerros Occidentales. The central area consists of a syncline filled with Quaternary sediments of lacustrine and fluvial origin. In the foothills an extensive colluvial system developed, transitioning to a flat area where the center of Chía is located.

Intramountain colluvium: These refer to ancient deposits associated with in situ weathering and Pleistocene periglacial activity, which are located primarily at the base of the Yerbabuena syncline (Cerros Orientales). The **Acim** (Accumulative intramountain colluvial) unit mainly features slopes between 7% and 12%, at an elevation range between 2,800 and 2,900 m a.s.l., with small landslides, slow solifluction, creep, undulations, and ground fractures; these are in the sub-basins of the Santiamén and Honda streams.

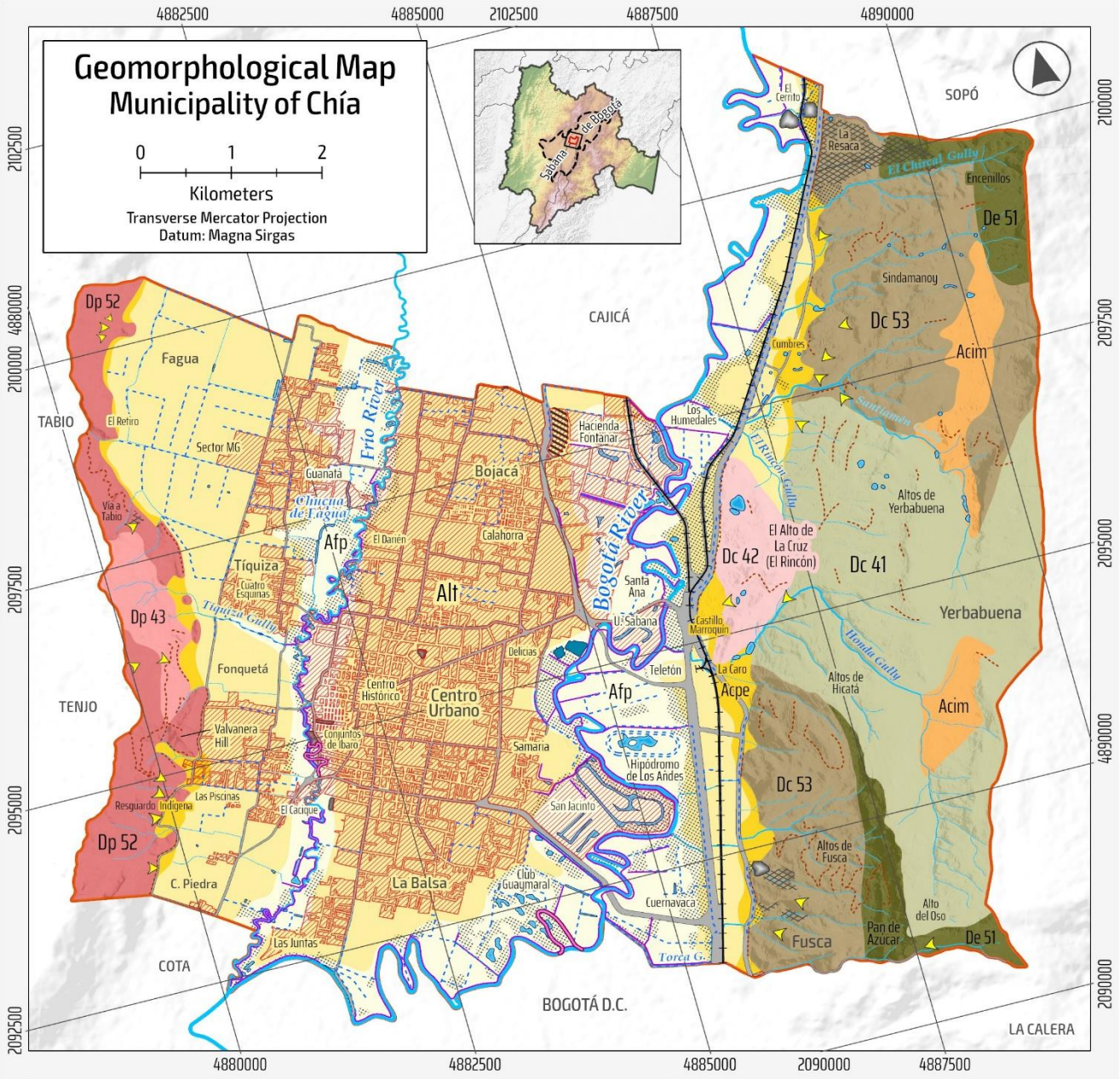
Plain-edge colluvium: It refers to chaotic slope deposits at the interface between the hills and the Savanna of Bogota. The **Acpe** (Accumulative plain-edge colluvial) unit is characteristic of the altitudinal range between 2,570 and 2,600 m a.s.l., has slopes between 3% and 7%, and is partly shaped by torrential debris flow from secondary drainage systems originating in the hills (El Chircal, Sindamanoy, Santiamén, Honda, Fusca, Torca, Tíquiza, among others). These landforms are also indicators of the occurrence of large-scale mass movement events, such as those in the Resguardo Indígena, Las Piscinas, Cumbres, La Caro, and Castillo de Marroquín sectors (Figure 9).

Lacustrine terraces: It comprises large areas of Pleistocene lacustrine clay deposits. The **Alt** (Accumulative lacustrine terrace) unit consists of various terrace levels located primarily between 2,550 and 2,570 m a.s.l. with slopes ranging from 0 to 3% and up to 7% on the terrace slopes. In these environments, processes such as compaction, desiccation, subsidence, rainwater pooling in small depressions, and surface dissection by small streams (Santiamén, El Rincón, Honda, Tíquiza) occur, as well as filling with sediments, biomass, and human intervention. Most of Chía's urban areas are situated on the lacustrine terraces, including the Historic Center.

Fluvial plains forms: These landforms occupy the lowest, flattest, and most depressed areas of the municipality; they correspond to the river valleys shaped by runoff and sedimentation from the Bogotá and Frío rivers. The **Afp** (Accumulative fluvial plain landforms) unit consists of silts and clays from the Chía Formation; it lies at an average elevation of 2,550 m a.s.l., in a flat area less than 3%, and is characterized by active channels, abandoned meanders, levees, riverbanks, and settling basins that harbor chucua-type wetlands (swamps and lakes). Periodic river flooding is common on these plains, with lateral overflows, rainwater accumulation, high water tables, silting of water bodies, channel meandering, and river erosion with lateral scouring. The river plains extend from north to south across the Bogota Savanah.

4.5.3. Current natural and anthropogenic forms

The sixth taxon corresponds to small-scale landforms resulting from continuous natural processes and those generated by human activities, identified through the interpretation of optical satellite images, digital elevation models, orthophotos, and profile analysis, complemented by field observations. The natural forms observed in the study area are the erosional scars present on the slopes of the Cerros Orientales and Cerros Occidentales. Therefore, they were divided as follows: Made Ground (anthropogenic accumulation), Worked Ground (anthropogenic excavation), and Landscaped Ground (urban areas). The sixth taxon is represented cartographically mainly by symbols and pictograms (Figure 9).



1º Taxon	2º Taxon	3º Taxon	4º Taxon	5º Taxon	6º Taxon
Morphostructures	Morphosculptures	Landform patterns	Types of landforms	Types of slopes	Current natural and anthropogenic forms
Quaternary plain and terrace deposits	Fluvial plains forms		Afp	0 - 3 %	Drainage network
	Lacustrine terraces		Alt		Erosion scar
Colluvial-alluvial deposits	Plain-edge colluvial		Acpe	3 - 7 %	Road cuts
	Intramountain colluvium		Acim	7 - 12 %	Artificial canals
Guaduas Formation	El Alto de La Cruz hill		Dc 42	25 - 50 %	Artificial river cut-off
Guadalupe Group	Cerros Occidentales		Dp 43	50 - 75 %	Artificial lake
			Dp 52	> 75 %	Waste pond
	Cerros Orientales		Dc 41	25 - 50 %	Artificial excavation
			Dc 53	50 - 75 %	Quarry mining
			De 51	> 75 %	Artificial mounds
					Modified levees (dikes)
					Railroad embankments
					Road embankments
					Technogenic deposits
					Urban areas

Figure 9. Geomorphological map.

Notable examples of Worked Ground include the sandstone quarries on the lower slopes of the Cerros Orientales, in the Fusca area to the southeast and La Resaca to the northeast (Figure 10a). Other forms include road cuts (Figure 10b), which are common in the Cerros Occidentales in the areas along the road to Tabio, La Valvanera, and Resguardo, and the Cerros Orientales in the Sindamanoy, Altos de Yerbabuena, El Alto de La Cruz (El Rincón), Altos de Hicatá, and Altos de Fusca sectors. Worked Ground also corresponds to a significant anthropogenic depression to the north in the Hacienda Fontanar sector, as well as to numerous artificial channels (ditches), which drain agricultural areas on the terraces (Figure 10c), waste ponds in the Delicias sector, and artificial lakes scattered across various sectors (Figure 10d).

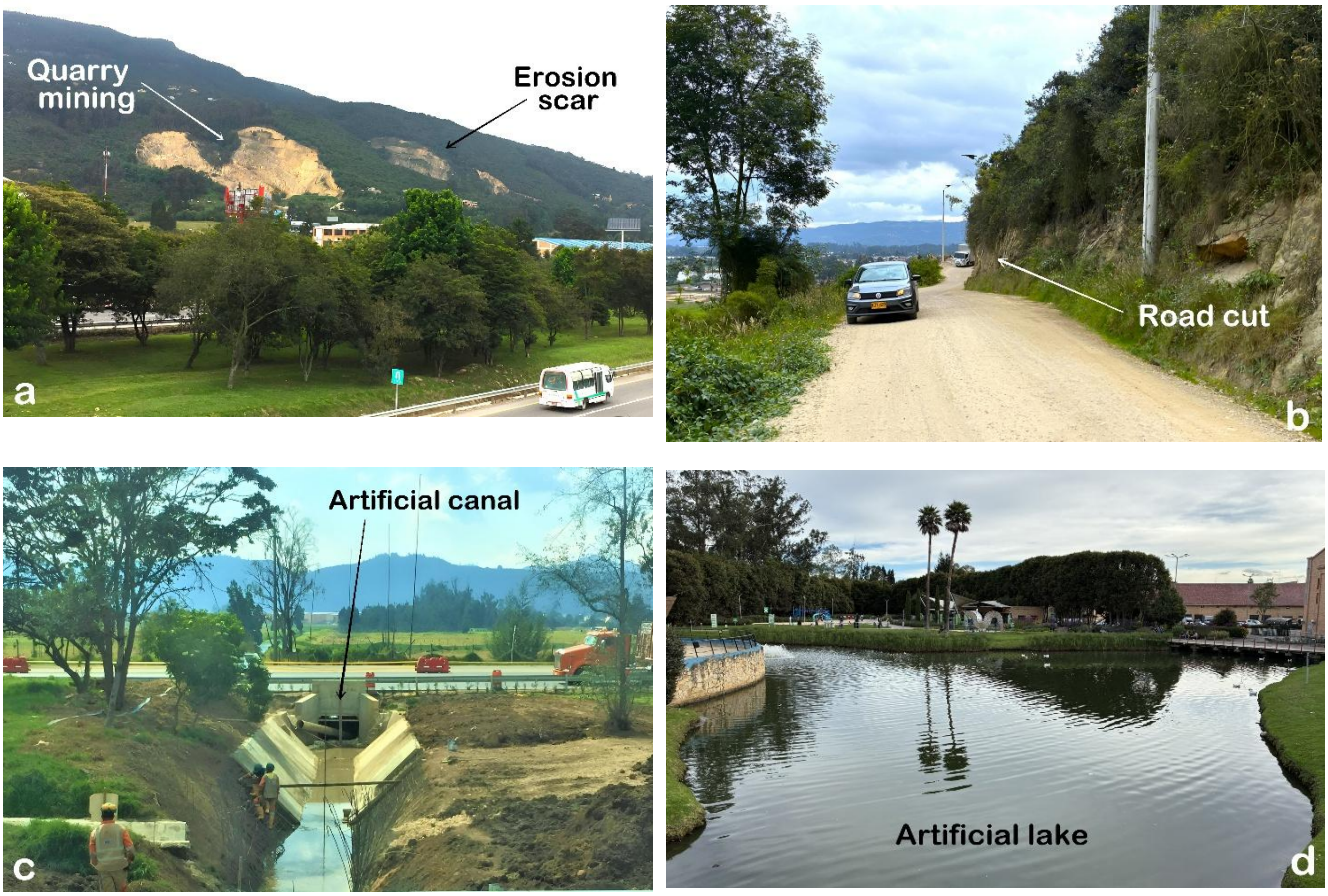


Figure 10. a) Quarrying in the Cerros Orientales of the Fusca sector. b) Road cuts in the Cerros Occidentales of the Vía a Tabio sector. c) Construction of artificial canals near the Los Andes Hippodrome. d) Artificial lakes on the floodplains of the Bogotá River, Santa Ana sector. **Photos**: Authors (2023 - 2025).

Made Ground include river levees (raising and widening), which primarily line the Bogotá and Frío rivers (Figure 11a); These hydraulic interventions are used to prevent overflows and flooding. The urban area has been expanding at a faster pace over the last three decades, progressively encroaching on the floodplains of the Frío and Bogotá rivers; significant landfills composed of various materials, referred to in this work as technogenic deposits, are found there (Figure 11b). In addition, road and rail landfills are also identified on the lake terraces, with wide avenues interconnecting the central urbanized areas; examples of this type of landfill include the Guaymaral Bypass, the road linking Cajicá to Zipaquirá, and the Autopista Norte (Figure 11c).



Figure 11. a) Modified and rebuilt concrete levee (dikes) on the floodplains, Frío River, bordering the Vereda Tíquiza. b) Expansion of urban areas, with artificial excavations and technogenic deposits on the floodplains of the Bogotá River, Samaria sector. c) Landscape featuring road and railway embankments, an artificial canal, and technogenic deposits extending from the lacustrine terraces toward the Bogotá River plain, Cumbres and Los Humedales sectors. **Photos**: Authors (2023 - 2025).

5. Discussion

The main contribution of this study is the application and adaptation of a geomorphological mapping methodology developed in Brazil to an Andean context, demonstrating that its conceptual framework can be transferred to different landforms while maintaining its integrative nature. The methodology integrates morphostructure, morphosculpture, morphometry, slope characteristics, and current landforms (both natural and anthropogenic), providing a comprehensive geomorphological synthesis. This is particularly relevant in Chía, where folded sedimentary rocks, structural landforms, fluvial depositional surfaces, and intense urban transformation coexist.

At the municipal scale, the proposed classification enhances mapping by maintaining the hierarchical relationship between regional geological controls and progressively more detailed landforms. The seven morphosculptural units were organized into ten landform patterns and ten types of landforms, while the dissection characteristics of the fourth taxon were incorporated into the integrated legend. This approach preserves information and avoids excessive cartographic fragmentation. The adaptation of the fifth taxon is particularly significant: since complex Andean slopes could not be satisfactorily delineated at the mapping scale, slope classes were incorporated into the legend, and detailed slope morphology was assessed using topographic profiles linked to lithology. Therefore, the methodology preserves analytical information without compromising map readability.

The sixth taxon represents a scientific advancement, as anthropogenic landforms have been extensively incorporated. This expands Ross's (1992) original framework in line with advances in anthropogenic geomorphology, demonstrating that human-modified landforms can be interpreted as integral components of contemporary geomorphological systems.

Compared to applications in Brazil, where Ross's methodology has been widely used at regional and state scales, this research extends the assessment to a contrasting Andean environment and a municipal scale. The results suggest that the methodology is transferable, although it requires adaptations. Similar applications in other parts of Colombia and in Andean countries should be encouraged, as should the exchange of knowledge with Brazilian geomorphologists. Consequently, the study contributes not only a detailed geomorphological map of the municipality of Chía but also to knowledge transfer among Latin American researchers and the potential expansion of the Brazilian geomorphological mapping methodology to other countries in the region.

6. Conclusions

This study demonstrates the applicability and adaptability of the hierarchical geomorphological mapping methodology developed by Ross (1992) to the Andean context of the municipality of Chía, Colombia, extending its application beyond the Brazilian environments where it was originally developed and widely applied. The primary scientific contribution lies in the evidence that the hierarchical organization, comprising morphostructure, morphosculpture, morphometry, slope characteristics, and current landforms (both natural and anthropogenic) can be maintained in a geomorphologically distinct region.

The main methodological contribution consists of adapting the fifth taxon and expanding the sixth taxon to account for the complexity of Andean terrain and contemporary anthropogenic landscapes. Since the fifth taxon could not be satisfactorily represented cartographically at the chosen scale, slope characteristics were incorporated into the integrated legend and complemented by topographic profiles linked to lithology. The sixth taxon was expanded through the explicit incorporation and classification of anthropogenic landforms, thereby enhancing the methodological framework's capacity to represent contemporary geomorphological systems.

Therefore, the study demonstrates that Ross's (1992) hierarchical framework is not restricted to a specific national geomorphological context. Its conceptual structure can be transferred to other South American environments through methodological and technical adaptations, providing a consistent basis for comparative and multi-scale geomorphological mapping.

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Conflito de Interesse: Os autores declaram não haver conflito de interesse.

Declaração de uso de Inteligência Artificial: Os autores declaram que nenhuma ferramenta de inteligência artificial generativa foi utilizada em nenhuma fase do desenvolvimento deste manuscrito.

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