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Summit typology and detailed geomorphological landscape units mapping through the application of direct and indirect methods. A case study in the Sierra de Guadarrama National Park, Spain

Tipología de cumbres y cartografía de unidades detalladas de paisaje geomorfológico mediante la aplicación de métodos directos e indirectos. Caso de estudio en el Parque Nacional de la Sierra de Guadarrama, España

García Esteban, R. [1]

(1) Departamento de Geografía, Universidad Autónoma de Madrid, 28049 Madrid, España. roberto.garcia@uam.es; rogaeste@gmail.com

Abstract

This paper analyzes the topography and the geomorphological characteristics of the central sector of the Sierra de Guadarrama (Spanish Central Range) from the point of view of the geomorphological landscape. Using Digital Elevation Models (DEM) and topographic maps, the aim is to supplement conventional geomorphological analysis by applying indirect morphometric methods for the detailed study of landforms through topographic analysis in order to obtain maps of diverse morphometric parameters, resulting in an exhaustive study, which is useful and revealing both in terms of geomorphology and of landscape. The morphometric maps obtained for each variable, such as the density of the dissection, the depth of the dissection and the energy of the relief, are overlaid on the derived maps from the DEM using Geographical Information System (GIS). Their analysis, using both indirect and direct methods during several field studies, in combination with the geology and the geomorphology of the study area, allows a more accurate study of the unit delimitation of the geomorphological landscape at a detailed scale. In a mountainous environment with smooth and apparently homogeneous summits, this detailed study of the geomorphological landscape shows the existence of different types of summits. The results are presented as a typology of summits and a map synthesizing the detailed units of geomorphological landscape that can be found in the Sierra de Guadarrama National Park (Central Spain).

Key words: geomorphology; geomorphological unit; morphometry; mapping; landscape; Sierra de Guadarrama.

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Resumen

Este trabajo analiza la topografía y las características geomorfológicas del sector central de la Sierra de Guadarrama (Sistema Central Español) desde el punto de vista del paisaje geomorfológico. Mediante el uso de Modelos Digitales de Elevación (MDE) y cartografía topográfica, se pretende complementar el análisis geomorfológico convencional con la aplicación de métodos morfométricos indirectos para el estudio detallado de las formas del terreno a partir del análisis topográfico para obtener mapas de diversos parámetros morfométricos que resulten reveladores y útiles en el estudio exhaustivo tanto de la geomorfología como del paisaje. Los mapas morfométricos obtenidos para cada variable, como la densidad de la disección, la profundidad de la disección y la energía del relieve, se superponen a los mapas derivados del MDE utilizando Sistemas de Información Geográfica (SIG). Su análisis en combinación con la geología y la geomorfología de la zona de estudio, tanto por métodos indirectos como directos durante varios trabajos de campo, permiten un estudio más preciso en la delimitación de unidades de paisaje geomorfológicas a escala de detalle. En un ámbito montañoso con cumbres suaves y aparentemente homogéneas, este estudio detallado del paisaje geomorfológico reveló la existencia de diferentes tipos de cumbres. Los resultados se presentan como una tipología de cumbres y un mapa que sintetiza las unidades de detalle del paisaje geomorfológico que se pueden encontrar en el Parque Nacional de la Sierra de Guadarrama (centro de España).

Palabras clave: geomorfología; unidad geomorfológica; morfometría; cartografía; paisaje; Sierra de Guadarrama.

1. Introduction

In the integral study of the natural landscapes of a mountainous area, the relief and the geomorphological processes acquire special prominence. The relief is the structure or skeleton of every natural mountain landscape. In this sense, depending on the scale of the study, other components such as vegetation, geomorphological elements or physiography are often the basis for the configuration of the landscape.

The study of the landscape requires the examination of each of these components both together as well as separately (Bolós, 1992; Antrop, 2000; Bertrand *et al*., 2006; Martínez de Pisón, 2009, 2010, 2014). For this purpose, direct or indirect methodologies, or combinations of both have traditionally been used (Loures *et al*., 2015; Mayoh and Onwuegbuzie, 2015).

The first to appear were the direct methodologies (1970s), which are based on the subjective evaluation of landscape aesthetics based on sensory perceptions such as visual or sound (Arthur *et al*., 1977). However, some authors began to emphasize the need for quantitative landscape measurements to define indicators of landscape evaluation that would contribute to a conceptual framework for landscape planning (Tveit *et al*., 2006; Ode *et al*., 2008). In this way, indirect methods were developed that analyze the distribution of landscape components (vegetation, orography, etc.) whose combination defines the elements of the natural landscape.

Advances in geographic information technologies in recent decades have made possible more accurate studies, and sometimes reveal information that was previously difficult to access, among many other aspects. Indirect methods have increased since the advance of Geographic Information Systems (GIS) at the beginning of the 21st century (Perk *et al*., 2007; Veronesi and Hurni, 2015), and a series of study factors were established and their impact on the landscape was evaluated (Martínez-Graña *et al*., 2017). For these reasons, a comprehensive study of the landscape requires multidisciplinary teams capable of analyzing each of these components separately, but without losing the overall picture. In this sense, geographers are well placed to provide an overarching point of view (Martínez de Pisón, 2009).

The Sierra de Guadarrama mountains have attracted the attention of many researchers and a large amount of work and research has been carried out on the fundamental components that composehe natural landscape of the mountains in the study area, such as its relief, the vegetation cover, its geomorphology, and even the morpho-tectonic evolution of the whole mountain range in which it is inserted (Bullón, 1988; Sanz, 1988).

However, the studies focused on the landscape and the delimitation of landscape units are scarce in general. Throughout the last few decades, especially since the declaration of the European Landscape Convention signed in Florence on October 20th, 2000, the landscape began to be considered as another resource to be protected, benefited from and preserved (European Landscape Convention, 2000). This resulted in the proliferation of landscape studies during the last three decades. Consequently, many of the components, such as geomorphology or vegetation, were reviewed and studied again in this region (Pedraza *et al.,* 2004; Bullón, 2006; Palacios *et al*., 2012; García-Esteban, 2019). This, together with the technological advances (remote sensing and geographic information systems), allowed new contributions with more accurate and detailed studies complementing the knowledge of previously well-studied areas (Smith and Pain, 2009; Florinsky, 2017).

The principles underlying the methodology proposed and applied in this manuscript belong to the set of methodologies that are being used in a major project in the Sierra de Guadarrama. This overall methodology has been applied in other studies in some regions of Spain (Martínez de Pisón *et al*., 2001, 2008) and is based on the dissociation of each of the main components of the physical environment (vegetation, physiography, geomorphology, etc.) for their separate analysis and subsequent association. Landscape units are obtained from the interaction, combination, and integrated analysis of each of the components (Martínez de Pisón *et al*., 2001; Bertrand *et al*., 2006).

In this sense, the methodology proposed in this paper corresponds to the methodology applied in the overall project for the study of the geomorphological characteristics of the natural landscape in a mountainous area. In the morphometric analysis of topography, relief and geomorphological processes, indirect quantitative methods, as a complement, were applied.

Taking into account the topography and relief of the study area and starting from the existing geomorphological maps from the Spanish Geological Survey (IGME), the objective of the current paper is the presentation of a new map of detailed units of the geomorphological landscape.

This work presents both the procedure of the analysis of the topography and the relief at a specific, local or large scale (Zhang *et al*., 2015), as well as the results of the quantitative morphometric analysis of the main characteristics of the relief of the central sector of the Sierra de Guadarrama. These results are very useful in the delimitation of detailed geomorphological units in the study area and are also relevant in the classification of different types of summits.

All this information is essential in order to understand the geomorphological characteristics of the natural landscapes of this mountainous area, which was declared a National Park in 2013 due to its natural value.

2. Materials and Methods

2.1. Study area

The study area is located in the Sierra de Guadarrama, in the Spanish Central System. This is the central sector of the Sierra and it is here that the highest altitude of all the Guadarrama mountain range is reached by Peñalara peak, at 2,428 meters above sea level (m a.s.l.). Within this region an area of 51,728 hectares has been defined, which constitutes the study area shown in Figure 1.

The studied area is a mountainous domain formed by elevated blocks, *i*-horts or "pop ups"[1] that form two large mountain ranges; one in E-W orientation, i.e. the Cuerda Larga range (Cabeza de Hierro, 2,380 m a.s.l.); and another contiguous and almost perpendicular to it, in a NNE orientation, which corresponds to the southern half of the Montes Carpetanos (Peñalara, 2,428 m a.s.l.) (Fig. 1 and 2).

These two mountain ranges, together with the Sierra de la Morcuera, which is outside of the study area, frame the Upper Lozoya River Valley. A tectonic trench, *i*-graben or "pop down" that sinks between the elevated blocks of the two mountain chains previously mentioned and that closes it, forming an isolated or closed intramountain valley unique in all the Guadarrama and important in the configuration of the landscape of these mountains.

A third small mountain range, Siete Picos (2,138 m a.s.l.), extends the study area towards the west, between the passes of Navacerrada (1,860 m a.s.l.) and Fuenfría (1,796 m a.s.l) as a continuous rocky outcrop (Fig. 1).

2.1.1. Geomorphological features, geological context, and tectonic background

In general terms, and differentiating several sectors and tectonic styles, the uplift of the Spanish Central System is interpreted as a great "pop up", which would represent the external limit of the system of compressive structures associated with the Betic orogeny linked to Alpine tectonics, and as a result of a "thin-skin thrust tectonic" which would affect the upper part of the crust (Banks and Warburton, 1991; González Ubanell, 1994; Pedraza, 1994; De Vicente *et al*., 2019).

The Cenozoic Age saw the formation of the relief of the Central System, mainly during the Lower Oligocene-Miocene, as a consequence of the intra-platform compressive stresses that caused a series of dipping faults which raised the Variscan basement over the Duero and Madrid basins in a system of "pop up" and "pop down", forming the current specific morphotectonic structure which the sector of the Sierra de Guadarrama presents within the Central Hispano-Portuguese System. Active dipping faults are only detected in the westernmost part of this intra-platform chain, in the Portuguese section (De Vicente *et al*., 2007, 2019; De Vicente, 2009).

There is also an asymmetrical arrangement between the N and S edges which delimit this ante-country or intra-plate chain: in the south, basically by means of a large fault (the Cabalgamiento del Borde Sur, with a vertical displacement of more than 5 km), while in the north, it appears to be more distributed by means of a series of thick-skinned imbricated thrust faults (De Vicente, 2009). Similarly, after the alpine phases, the two basins have remained at different altitudes, with the northern one remaining higher and, as a result, an increase and intensification of river erosion in the southern area due to the lower base level of the Madrid basin.

According to the Geological Map of Spain (MAGNA) of the IGME, at 1:50,000 scale (Sheets 457, 458, 483, 484, 508 and 509), the materials found in the area of study are divided into three large rock groups (Fig. 2). On one hand, there are the ancient crystalline rocks of the Variscan massif of which the raised blocks or "pop ups" are composed and

1. Nowadays, the terms "pop up" (raised block) and "pop down" (sunken block) are used to refer to the elevations and depressions that occur between two dipping faults of opposite vergence, through inverse faults, in regions of compressive tectonics. The aim is to differentiate this type of elevations and depressions from the terms "horst" and "graben" limited by normal faults associated with extensive tectonics. The "*i*" in *i*-horst and *i*-graben means horst and graben through inverse fault.

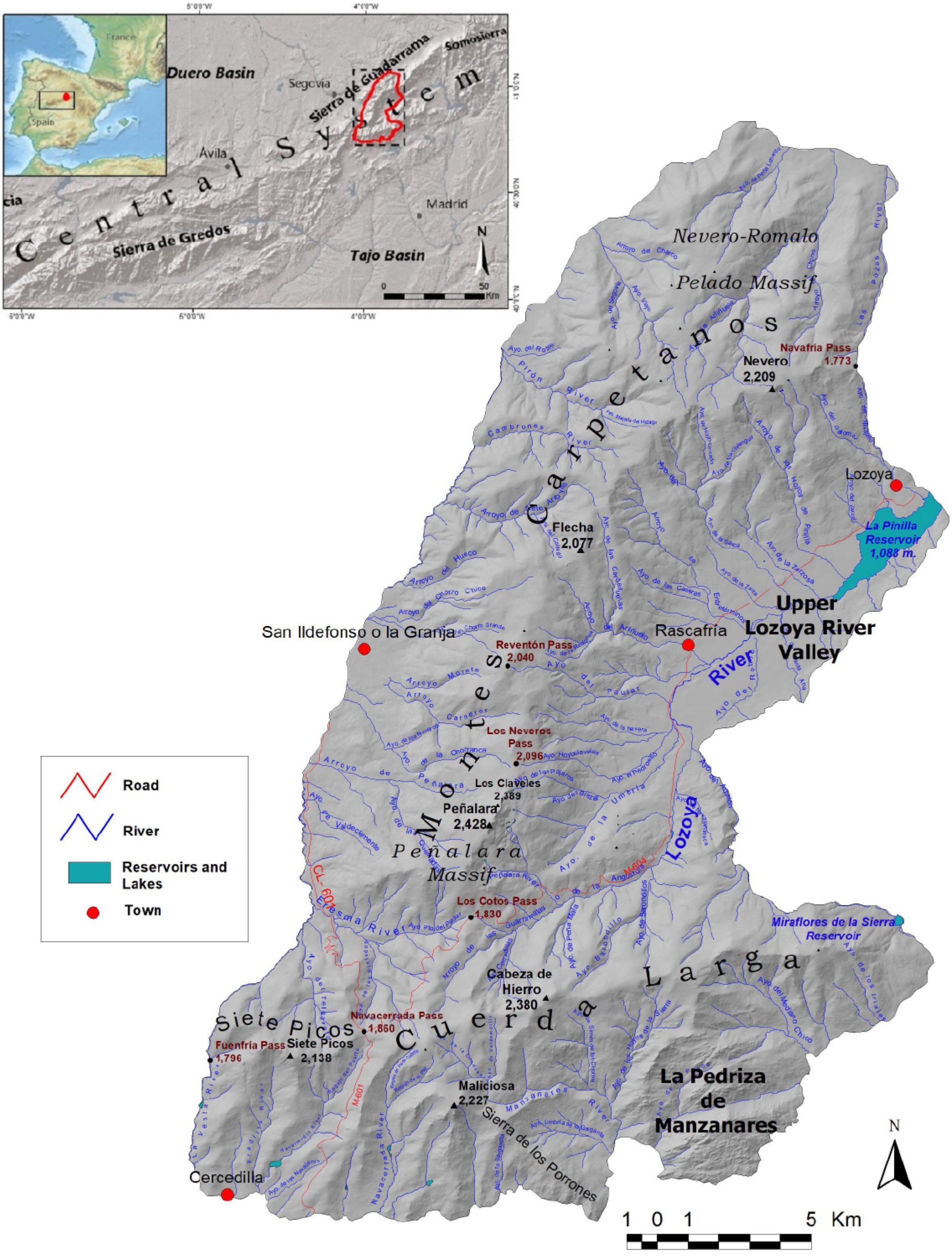

Figure 1: Study area location.
Figura 1: Localización del área de estudio.

which in the area of study can be divided in turn into two large geological groups: the prehercynian metamorphic rocks (gneissic domain) and the hercynian granitic rocks (granitic domain). And on the other hand, there are the sedimentary rocks.

The first set, the metamorphic rocks, correspond to the materials which underwent metamorphism during the Variscan orogeny in its different phases. The glandular orthogneisses are the most abundant, but also melanocratic glandular orthogneisses and leucocrates gneiss. In all of them, intrusions of philonian rocks, especially aplites, can be found.

The second unit that completes the crystalline rocks of the study area is the one constituted by the granitic materials.

These are plutonic rocks formed by intrusions. There are four types of granite which are most abundant: Adamellites with occasional amphibole, coarse-grained porphyritic (southwestern sector of the study area); oriented porphyritic adamellites (southern sector of the study area); biotitic adamellites (central sector of the study area); and coarse-grained leucogranites, type La Pedriza, (southern and south-eastern sector). Here you can find all kinds of shapes and microforms characteristic of granite such as tors, boulders, alterites, tafonis, panholes, among others.

The third large group of rocks in the area of study are the sedimentary rocks, belonging to the Mesozoic and Cenozoic (IGME).

Cretaceous sediments are found in the eastern sector of the study area (Fig. 2 and 3). They are mainly sands, clays, sandstones with dolomitic cement, gravels and dolomites which originated in the Mesozoic seas where several transgressions and regressions of the Cretaceous sea took place. They are often found on the right bank of the Lozoya Valley (Karampaglidis *et al.*, 2015).

The Cenozoic materials are mainly found on the opposite side, i.e. on the left bank of the valley. They are mainly composed of conglomerates of blocks and pebbles from the Paleogene as well as blocks and pebbles from the Middle and Upper Miocene, which appear here in direct tectonic contact with metamorphic materials (glandular orthogenesis) due to the inverse fault through which the "pop down" sank.

Finally, the study area also includes materials from the Quaternary, where we find the scarcely developed terraces at the bottom of the Lozoya river valley, composed mainly of gravel, sand and silt.

The rest of the deposits are mainly located on mountain peaks and slopes. On the summits, they usually form active periglacial terraces and small solifluidal slides (Sanz, 1988; Bullón, 1988, 1995; García-Esteban, 1998; Palacios *et al.*, 2012), while on the slopes they generally appear as alluvial sediments, such as sand, silt, gravel and pebbles of a polygenic nature (granite, gneiss, quartz, etc.); colluviums in areas of quarries or scree, formed fundamentally by sand, pebbles and blocks; and morainic deposits, very heterometric materials, blocks, pebbles and gravel, not very organised and angular, a product of Quaternary glacial activity. The latter belong to the moraines of the circus glaciers that were scarcely developed here and are found in some places such as the Laguna Grande de Peñalara or Pepe Hernando's cirques. These moraines are not only well preserved, but also form a relevant, unique and valuable part of the characteristics of the natural landscapes of the study area (Fig. 3).

2.2. Methodology

2.2.1. Data sources

There is an extensive bibliography on the study of the Guadarrama relief and geomorphology processes, as well as other components of the physical environment. Among the most relevant works about this sector of the Guadarrama mountain closely related to the pur-

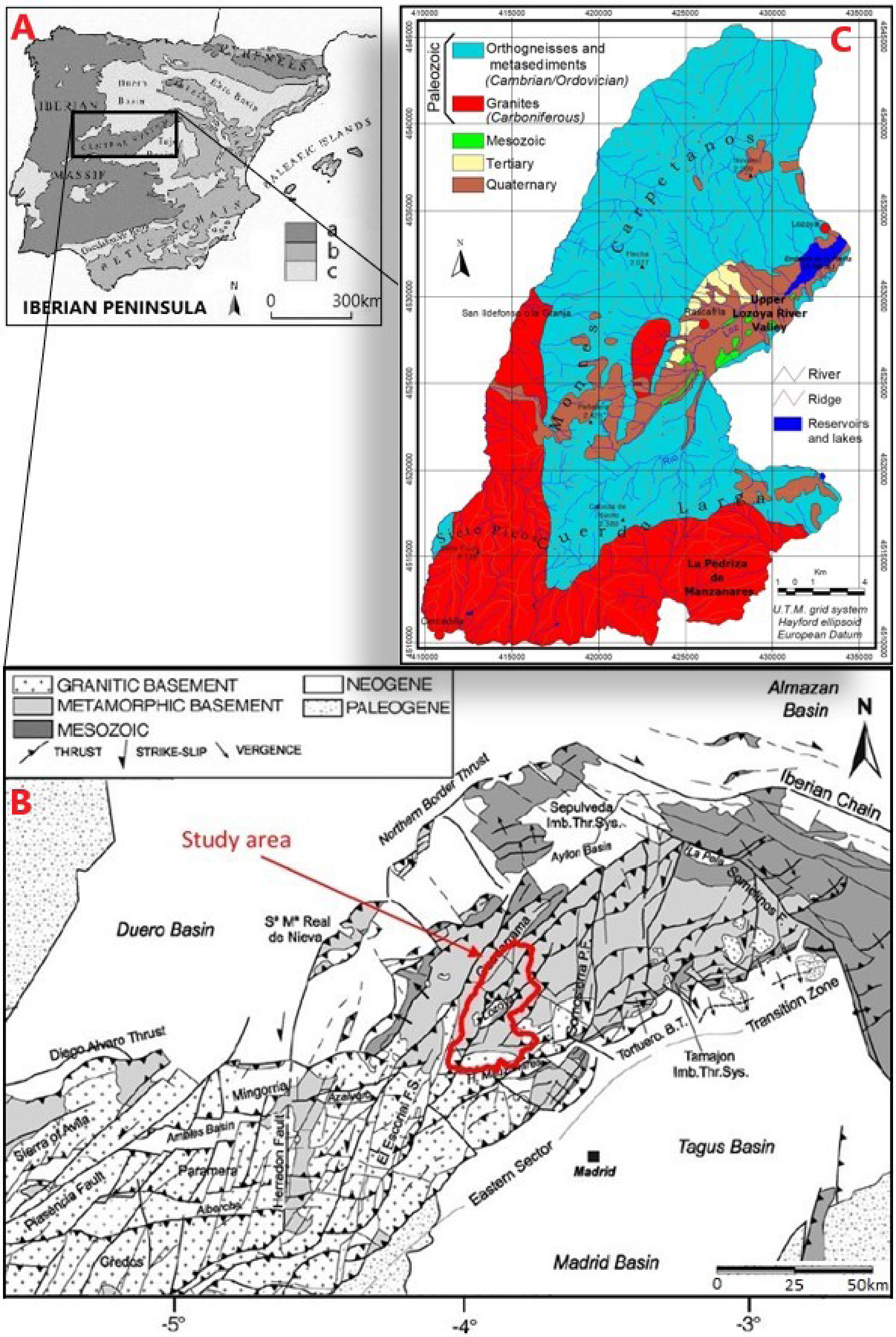

Figure 2: (A) Spanish Central System location within the Geological Iberian Regions: (a) Variscan basement; (b) Alpine orogens; (c) Cenozoic basins; (B) Tectonic map of the Cenozoic Central Ranges of Western Iberia (Modified from De Vicente et al., 2007); (C) Simplified geological map of the study area (Based on the Geological Map of Spain, MAGNA, IGME).

Figura 2: (A) Localización del Sistema Central dentro de las Regiones Geológicas de la Península Ibérica: (a) Basamento Varisco; (b) Orogenos Alpinos; (c) Cuencas Cenozoicas; (B) Mapa tectónico de las cadenas Cenozoicas Centrales del Oeste Peninsular (Modificado de De Vicente et al., 2007); (C) Mapa geológico simplificado del área de estudio (Basado en el Mapa Geológico de España, MAGNA, IGME).

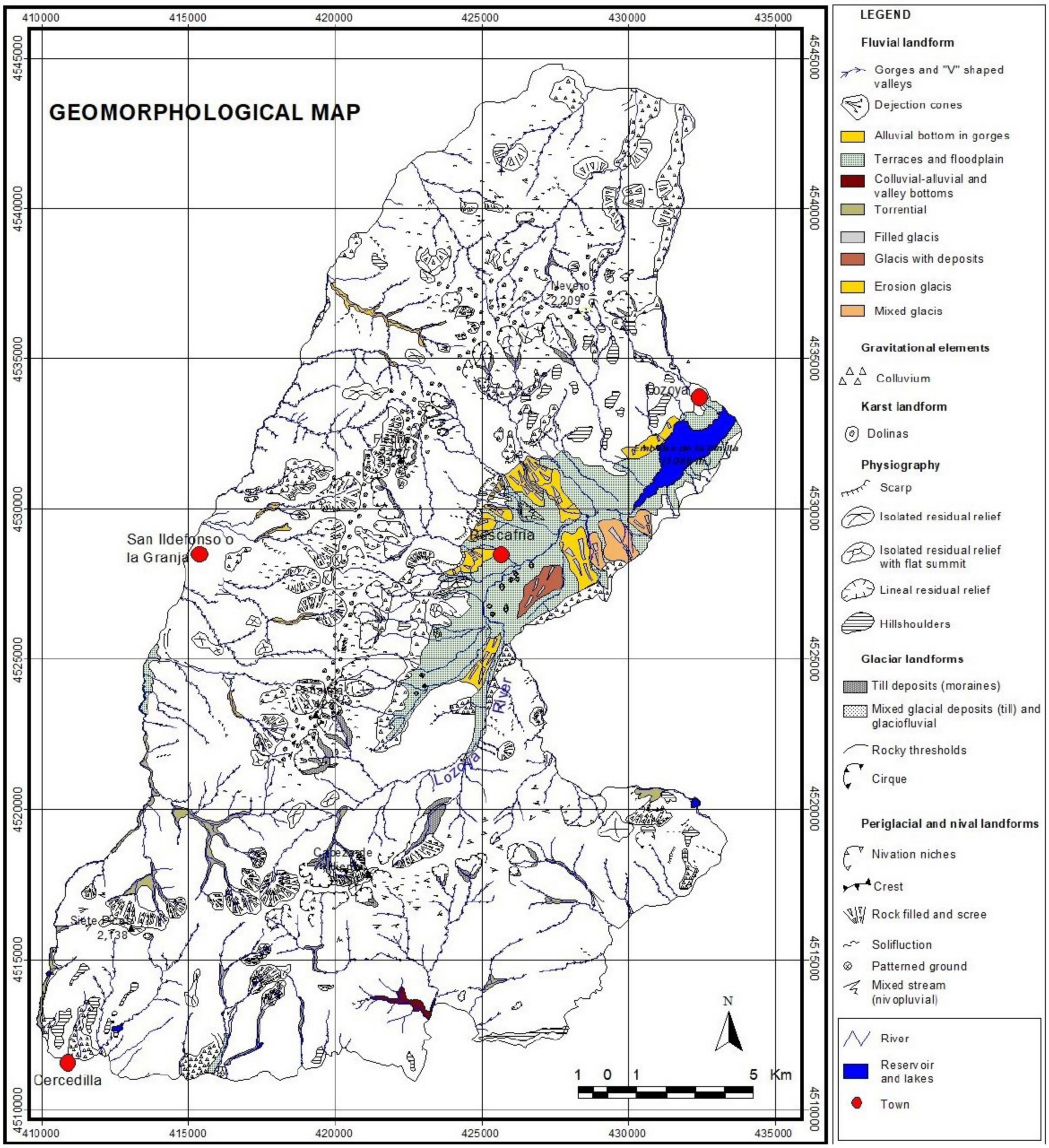

Figure 3: Geomorphological map of the study area (Based on Bardají *et al*., 1990; Pedraza *et al.*, 1990; Bardají *et al*., 1991; Fernández *et al*., 1991; Pedraza *et al*., 1991 and Sanz *et al*., 1991. MAGNA, IGME).

Figura 3: Mapa geomorfológico del área de estudio (Basado en Bardají et al., 1990; Pedraza et al., 1990; Bardají et al., 1991; Fernández et al., 1991; Pedraza et al., 1991 and Sanz et al., 1991. MAGNA, IGME).

poses of this study are: Centeno *et al.*, 1983; Bullón, 1988; Sanz, 1988; Capote *et al.*, 1989; Martín-Serrano, 1994; Pedraza, 1994; Carrasco *et al.*, 1996; Pedraza *et al*, 2004; Vegas, 2006; De Vicente, 2009; Palacios *et al.*, 2012. Among the data sources for the study of topography and relief, this research is based on the use of the National Topographic Map (MTN) from the National Geographic Institute of Spain (IGN) at 1:50,000 (Sheets 457, 458, 483, 484, 508 and 509) and 1:25,000 scales (MTN50 and MTN25, respectively) and the DEM of the National Geographic Information Center of Spain (CNIG). Features of the DEM: Geographic Reference System (GRS) ETRS89 (compatible with WGS84); UTM projection; 5 meters resolution; Download file in ASCII ESRI format (.asc).

Both MTN25 and MTN50 were used for deriving the less complex maps from the DEM namely hillshade, slopes and altimetry. MTN25 and MTN50 (were further used for the analysis, interpretation and main value collection from the three main relief morphometry maps (Fig. 4).

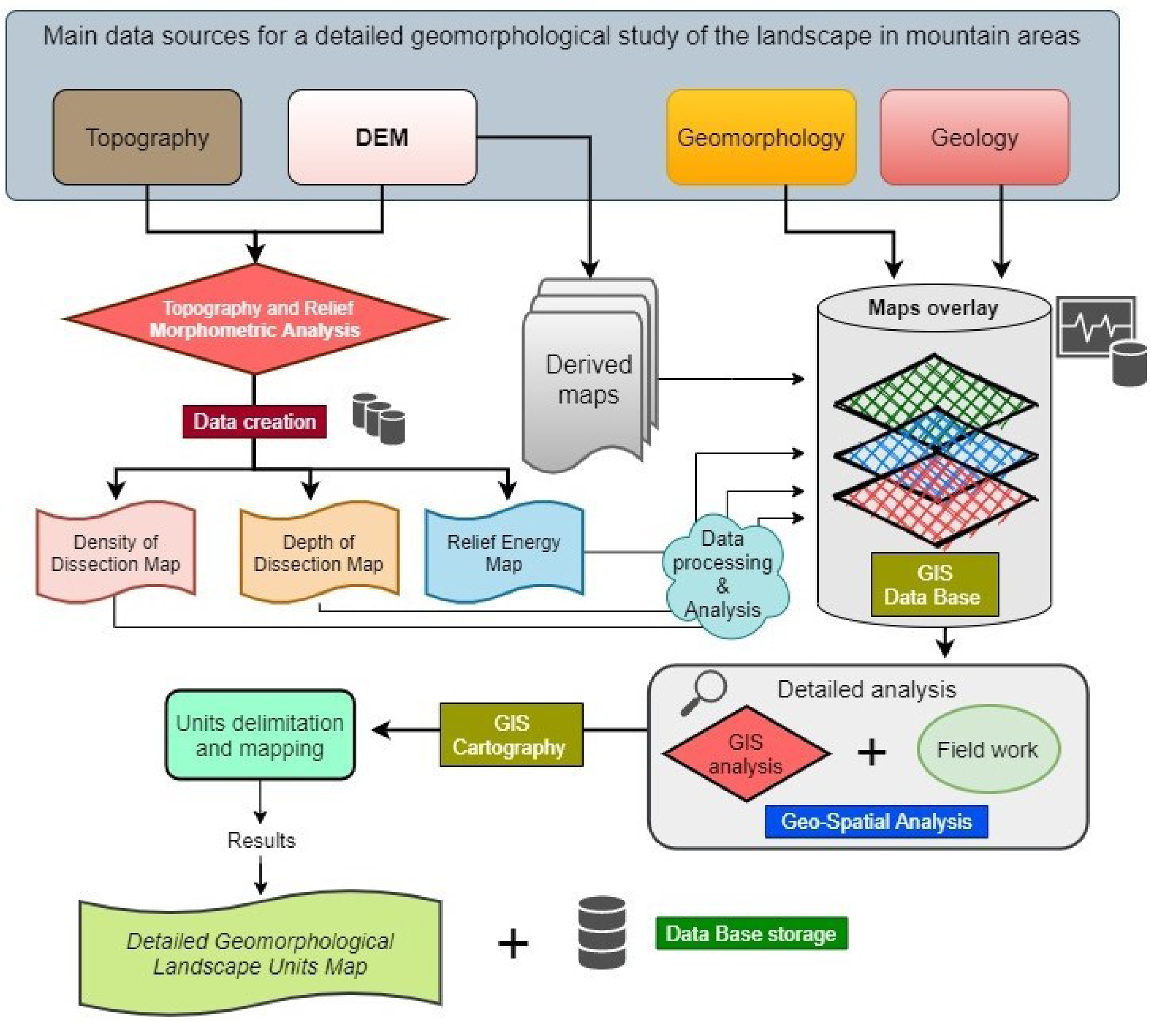

Figure 4: General methodology of the manuscript.
Figura 4: Metodología general del manuscrito.

In the same way, this research is grounded in the study of existing thematic maps of the most significant natural aspects of the landscape, such as geological maps from the IGME (Sheets 457, 458, 483, 484, 508 and 509 of the MAGNA Series at 1:50,000 scale) and aerial photographs published by the Ministry of Territorial Policy of the Autonomous Community of Madrid.

2.2.2. Basic relief maps. DEM and derived maps

The area of study was defined following the contour line that marks the break in the slope at the foot of the elevations (approx. 1,200-1,300 m a.s.l). Only the lower areas corresponding to the Lozoya "pop down" in the upper valley remain as flatter areas. The first maps created are the most basic and derived, such as the hypsometric map, the slope or the hillshaded (Fig. 5) which nowadays are easily obtained with the automated tools offered by the Geographic Information Systems (GIS) from the digital elevation model (DEM) of the study area (Moore *et al*., 1991; Deng, 2007). GIS make it easier and faster to calculate and chart maps derived from the DEM (Veronesi and Hurni, 2015). In this work, ArcGIS (ESRI) was used. Based on the DEM, and utilizing a series of tools already created (Slope and Hillshade Tools in *spatial analyst tools> surface* menu) in a simple and automatic way, it is possible to obtain all the basic derived maps of the relief.

2.2.3. Morphometry

Morphometry or geomorphometry is the quantitative analysis of the earth's surface. Among its fundamental variables are altimetry, slope, and drainage density; although many more can be formed depending on morphodynamics and morphogenesis. Morphometric methods have long been used in many fields for the study of relief and geomorphology processes (Hengl and Reuter, 2008; Florinsky, 2017). Its application considers the vertical and horizontal resolution and applies interpolation algorithms as well as derivative calculations and smoothing of its results (Goudie, 2004). The data processing can be done with different computer programs and GIS. In this study mainly Excel, Surfer, and ArcGIS were used.

This paper applies indirect quantitative morphometric methodologies using the DEM and topographic information as a complementary methodology to the geomorphological analysis. The products of this type of analysis are morphometric maps, which are useful in studies of slope evolution, erosion assessment and susceptibility to hazards (Peña Monné, 1997). The morphometric methods used are based on the works of Simonov (1985) and Lugo Hubp, (1988). This methodology is based on the division of space into grids with UTM coordinates of 1 km², allowing work at the scale of 1:25,000 and 1:50,000 to obtain good surface data (Lugo Hubp, 1988). The three variables used are the dissection density, dissection depth and the energy of the relief.

To obtain the density and depth values of the dissection, the National Topographic Map was used at 1:50,000 scale, whose resolution UTM grid is 1 km².

— Dissection density values: this density is obtained by the summation of all the measured lengths of the rivers, streams or talwegs in kilometers (length) taken per square kilometer (area).

— Dissection depth values: this value corresponds to the maximum depth from the central axis of the talweg to the steepest slope break. This map reflects the greater or lesser intensity in time of the fluvial processes, depending mainly on the lithological, tectonic, structural and bioclimatic characteristics (Lugo Hubp, 1988).

The same grid has also been used for the Energy of Relief Map and the area of study has been divided into the same one-kilometer squares. For each one of them a numerical value is obtained that results from the amplitude of the relief.

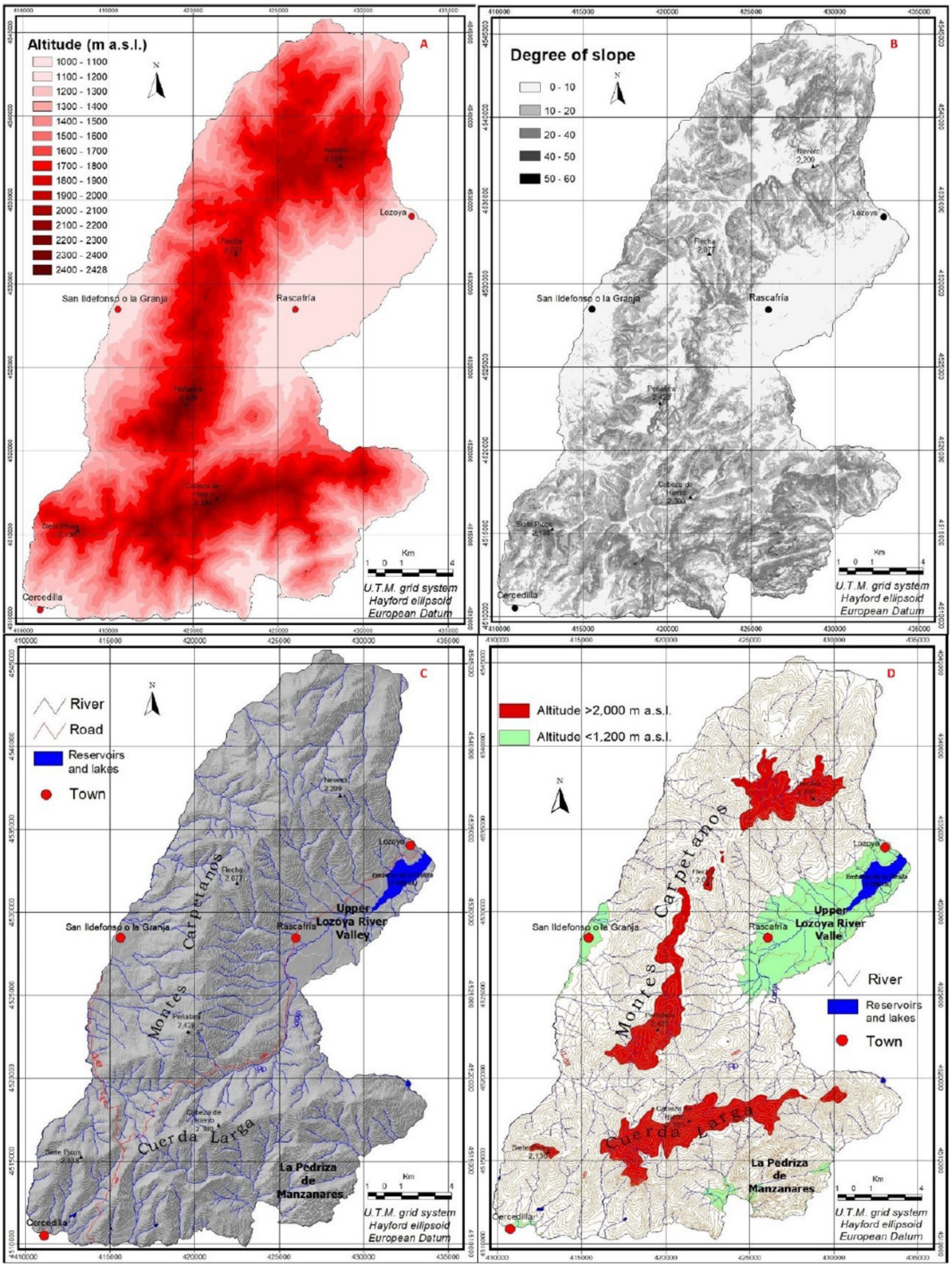

Figure 5. Basic maps of the relief characteristics and derived maps: (A) DEM; (B) Slope; (C) Hillshaded; (D) Areas above 2,000 m a.s.l. and below 1,200 m a.s.l. of the study area. (Based on the National Center for Geographical Information DEMs, IGN).

Figura 5: Mapas básicos de las características del relieve y derivados: (A) MDE; (B) Pendientes; (C) Sombreado; (D) Áreas por encima de 2.000 m s.n.m y por debajo de 1.200 m s.n.m. del área de estudio. (Basado en el MDE del Centro Nacional de Información Geográfica, IGN).

— Energy values: The difference between the maximum and minimum altitudes in meters was calculated in each of the grids and its value was noted. These values can be obtained manually or automatically using GIS. In this case, the amplitude values of the relief, the DEM was used by automated procedures.

Once the values for each 1 km² grid are obtained, a data matrix is produced for each of these variables. These matrices or tables are introduced in x,y,z files of any valid format for the program with which they are going to be processed, where the value of z corresponds to the value of each of the variables studied. In this case Excel sheets were used to be able to process the data in different software. The procedure continues with the data interpolation to create each of the variables. In this case the data was interpolated using the method of kriging (Ordinary), an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with z-values (Calaña-Azcuy and Belete-Fuentes, 2014; ESRI, 2020).

After their interpolation, the respective maps were generated with the different morphometric variables that were used for the analysis and interpretation of the geomorphological study and the relief of this mountainous area's natural landscapes.

The method of analysis of these three maps of morphometric variables is based fundamentally on the overlapping and combining of each one of them with other layers such as the lithology, slope or geomorphological elements, using GIS.

2.3.3. Geomorphological landscape units mapping

The methodology for the geomorphological units mapping is based on the analysis of geomorphological processes and landforms, for the identification and delimitation of homogeneous areas, both in terms of geomorphological elements and dominant modelling (Demek *et al.*, 1972; Demek and Embleton, 1978; Peña Monné, 1997; Bertrand *et al.*, 2006; Dramis *et al*., 2011; Knight *et al*., 2011; Verstappen, 2011).

The geomorphological landscape units were obtained, fundamentally, from the morphometric analysis of the relief and especially from the analysis of the overlapping and combining of each of the variables obtained with other layers of information such as lithology, derived from DEM maps and geomorphological elements (Bardají *et al*., 1990; Pedraza *et al*., 1990; Bardají *et al*., 1991; Fernández *et al*., 1991; Pedraza *et al*., 1991 and Sanz *et al*., 1991) using GIS.

By overlapping all these geoinformation layers with the geological component and the geomorphological elements, and analysing it in detail, areas of similar geomorphological characteristics can be defined and, in this way, geomorphological units can be mapped (Demek and Embleton, 1978; Peña Monné, 1997; Dramis *et al*., 2011).

Indirect methods for the analysis of relief, topography and morphological elements were complemented with direct methods, with several field works allowing a more detailed study of the geomorphological landscape (Loures *et al*., 2015). Laborious and continuous field work was as important as it was necessary and fundamental as part of the direct methods in the detailed analysis of the landforms. These works were mainly based on survey and reconnaissance hikes, sampling and photography.

3. Results

3.1. Morphometry

3.1.1 Map of Dissection Density

This map (Fig. 6) shows the fluvial density in the studied area. The highest values correspond to the slopes. In a mountainous area

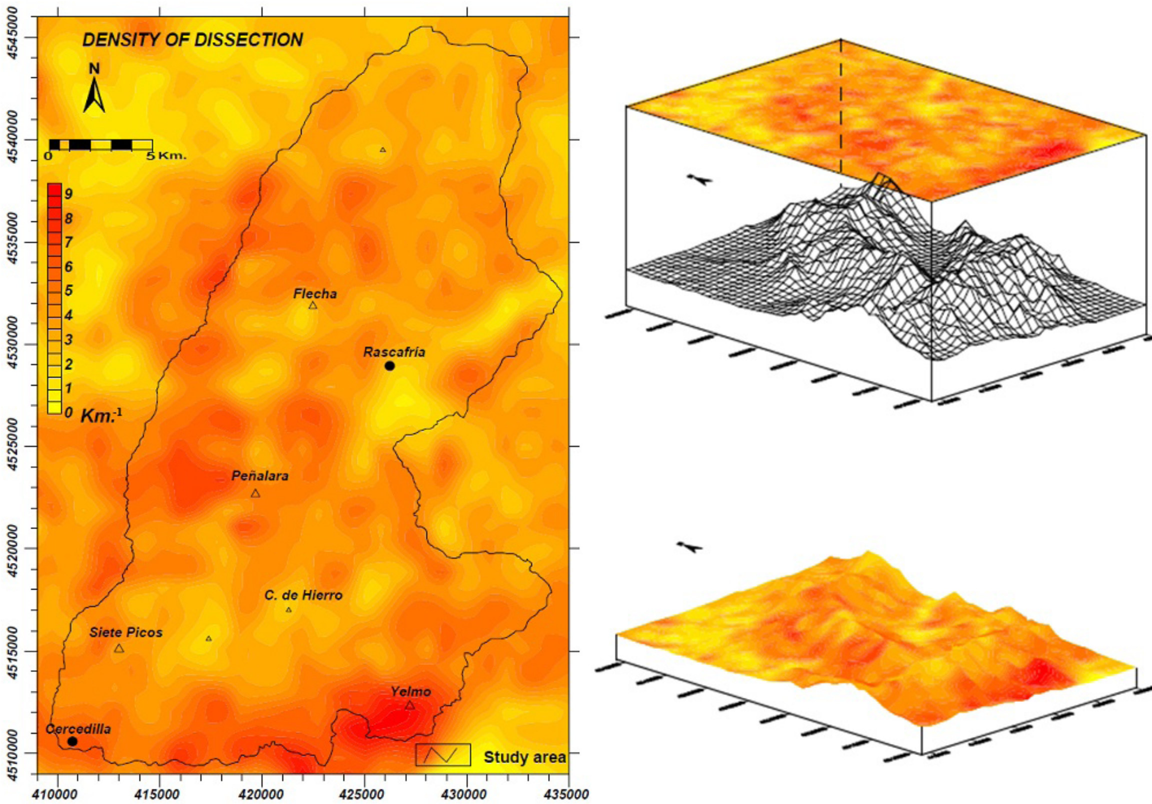

Figure 6: Map of Dissection Density.
Figura 6: Mapa de Densidad de la Disección.

with high morphotectonic control, the tendency is to concentrate the fluvial processes exploiting the weakness lines.

While in the largest area of the study with similar values, they show a clear tectonic control, as the runoff makes the most of the fracture network, which decreases the dissection density, in other sectors, the high tectonic-structural and lithological control is what determines this high density of the relief's dissection, as is the case for the granitic outcrop of La Pedriza de Manzanares. As a result of this and after an exhaustive analysis, among the areas with higher density of dissection, the following can be highlighted:

— The southeast, the Pedriza de Manzanares area: This is related to the intense fracturing and jointing, with the geomorphology and roughness of this sector. The lithological and structural control here is fundamental. Due to the impermeability of the rocky substratum and the intensity of the fracturing, the fluvial system runs through the dense morphological and lithostructural weave looking for the lines of weakness by gravity. As this happens, the regolith is evacuated, creating numerous valleys and small incisions in a wild environment where we also find strong encasements. These frequently create cliffs, gorges and other small corridors and nooks and crannies that have a great impact on the landscape.

— The western side of the Peñalara massif: In relation to features such as the mixed nivoperiglacial dynamics in the high slopes.

— The northern zone, near the Pirón River headwaters: Elevated and flattened summits that allow the formation of small valleys and streams. These are concentrated in incised gorges that cut through the morphostructural steps that articulate the entire study area.

In contrast, the areas with lower dissection density generally correspond to the summit areas. This is primarily due to the fact that they naturally act as watersheds but also to other factors such as lithology, morphogenetic evolution or the protection against erosion offered by the snow cover accumulated during winter. Among these areas, the lower values of the eastern central sector summits of Cuerda Larga —in the southern third of the studied area— stand out as a consequence mainly due to their convex and rounded morphology, and the bottom of the valley of the main river, Lozoya River, which concentrates all the density of dissection in a single talweg.

3.1.2. Map of Dissection Depth

The dissection depth map (Fig. 7) depicts the greatest depth of incision of the most prominent watercourses in each 1 km² cell into which the study area has been divided.

In this case, it is clearly visible that the area with the highest density of dissection does not coincide with the area with the greatest dissection depth, as in the case of the Pedriza de Manzanares. Despite being one of the areas with the highest density of dissection, it is clear that in a large part of the area, its

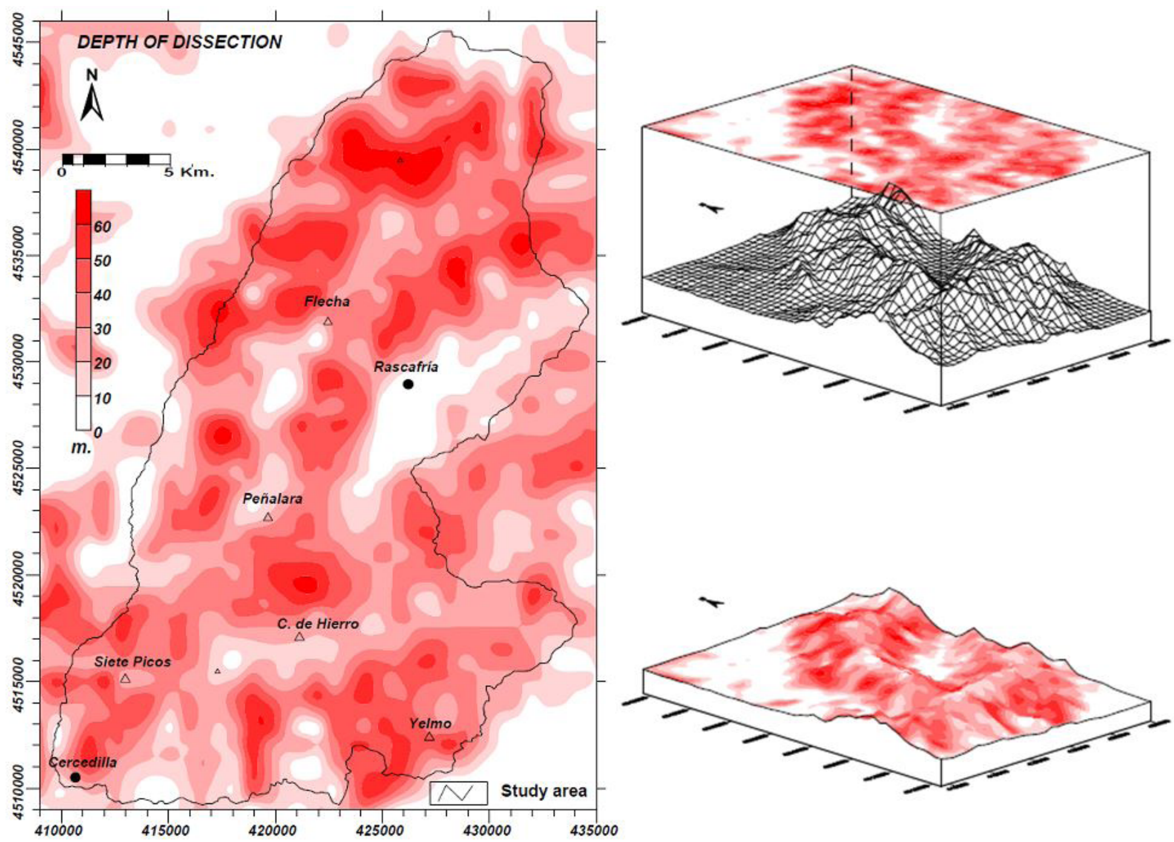

Figure 7: Map of Dissection Depth.
Figura 7: Mapa de Profundidad de la Disección.

courses do not show great depth in the river bed, except in the main gorges.

In general, the northern area stands out for its greater extension and concentration of high values of depth of dissection. This zone corresponds to the area of the Nevero-Los Pelados massif and the strong incision of the courses that dismantle it such as the Viejo stream, the Artiñuelo stream and the Las Pozas river in the northern slope; or the Palomar stream, the Hoyos de Pinilla stream and the Sauca stream in the southern one (Fig. 1). These last streams, in the southern slope, are embedded in the numerous torrential and colluvial deposits on their way down to the Lozoya River.

The remaining areas with greater dissection depth are more scattered. They also reveal the main gorge locations and the pronounced embedding fluvial encasements. They are located in the southern sector of the study area, because in their connection with the piedmont slope of the Madrid basin they have to overcome a greater unevenness. However, this not only happens in this sector but also on some of the Carpetanos' slopes that drain towards the Lozoya "pop down" giving rise to deep incisions.

Therefore, it can be seen how in the "pop up" of the Carpetanos a strong embedding in the pronounced slopes is produced, exploiting the fracture network and cutting the morphostructural steps. Normally, when the river beds leave these steps, the slope weakens severely and as a result some torrential cones appear.

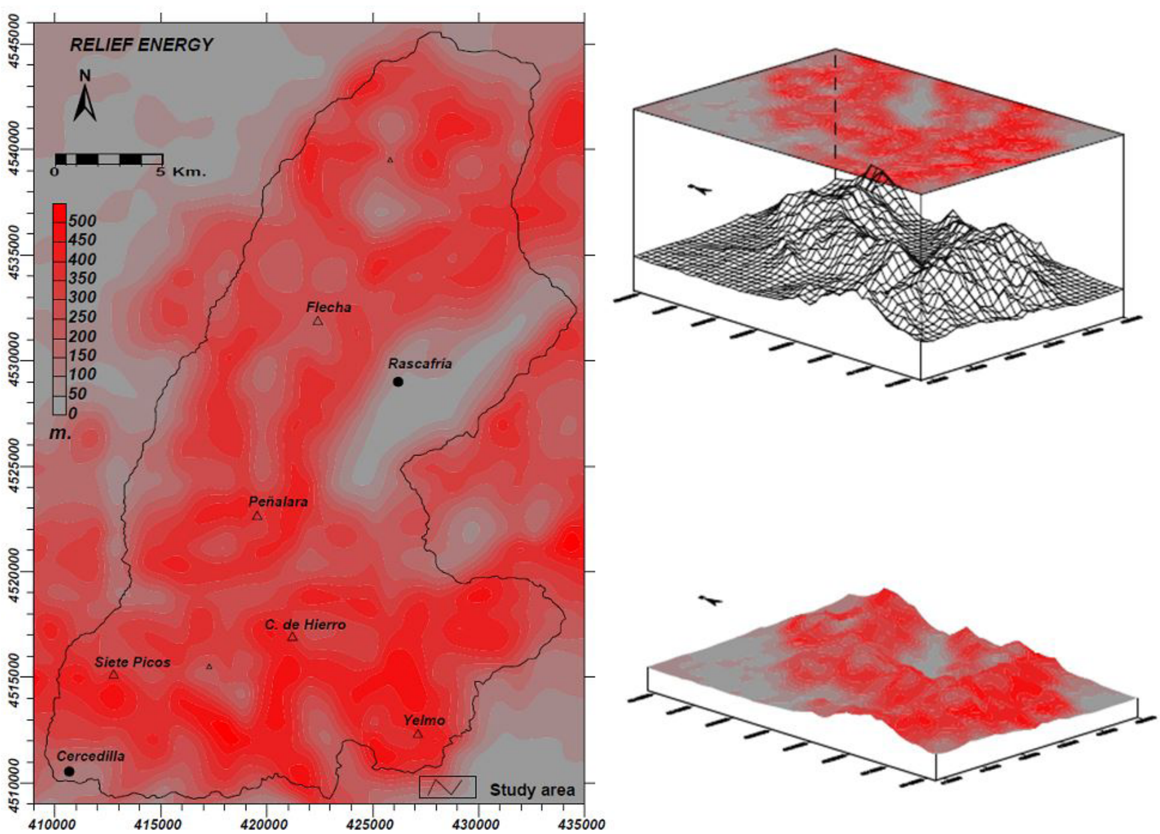

Figure 8: The Energy of the Relief Map.
Figura 8: Mapa de Energía del Relieve.

In the southern sector of Siete Picos and the Cuerda Larga, the perpendicular disposition of these strongly incised rivers is observed, creating incised rectilinear valleys such as the Pradillo River or the Gargantilla stream, and other deep incisions such as the Majadilla Stream in La Pedriza.

3.1.3. The Energy of the Relief Map

Two considerations can be extracted from this map (Fig. 8): first, the differentiation between the main "pop ups" and the Lozoya "pop down", represented by maximum and minimum values, respectively; second, the map prompts us to a possible deduction of the arrangement of the main blocks that form the "pop ups" which form the major alignments of the area of study.

High values of energy or amplitude of the relief are also observed, for example, in the "pop up" of the Carpetan Mountains. These values fully coincide with: incised and deep valleys; glacial morphological elements such as cirque walls; and also with the strong unevenness produced between the morphostructural steps of the high slopes and the medium and low slopes.

The clearest result in this map is the difference between the two main alignments that make up the framework of the studied area: the Montes Carpetanos "pop up" —their southern half— oriented NNE and NE; and in the southern sector, those of the Cuerda Larga and Siete Picos, which follow the E and ENE orientation (Fig. 1). As can be observed, in the southern area corresponding to the Siete Picos and the Cuerda Larga mountains is where the highest values of the energy of the relief are concentrated. In both the Siete Picos and the Cuerda Larga mountains, the northern slopes share greater similarities with those of the "pop up" of the Carpetanos while it is in the southern slopes where we find the greater values of amplitude of the relief.

The Carpetanos "pop up" shows lower than average values.

3.2. Map of detailed geomorphological landscape units

As a result of this study, the following detailed geomorphological landscape units of the study area were obtained and mapped (Fig. 10).

3.2.1. Summits and high hillsides. Summits Typology.

The summits and high slopes of the study area are mostly above 1,850-1,900 m a.s.l.

Although it is true these mountains have been extensively worn and eroded throughout its geological history and, therefore, offers a mountain silhouette with smooth and rounded peaks, the results of this research reveal that this is not always the case. These profiles of smooth and hilly summits culminate in a narrower and more rugged way more frequently than was previously thought.

Within the three main groups of summits, the third group is further subdivided into three types, totalling five types which are described below (Fig. 9):

- Flattened wide summits

The wide flattened summits occupy the largest area among all the summits in the study area (Fig. 9-1). This is due not only to the fact that it is the typical peak morphology of the entire area, but it is also due to the special development in width that this summit unit reaches in certain sectors of the Montes Carpetanos alignment, as evidenced by the low slopes. The peaks of the Nevero-Romalo Pelado massif, in the north of the study area, or Dos Hermanas in Peñalara Massif, are two of the most representative examples of this type. In fact, it is in the gneissic lithology sectors where this type of summit acquires a greater width, although it is true that most of the summits are also gneissic substrate, except those of the Siete Picos. In the Cuerda Larga, the lithological limit of granites and gneisses almost coincide, but the dividing line is still gneissic (Fig. 2). In the latter mountain, the

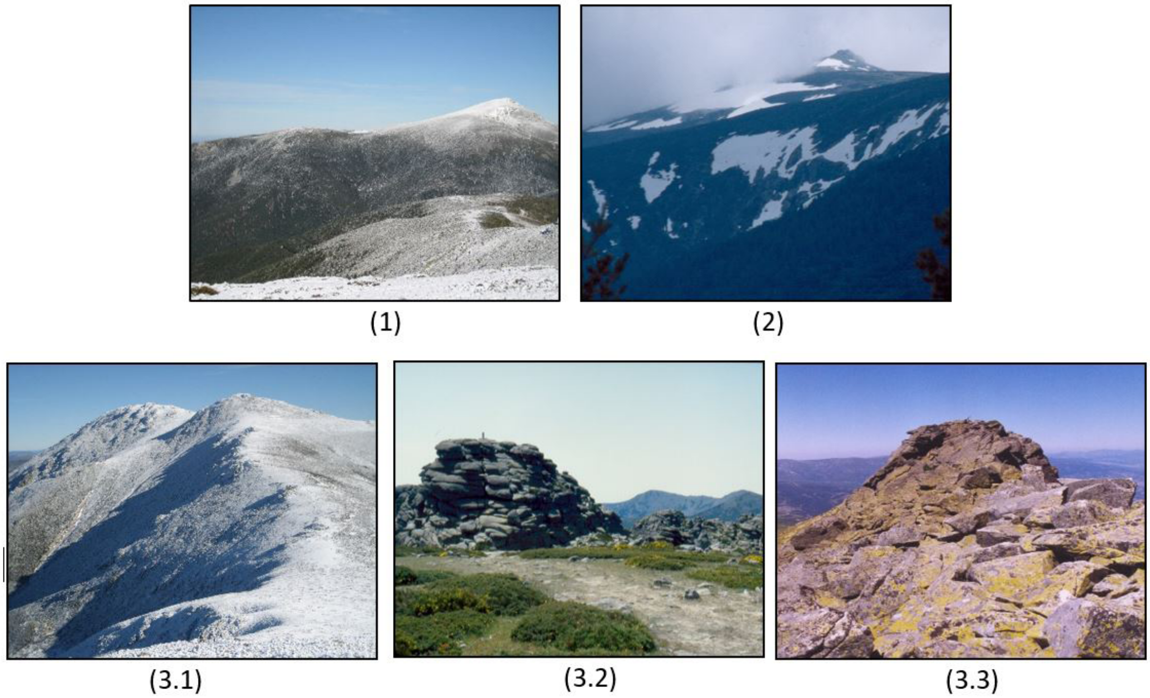

Figure 9. Summits typology of the study area: (1) Flattened wide summits (Dos Hermanas, Peñalara Massif); (2) Cirques and nivation niches with nivo-periglacial modelling (Hoyo Poyales cirque from Reventón Pass). (3) Narrow rounded and flattened summits with rocky outcrops: (3.1) Small scattered rocky outcrops along the summits (Cuerda Larga); (3.2) Tors (Siete Picos); (3.3) Crests and crags (Los Claveles crag).

Figure 9. Tipología de cumbres del área de estudio: (1) Cumbres amplias y aplanadas (Dos Hermanas, Peñalara Massif); (2) Circos y nichos de nivación con modelado nivo-periglaciar (Circo de Hoyo Poyales desde el Puerto de Reventón); (3) Cumbres estrechas, redondeadas y aplanadas, con afloramientos rocosos: (3.1) Pequeños afloramientos rocosos dispersos a lo largo de las líneas de cumbre (Cuerda Larga); (3.2) Tors (Siete Picos); (3.3) Crestas y riscos (Risco de Los Claveles).

rounded and flattened surfaces of the summits are less extensive and discontinuous, and always with slopes below 10 degrees.

- Cirques and nivation niches with nivo-periglacial modelling

This type includes the zones with the glacial and periglacial elements that are in the highest hillsides linked with the summits (Fig. 9-2). Several criteria have been taken into account to group elements typical of glacier modelling in the same unit with elements generated by periglacial processes.

This is mainly due to the limited development that these elements acquire separately in the study area and that it is not enough to constitute entities with the category of units as such.

Another reason for this grouping would be not only the age of the forms but also that of the operating processes. Although it is clear that the glacial elements correspond to the proper forms generated by the Pleistocene glacial processes that affected the Guadarrama mountain in the past, the periglacial elements can be attributed to current processes, which in many cases continue to act on the inherited glacial modelling. As a consequence of this, this work proposes to group both elements, glaciers and periglacial, in the same unit, taking as the main criterion of union that both elements are part of the high mountain modelling.

Among the elements of glacial morphology, the glacial cirque stands out. The most important examples of these are the Laguna Grande de Peñalara and the Pepe Hernando cirques, in the Peñalara massif. Most of the other cirques show little development.

Most of these cirques have developed above 2,000 m a.s.l., some on lower altitudes, and on previous morphologies favourable to the snow accumulation, placing their accumulation zones between 2,000-2,300 m a.s.l. Their terminal moraines extend from 1,700 to 1,900 m a.s.l., and even lower as in the Hoyo Poyales cirque or that of the Arroyo del Artiñuelo stream, where the moraine fronts reach 1,600 m a.s.l.

The representative glacial and nivoperiglacial elements in the geomorphological landscape are completed by: thresholds, moraines and mixed glaciofluvial deposits, glacial landforms; and nivation niches, crests, scree slopes, blockfields and block corridors, as periglacial elements (Fig. 3).

- Narrow rounded and flattened summits with rocky outcrops

This typology shows similar characteristics to the rest of the summits in the area. They differ in that they represent narrower summits and according to the results obtained through the morphometric analysis of the relief, with slightly higher slope values. From the average maximum slope of 10 degrees in the type of wide summits (Fig. 9-1), it becomes 15 degrees in this type.

In addition, this type of summit is characterized by the presence of a series of rocky outcrops. Due to their morphology, distribution, representativeness and importance in the configuration of the natural landscape of the study area, these types of summits are further subdivided into the three following types of summits:

— *Small scattered rocky outcrops along the summits*

These rocky outcrops are scattered along the summit lines as small residual reliefs. They are composed of gneissic lithology with a marked tendency to weather into slabs. The gneissic rock outcrops are elements associated with the smooth surfaces that appear on summits and hills throughout the area. They are divided into a different typology due to their importance in the configuration of the natural landscape by highlighting more in this type of narrow rounded and gentle summits (Fig. 9-3.1). They are very significant in the shape and texture of the summit landscapes.

This type of summit is found on the peaks of the Cuerda Larga range that, although equally smooth and rounded, are narrower than those of the other unit. This typology coincides with the highest levels of this mountain range, Cabeza de Hierro (2,380 m a.s.l.) and Cabeza de Hierro Menor (2,376 m a.s.l.).

— *Tors*

These rock formations are found scattered in many places, but on the hill summits and due to their disposition, they stand out in the Sierra de Siete Picos.

A tor, also locally known as *tolmo*, is a free-standing rocky outcrop that rises abruptly from the surrounding smooth slopes of a rounded hill summit. They are typical of the rocky projections of strongly fractured massifs (Fig. 9-3.2). In the study area, they appear abruptly crowning the gentle culminations of the Siete Picos granite mountain range in the southwest of the study area, giving them a more abrupt physiography in contrast to the rounded summits on which they root. In addition to these formations, there are also other hemispherical landforms in the study area since many of the summit domains such as Siete Picos or La Maliciosa-Camorritos are open domes due to the distension, typical of the summit domains.

While there are tors in other localities of the study area, their delimitation and mapping were not considered as units due to their significant dispersion.

— *Crests and crags*

Crests and crags appear where the summits become most narrow. The flattened and rounded summits are replaced by rocky projections configured by the presence of blocks in a chaotic arrangement from intensely fractured bedrock, forming crests where the process of frost shattering takes place (Fig. 9-3.3). They differ from the previous types in that these crests and crags do not rise abruptly from the surrounding smooth slopes of a rounded hill summit. They present a very pronounced unevenness that directly links the steep slopes of the block's chaotic arrangement that form the crest with the acute slopes of the high hillsides.

In the study area, these peaks are found in the configuration of the high mountain landscape in the central zone in the Peñalara Massif, in the vicinity to the north of Peñalara peak (2,428 m a.s.l.), on the crag named as Los Claveles (2,389 m a.s.l.).

3.2.2. Polygenic foothills with valleys and hillshoulders

The summits of the mountain foothills correspond to this unit and are articulated from the main alignments which present flat areas and cols at different altitudes, often culminating in rocky outcrops. With a morphology at the summit similar to the high mountain peaks, they also present periglacial activity. This unit is configured where this type offers a greater concentration and it is represented and mapped in a set of separate elongated polygons, each corresponding to the summit surfaces of each foothill or spur.

This occurs in two areas: in the southern area, the southern slope of the Siete Picos-Cuerda Larga mountain alignment; and in the northeast area, the southern slope of the Nevero massif. The summit surfaces of mountains such as Camorritos, Los Porrones or Cuerda de las Milaneras, with the top sectors of Cerro de los Hoyos-Torre de los Buitres, frame the Circo de la Pedriza Posterior, correspond to this unit.

3.2.3. Heavily fractured rocky outcrops with granitic modelling

This unit corresponds entirely to the Pedriza de Manzanares. Located in the extreme southeast of the study area, this large rocky outcrop formed by coarse-grained leucogranites, presents a pattern so characteristic of this type of lithology that it considerably stands out in the landscape. This rocky area, which is part of the southern foothills of the Cuerda Larga, acquires great relevance in the configuration of the natural and geomorphological landscapes of this area. Its marked fractures and dense jointing are perceptible at any scale. This also favours the effectiveness of the erosive agents, forming a rocky area with a labyrinthine appearance. Here a great variety of granite landforms are found at all scales (macro-meso-microforms).

3.2.4. Hillslopes with generalized fluvio-torrential and gravitational modelling

This unit makes up the rest of the hillslopes in the area. These are generally rectilinear surfaces, only interrupted by small inflections; and scarps with steep slopes, only modified by the generalized fluvio-torrential and gravitational modelling. This morphology of hillslopes is strongly related to the large faults that articulate the relief of the area and, therefore, linked to the structural characteristics of the tectonic blocks that make up these mountainous massifs. The main landforms have a fluvio-torrential or gravitational origin.

In this sense, by means of the morphometric analysis of the relief carried out with the methodology applied in this study, morphological differences have been detected in some of the torrents, streams and rivers in the area. Consequently, in this larger unit three typologies are differentiated that give rise to three sub-units or more detailed geomorphological landscape units.

- Generalized fluvio-torrential and gravitational modelling

This is the unit to which most of the hillslopes of the study area belong. It coincides with the previous general explanation regarding the morphology and forms of fluvial modelling generated by the linear incision of torrents, streams and rivers. That is, scarp surfaces with fluvial modelling typical of the upper river course. The other type of modelling that generally identifies this unit are the gravitational deposits: colluvial material deposited in the middle and lower parts of the slopes, caused by gravity but sometimes regulated, to a greater or lesser extent, by other processes such as flash floods or solifluction.

- Deep fluvio-torrential modelling and gorges

Within the generalized modelling of the hillslopes, certain elements of fluvial modelling stand out. This unit is formed by elements of fluvio-torrential modelling that with greater development in depth present a more incisive morphology on the stream bed, forming gorges. It is important to note that among those not selected there are gorges with very steep slopes but which are wider, which in turn allowed the development of an alluvial- colluvial bottom.

In the study area, this unit is represented in the Arroyo de la Gargantilla stream, whose source is found in the southern vicinity of La Maliciosa (2,227 m a.s.l.), in the southern area of the study area; in scattered gorges of the head of the Eresma River, in the western sector of the Montes Carpetanos; in the northwest, with the Pirón River gorge; and to the north, with the headwaters of the Arroyo Viejo and Artiñuela streams, both in which take advantage of the fracturing system and contribute to the erosion and dismantling of the Nevero-Romalo Pelado massif.

- Flat-bottomed rectilinear fluvial corridors

This corresponds to valleys of linear or rectilinear morphology with a tectonic origin, like most in the area, where the watercourse descends on a flat bottom with greater or lesser width and with mostly mixed, colluvial and torrential deposits, giving rise to a physiography of wide valleys despite the steep slopes of the hillslopes. Within the limits of the area, the bottoms of the valleys of the La Venta River located in La Fuenfría valley, and the Navacerrada River southwest of Maliciosa, both in the southwestern sector of the study area, belong to this unit.

3.2.5. Intramountain valleys

The intramountain depressions correspond to this unit. In the study area there are two types of this class of depressions: an isolated or closed one, which is almost completely located within the perimeter of the studied area and play an important role in the configuration of the natural landscapes corresponding to the "pop down" or Alto Lozoya´s trench; and an open one, of smaller dimensions, that reaches the contact with the piedmont slope of Duero basin and that corresponds to the head of the Eresma valley or Valsaín´s depression. Of the latter, only its right bank falls inside the limits of the study area.

- Closed intramountain depression. Upper Lozoya Valley

This is the best example of intramountain "pop down" found in the whole Sierra Guadarrama as well as being the only isolated or closed tectonic trench found in the entire Central System.

This whole set was articulated in the alpine deformations as a consequence of the intraplate compressive forces that caused a series

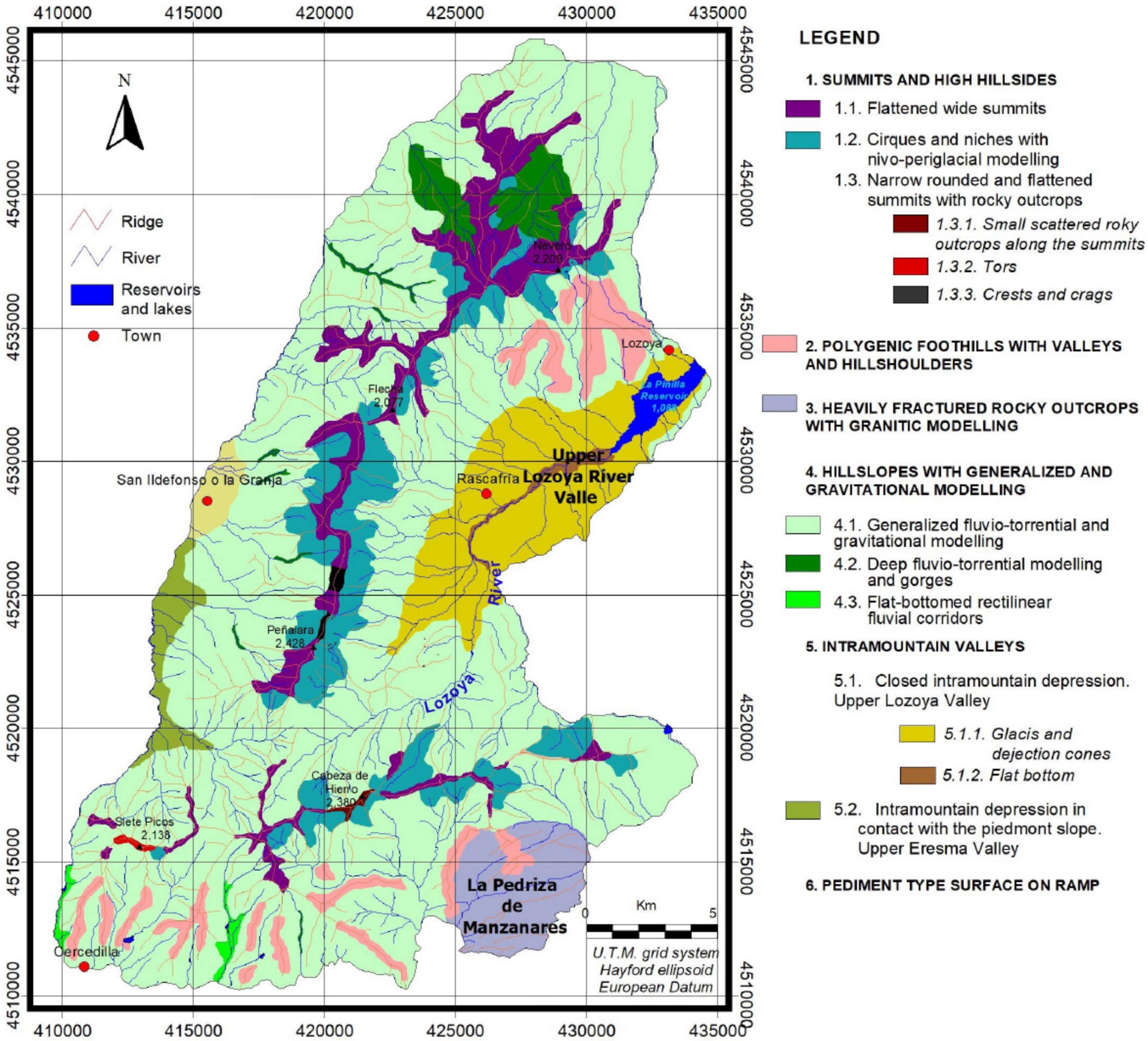

Figure 10: Map of detailed geomorphological landscape units.
Figura 10: Mapa de unidades geomorfológicas detalladas.

of thrusts that raised the Variscan basement over the Duero and Madrid basins in a system of "pop up" and "pop down" by means of a system of large faults, with a NE direction. These faults frame the trench within the upthrown blocks between two thrusts of opposite vergence.

Currently, a smooth topography at the center is shown at the bottom of the valley and somewhat more inclined at the edges in the glacis area, sometimes being slightly inclined at the vergence of the dejection cones, with an absolute amplitude of the relief around 300 m. Subsequently and according to the morphometric analysis, some gentle average slope values appear that differentiate two sets or smaller units in this geomorphological unit: cretaceous slopes, glacis and generalized dejection cones, with greater slope values and the flat bottom of the valley that configures the alluvial plain.

— *Glacis and dejection cones*

Footslopes or glacis and dejection cones form the last step or geomorphological element, before descending to the alluvial plain at the bottom of this valley. The glacis appear from fault fronts directly from the slopes, being able to reach significant slopes always directed towards the current river courses and, although it is normal that they have slopes lower than 10°-12°, most of them register gentle slopes lower than 7°. There are three different typologies in the study area: erosion glacis, associated with the initial downcutting of the hydrographic network, which affects both sedimentary fill and crystalline materials, even degrading previous morphologies; glacis with deposits, associated with processes of definition of the hydrographic network and the genesis of slopes or pediments, and covered by a thin debris layer; and mixed glacis, mixed forms between the alluvium of the main channel and the superposition of materials from the tributaries, associated with terracing processes and torrential phenomena.

Other geomorphological elements are the dejection cones or alluvial fans. These occur throughout most of this area on both banks of the Lozoya River, intermingling with the previously mentioned glacis. They are composed of thick materials and they were formed due to the abrupt change in slope gradient at the point where the mountain streams flow into the valley, which reduces the carrying capacity of the flow and as a result, much of the sediment load is deposited.

— *Flat bottom (Flood plain)*

This corresponds to the most depressed and flat area. It would be defined by what is the channel and the current flood plain. In the geomorphological landscape units map (Fig. 10) it is only defined by the presence of a narrow strip located from the source of the Lozoya River, at the outlet of the main streams and torrents, to the Pinilla reservoir.

- Intramountain depression in contact with the piedmont slope. Upper Eresma Valley

This unit corresponds to the other intramountain valley. Smaller than the upper Lozoya valley, it is the upper part of the transverse foothill trench of Valsaín in the N-S direction, which is limited to the south by the Siete Picos massif and to the east by the Peñalara massif, as only its right bank is within the limits of the study area. Lacking a powerful sedimentary cover, only recent formations appear which connect directly with the Segovia piedmont slope.

3.2.6. Pediment type surface on ramp

This corresponds to a small section of the Duero basin piedmont slope on a pediment type surface in the upper Eresma Valley.

4. Discussion

Landscape analysis always presents certain difficulties to take into account before starting any project for its study. This is mainly due to the complexity of the landscape concept itself (Martínez de Pisón, 2009; Mejías Moreno *et al*., 2016). To a certain extent, this is also due to the nature of the concept and the different meanings that have been given to it.

The study area is a mountainous area where there is a predominance of natural environmental elements in the configuration of the landscape. Among these elements, geomorphology and vegetation cover are the basis for their configuration. In order to study the topographic and geomorphological basis of the landscape, the proposed methodological model includes direct and indirect methods for the study of the landscape (Loures *et al*., 2015; DiPietro, 2018).

The units are shown as those mappable spaces that present a certain homogeneity of their geomorphological elements but, in spite of the major advances in geographic information technologies, DEM or remote sensing and unlike other studies where morphometric models can be designed, such as maps of natural hazards, landslides, etc. (Pérez Gómez, R. and Martínez Marín, R. 2004; Rubio *et al*., 2009; Moreno, 2010; Quesada and Barrantes, 2017), there are limitations and disadvantages in the use of automatic/semi-automatic geographical feature classification to solve geomorphological mapping issues (Tricart, 1971; Peña Monné, 1997). This is mainly due to the need to use both quantitative (morphometric variables) and qualitative (landform, lithology, etc) variables. This aspect offers difficulties when implementing a model, so interpretation is often needed to be able to formulate proposals and solve cartographic problems. In this respect, direct methods were equally fundamental in the delimitation of units. Despite the great help of data acquisition, be it elevation or morphology, there are certain peculiarities and characteristics that can only be noticed in situ. The landscape has a shape, but also a face, a texture and a structure (Lobeck, 1939; Martínez de Pisón, 2010, 2016). At a detailed scale, field work can be key not only to validate but also to differentiate some units from others in relation to the texture of the landscape. Indirect morphometric methods allow us to explore the suitability of scales of greater or lesser detail for each of the purposes, but often it is the field work that is decisive in the process of classifying the characteristics of the detailed geomorphological landscape (Smith *et al*., 2011).

The morphometric analysis of the relief allows analysis at different scales depending on the working resolution. This makes it possible, for example, to redefine fractures with a dominant NE-SW direction, which often intersect with others in the N-S direction and others, almost perpendicular to both, in a transverse E-W direction. This aspect, together with the lithology of mainly granites and gneisses (Fig. 2), subject the area to lithotectonic and structural controls that are very evident in maps such as that of the energy of the relief (Fig. 8). This feature constitutes one of the main physiographic characteristics of the massifs and valleys in this sector of the Guadarrama (Bullón, 1988; Sanz, 1988). In this case, it was found that high energy values of the relief can sometimes be related to areas of greater tectonic activity (Lugo Hubp, 1988). In Montes Carpetanos, moreover, the most energetic environments are those that were glaciated or with a post-glacial dynamic where periglacial activity was concentrated (García-Esteban, 1998; Carrasco *et al*., 2016; Palacios *et al*., 2017). In addition, the fitting processes in the fluvial network were more efficient by exploiting the network of fractures in this fundamentally gneissic lithology. These also coincide with the areas of highest altitude of this massif.

In the same way, at a more detailed scale, it was possible to obtain information about the intensity of fluvial processes and their distribution, through the values and the elaboration of maps of the dissection density (Fig. 6) and the dissection depth (Fig. 7). It was also possible to deduce information on permeability, runoff, rock type, and even structures or rainfall, and other features hidden in the cartographic information of the conventional topography map.

The highest values of dissection density are concentrated in La Pedriza de Manzanares (Pedraza *et al.*, 1989, 2014; Pedraza, 1994; García-Rodríguez and Centeno, 2014; García-Rodríguez *et al.*, 2015). Other high values are mainly distributed where the post-glacial evolution of the slope affected the river system densification (Palacios and De Marcos, 2004, Palacios *et al*., 2012).

In this sense, due to glacial and periglacial morphologies (Palacios *et al*., 2012, 2017; Bullón, 2016), which affect some sectors of the highest slopes, the processes of mixed nivo-pluvial streams generate a considerable increase of small incisions and trenches at the base of the cirques and nivation niches. As shown in the map (Fig. 6), this is reflected by the high values of dissection density in some sectors such as the high slopes of the Peñalara massif or in the northern third of the study area, in Flecha and the Pelados area.

On the other hand, the northern area, Nevero-Romalo Pelado massif, is an area where the Carpetanos' "pop up" is wider than elsewhere in the study area, with a morphology of broad, flattened summits that give way to steeply descending slopes where the river incises deeply (Capote *et al*., 1989; De Vicente, 2009). On the northern slope some periglacial forms are installed on these high slopes while on the southern slope it is the small glacial cirques that often form the fluvial headwaters of the streams that cut and dismantle moraine deposits (Carrasco *et al*., 2016; García-Esteban, 2019).

It became clear that scale is a determining factor, although it is true that the grid area for which the data is acquired will depend both on the phenomenon or variable that needs to be quantified and on the extension of the studied area. For an area of about 1,000 km² like the one dealt with here, this scale proved to be appropriate and advisable as it allowed work on scales of 1:25,000 and 1:50,000 and obtained good results.

For these reasons, the application of these combined methodologies also made it possible, within this delimitation of units, to obtain a classification of the different types of peaks and summits that can be differentiated in the study area:

— The wide flattened summits unit coincides with the summits surface of Schwenzner (1937). It is dotted with some monadnock type of relief and in high mountain areas it is affected by nivoperiglacial processes, as evidenced by the presence of elements such as geometric or structured soils, slabs, altered substratum by gelifraction, mixed nivopluvial stream, and nivoperiglacial modelling like solifluction processes (Sanz, 1988). This unit also corresponds with the snow accumulation areas, which apart from being one of the erosive agents in the area (Palacios and Sánchez-Colomer, 1996; Palacios and De Marcos, 2004; Palacios and Andrés, 2004a, 2010) adopts a primary role in the configuration of the natural landscapes and their phenology.

— The cirques and nivation niches with nivoperiglacial modelling unit, where only the cirque of the Laguna Grande de Peñalara presents successive moraine series in several phases, whose chronology and evolution have been, and still are today, discussed by several authors since the beginning of the 19th century (Macpherson, 1893; Obermaier and Carandell, 1917; Fränzle, 1959; Ontañón and Asensio, 1974; De Prado, 1975; Fuster and Cacho, 1979; Centeno *et al*., 1983; Medina, 1986; Bullón, 1988; Sanz, 1988; Palacios *et al*., 2012, 2017).

— And small scattered rocky outcrops along the summits, crest and crags, and tors (Bullón, 1988), within the narrow rounded and flattened summits with rocky outcrops type of summit.

5. Conclusions

The study area is a mountainous area in the interior of the Iberian Peninsula of generalized flattened or rounded peaks, sometimes interrupted by crests and rocky outcrops that enrich the physiographic variety of this mountainous landscape. The relief is organized in this sector forming two main mountain ranges of "two-thousanders", with the peak of Peñalara as the maximum altitude (2,428 m a.s.l.). Both block-mountains converge, forming an angle in which the head of the Lozoya valley is fitted. The physiographic characteristics of the studied area are defined by these mountain systems and valleys that are the result of the elevation of large blocks, or "pop ups" of the Variscan massif, articulated by means of large faults and fractures that separate them from each other.

This work achieved two fundamental objectives. Firstly, to explore the possibilities of this type of morphometric methodology that are well established and used for the study of relief and geomorphological processes. Secondly, in a national context, the dissemination and contribution of unpublished maps focusing on certain features of the relief and the geomorphology processes of the Guadarrama mountains and their configuration as detailed geomorphological units in landscape.

Experimentation with working at different scales in relation to obtaining, creating and processing data on these morphological variables of the relief revealed the applicability of this type of methodology for future research.

The geomorphological heritage is an inseparable part of natural heritage and is made up of geomorphological elements that are particularly unique, mainly due to their scientific and/or educational interest. The methodology used in this work is useful for mapping the inventory of geomorphological elements. In this sense, the creation of this type of database is especially useful for the management and monitoring of the natural patrimony of protected natural areas; in this case, the national park.

This last observation is supported by the fact that sometimes large changes in the natural system can be detected through micro-changes and the interrelations between its agents and processes. We firmly believe it would be interesting to do an in depth investigation of how a detailed holistic study of the landscape and the interaction between each of its components could result in the early detection of changes which otherwise might go unnoticed at a regional spatial scale or in specific thematic studies.

Conversely, but also related to the scale of work, the results obtained for the summit and high hillslopes areas and their role and importance in the configuration of the physical-geographic landscapes of the study area should be highlighted. This research showed that these profiles of smooth and hilly summits culminate in a narrower and more rugged way more frequently than was previously thought. Through this investigation it was possible to define the area of peaks and high hillsides as a unit of the geomorphological landscape at a detailed scale and also to establish a differentiation and typology of summits mapped as detailed units. Up to five summits typologies were determined and located, all of them revealing a marked lithological and structural control over the landform. This is supplemented by the value added by the uniqueness represented by the glacial modelling of the high slopes in the Sierra as a whole; its location, the distribution of its characteristic elements or its morphometric properties, which in many cases have even allowed us to differentiate landscape units. In this sense, a series of field works were fundamental.

Finally, it can be concluded that the application of these indirect methods such as quantitative morphometric analysis, and their superposition with other qualitative variables, such as geological composition, together with field work, were essential in the study, analysis and evaluation of the geomorphological bases of the natural landscape. In a regional context, the methodologies applied in this study have facilitated and allowed the detailed analysis of the relief and the elements of the geomorphological landscape; both of the most well-known sectors of the National Park, on which there are numerous studies carried out (certain sectors of Montes Carpetanos and Cuerda Larga mountains), as well as others scarcely investigated, which constitutes another of its contributions.

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