

TERRAIN SURFACE COMPLEXITY DERIVED BY REMOTE SENSING: A CASE STUDY OF BULGARIA

Rosen Iliev, Boyko Rangelov, Lachezar Filchev

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: ilievrosen88@abv.bg, brangelov@gmail.com, lachezarhf@space.bas.bg

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Abstract: Digital Terrain Models (DTMs) offer a robust framework for quantitative landform analysis by integrating high-resolution elevation data and morphometric parameters. This study applies the unsupervised nested-means algorithm to classify the topography of Bulgaria (41°14' and 44°13' N; 22°21' and 28°36' E) into sixteen distinct terrain surface types, based on slope gradient, surface convexity, and texture. Each morphometric class is further evaluated using the box-counting method for estimating fractal dimension (D), as a measure of surface complexity. The results reveal a strong correlation between slope steepness, texture fineness, and convexity with the fractal dimension, indicating that steeper and fine-textured terrains with high convexity exhibit higher degrees of geomorphological complexity. Conversely, gentle slopes with fine texture display the lowest D values, signifying smoother terrain morphology. The classification highlights the heterogeneous nature of Bulgaria's terrain, shaped by tectonic, erosional, and depositional processes.

СЛОЖНОСТ НА РЕЛЕФНАТА ПОВЪРХНОСТ ИЗВЛЕЧЕНА ЧРЕЗ ДИСТАНЦИОННИ ИЗСЛЕДВАНИЯ: КАЗУС ОТ БЪЛГАРИЯ

Росен Илиев, Бойко Рангелов, Лъчезар Филчев

Институт за космически изследвания и технологии – Българска академия на науките
e-mail: ilievrosen88@abv.bg, brangelov@gmail.com, lachezarhf@space.bas.bg

Резюме: Цифровите модели на релефа (Digital Terrain Models, DTMs) предоставят надеждна основа за количествен морфометричен анализ чрез интегриране на данни с висока разделителна способност за надморската височина и релефни параметри. В настоящото изследване е приложен алгоритъмът на ненаблюдавани вложени средни стойности (unsupervised nested-means algorithm) за класифициране на релефа на България (41°14' – 44°13' N; 22°21' – 28°36' E) в шестнадесет морфометрично обособени типа повърхности, дефинирани на база наклон, изпъкналост и текстура. Всяка от класовете е допълнително оценена чрез метода на броене в кутии (box-counting) за изчисляване на фракталната размерност (D) като индикатор за сложност на релефната повърхност. Резултатите разкриват отчетлива корелация между стръмност, текстурна финост и изпъкналост с фракталната размерност, като показват, че стръмните, финно-текстурирани и силно изпъкнали терени се характеризират с по-висока степен на геоморфоложка сложност. Обратно, полегатите склонове с по-гладка текстура демонстрират най-ниски стойности на D , което свидетелства за по-изгладена морфология. Класификацията подчертава хетерогенния характер на българския релеф, резултат от взаимодействието между тектонски, ерозионни и седиментационни процеси.

Introduction

Digital Terrain Modelling (DTM) plays a foundational role in contemporary geomorphological analysis, offering precise, scalable, and replicable representations of Earth's surface morphology. As an extension of digital cartography and remote sensing, DTM has transformed the way geomorphologists conceptualize and quantify landform features, moving from qualitative, field-based interpretation to high-resolution numerical models that support spatially explicit and multi-scale analysis (Evans, 2012; Hengl & Reuter, 2009). A DTM is a digital representation of the Earth's bare surface, typically constructed from elevation data obtained via remote sensing techniques such as

LiDAR, photogrammetry, radar interferometry, or satellite altimetry (Wilson & Gallant, 2000). It provides the foundation for a wide array of terrain derivatives, including slope, aspect, curvature, flow accumulation, and topographic wetness index, which serve as inputs for geomorphological, hydrological, and ecological models.

In geomorphology, DTMs enable the quantitative analysis of landforms, allowing for systematic classification, process modelling, and landscape evolution studies. For instance, detailed curvature analysis of a DTM can reveal erosional vs. depositional regimes, while slope and aspect support assessments of hillslope stability, solar radiation balance, and soil redistribution (Minár & Evans, 2008). Moreover, multi-resolution analysis using DTMs allows researchers to examine both fine-scale microtopography and large-scale tectonic or fluvial structures within a unified framework (Florinsky, 2012).

DTMs also serve as the input layer for terrain classification algorithms, including both supervised and unsupervised approaches. For example, geomorphometric classification schemes like the Iwahashi and Pike method (2007) and the Geomorphons approach (Jasiewicz & Stepinski, 2013) rely heavily on DTM-derived morphometric variables to segment terrain into meaningful units based on form, process, or genesis.

Despite their strengths, DTMs are not without limitations. The accuracy of a DTM is highly dependent on the resolution, sensor quality, and terrain complexity. Therefore, careful pre-processing, error assessment, and appropriate scale selection remain essential components of DTM-based geomorphological research (Wechsler, 2007).

In conclusion, Digital Terrain Modelling has revolutionized the field of geomorphology by enabling detailed, objective, and reproducible terrain analysis across spatial and temporal scales. It supports both fundamental research on landform dynamics and applied studies in natural hazard assessment, land management, and environmental monitoring. By incorporating fractal analysis as a modern mathematical tool, this study introduces an innovative approach that provides a novel perspective on the subject.

Study area

The object of present study is topography of Republic of Bulgaria (Fig. 1). Bulgaria is located in Southeastern Europe, occupying the eastern part of the Balkan Peninsula. It lies approximately between 41°14' and 44°13' N latitude, and 22°21' and 28°36' E longitude, covering a total area of about 111,000 km². The country is bordered by Romania to the north (along the Danube River), Serbia and North Macedonia to the west, Greece and Turkey to the south, and the Black Sea to the east.

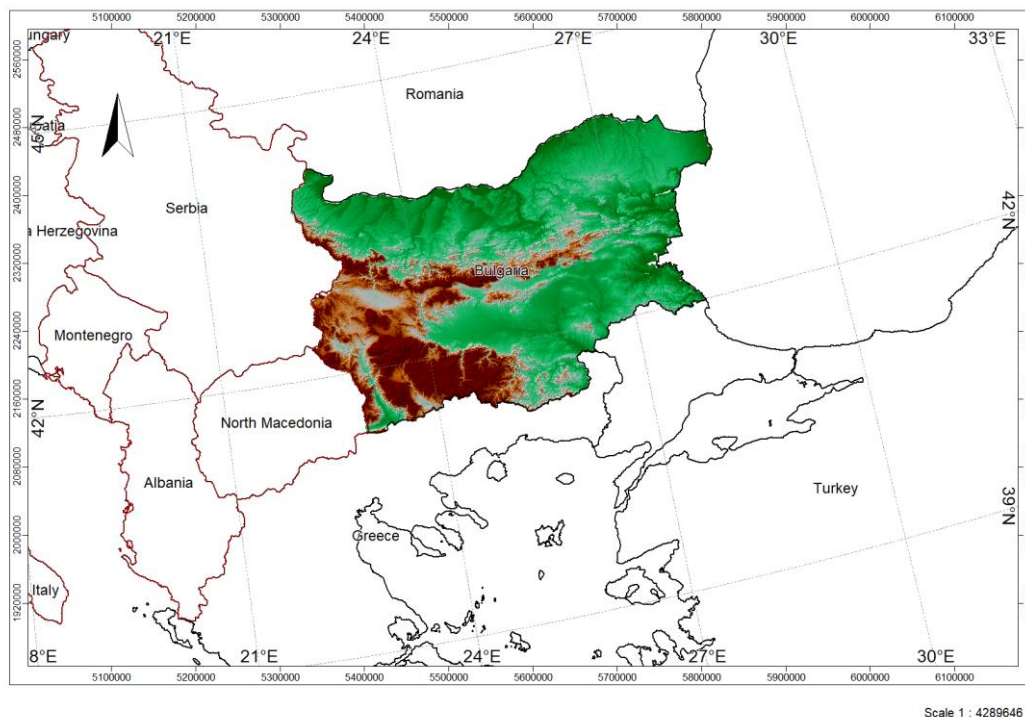


Fig. 1. Location map of the study area

Topographically, Bulgaria exhibits pronounced relief diversity, dominated by alternating mountain ranges, basins, and plains. The Balkan Mountains (Stara Planina) run horizontally through the center of the country, forming a natural climatic and geographic divide. To the south, the Rila, Pirin, and Rhodope Mountains form part of the Alpine orogenic system, with Musala Peak (2,925 m) in Rila being the highest point in both Bulgaria and the entire Balkan Peninsula.

Northern Bulgaria is primarily composed of the Danubian Plain, characterized by gently rolling terrain and loess plateaus. In contrast, the Upper Thracian Plain in the south-central region is a lowland basin known for fertile soils and agricultural use. The Struma and Maritsa river valleys provide key lowland corridors and are aligned with active tectonic zones and grabens, contributing to both seismic activity and geomorphological complexity. This combination of mountains, plains, and river systems results in a highly fragmented relief, offering a rich context for geomorphological classification, terrain modelling, and land use analysis.

Methods and Data

Unsupervised nested-means algorithm for terrain surface classification

Within the present research the terrain surface analysis and classification have been performed using the so called „nested-means terrain classification“. The unsupervised nested-means algorithm developed by Iwahashi and Pike (2007) represents a data-driven, objective methodology for classifying landform types based solely on digital elevation model (DEM) derivatives. Unlike traditional geomorphological classifications which often rely on subjective interpretation and qualitative parameters, this algorithm utilizes a hierarchical clustering approach to categorize the land surface according to its morphometric properties.

At the core of the method is the extraction of three primary terrain variables derived from DEM data: slope gradient, surface convexity, and surface texture. Slope gradient and convexity are calculated using standard digital terrain analysis techniques, while surface texture is defined by the local standard deviation of elevation within a fixed-size moving window, typically 3×3 or 7×7 pixels (Iwahashi & Pike, 2007).

The nested-means algorithm applies a non-hierarchical k-means clustering approach iteratively. First, the terrain is partitioned into coarse classes using k-means clustering in the multivariate space defined by the three morphometric variables. Subsequently, each initial cluster is further subdivided by applying k-means clustering again within its data subset. This nesting procedure is repeated until a predefined number of classes is achieved or until further subdivision yields no significant improvement in classification homogeneity (Iwahashi & Pike, 2007).

The final output consists of automatically derived terrain classes that can be broadly interpreted in terms of geomorphological features such as mountains, hills, plains, and depressions. These classes correspond to common topographic patterns, but their identification is based entirely on statistical properties rather than semantic labels. Notably, the authors demonstrate that a classification into 16 terrain types provides an effective compromise between generalization and detail, useful for continental- and regional-scale applications (Iwahashi & Pike, 2007).

The Box-counting Method for Fractal Dimension Estimation

Surface complexity analysis is based on classical tool for fractal analysis – “box-counting method”. The box-counting method is one of the most widely used techniques for estimating the fractal dimension (D) of irregular spatial patterns, particularly in geographical and geomorphological analyses. It is especially suited for analysing complex natural structures such as coastlines, drainage networks, topographic surfaces, and land cover boundaries (Mandelbrot, 1983; Lam & De Cola, 1993).

The basic principle of the method involves overlaying the object or binary raster with a grid of square boxes of size ϵ , and counting the number of boxes $N(\epsilon)$ that contain part of the object. This process is repeated for progressively smaller box sizes. The fractal dimension D is then estimated using the logarithmic relationship:

$$(1) \quad \text{Fractal Dimension (D)} = \log(N(\epsilon)) / \log(1/\epsilon)$$

Where:

- $N(\epsilon)$ is the number of boxes of size ϵ that contain part of the object.
- ϵ is the side length of the box (scale).
- D is estimated as the slope of the linear regression line in a log-log plot of $N(\epsilon)$ versus $1/\epsilon$.

In practice, a log-log plot of $N(\epsilon)$ versus $1/\epsilon$ is constructed, and the slope of the linear portion of the curve is taken as an estimate of D. The closer the fit (often measured by the coefficient of determination R^2), the more reliable the dimensions estimate are.

The box-counting dimension reflects the scale-invariance and space-filling capacity of the analysed object. For instance, a value of D close to 2 indicates a highly fragmented, space-filling structure on a 2D surface, while values closer to 1 imply linear or less complex patterns.

This method has been effectively applied to digital elevation models (DEMs), where elevation contours or slope threshold masks are binarized, enabling fractal analysis of terrain roughness and landform complexity (Sánchez et al., 2006; Florinsky, 2012).

DEM data

Terrain surface analysis of the study area was performed using digital elevation data acquired by EU-DEM v1.1. The EU-DEM v1.1, developed under the Copernicus Land Monitoring Service, is a pan-European digital surface model (DSM) with a 25-meter spatial resolution. It is derived through the fusion of two global elevation datasets: the SRTM (Shuttle Radar Topography Mission) and ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer). The fusion process involved weighted averaging, void-filling, and smoothing to ensure consistency across Europe's diverse landscapes (EEA, 2019).

EU-DEM data are referenced to the ETRS89 / LAEA Europe projection (EPSG:3035) and are distributed in $1^\circ \times 1^\circ$ tiles. As a DSM, it includes elevation values that reflect not only ground surface but also vegetation and built structures. While this may limit its use for bare-earth analyses, it remains highly valuable for regional-scale terrain modelling, hydrological assessments, and landform classification.

Results and Discussion

The results obtained in this study are summarized in Table 1 and Figure 2. The main conclusions and interpretations are discussed further.

Table 1. Terrain surface classification within the study area. The numbering of the terrain classes is in accordance with the original nomenclature of Iwahashi and Pike (2007)

No	Name of class	Area (km ²)	Share of total area (%)	D
1	very steep slope, fine texture, high convexity	9869.7675	14.91	1.53
2	very steep slope, coarse texture, high convexity	3331.7194	5.03	1.39
3	very steep slope, fine texture, low convexity	7502.9450	11.33	1.51
4	very steep slope, coarse texture, low convexity	3710.1213	5.60	1.41
5	steep slope, fine texture, high convexity	3974.5006	6.00	1.44
6	steep slope, coarse texture, high convexity	5126.9825	7.74	1.47
7	steep slope, fine texture, low convexity	3677.6869	5.55	1.42
8	steep slope, coarse texture, low convexity	5121.4094	7.73	1.47
9	moderate slope, fine texture, high convexity	1311.5325	1.98	1.16
10	moderate slope, coarse texture, high convexity	4603.0156	6.95	1.46
11	moderate slope, fine texture, low convexity	1128.1831	1.70	1.12
12	moderate slope, coarse texture, low convexity	4129.5394	6.24	1.44
13	gentle slope, fine texture, high convexity	474.4788	0.72	0.92
14	gentle slope, coarse texture, high convexity	5871.4144	8.87	1.46
15	gentle slope, fine texture, low convexity	782.1044	1.18	0.99
16	gentle slope, coarse texture, low convexity	5597.5606	8.45	1.43
–	Total	111000.00	100.00	–

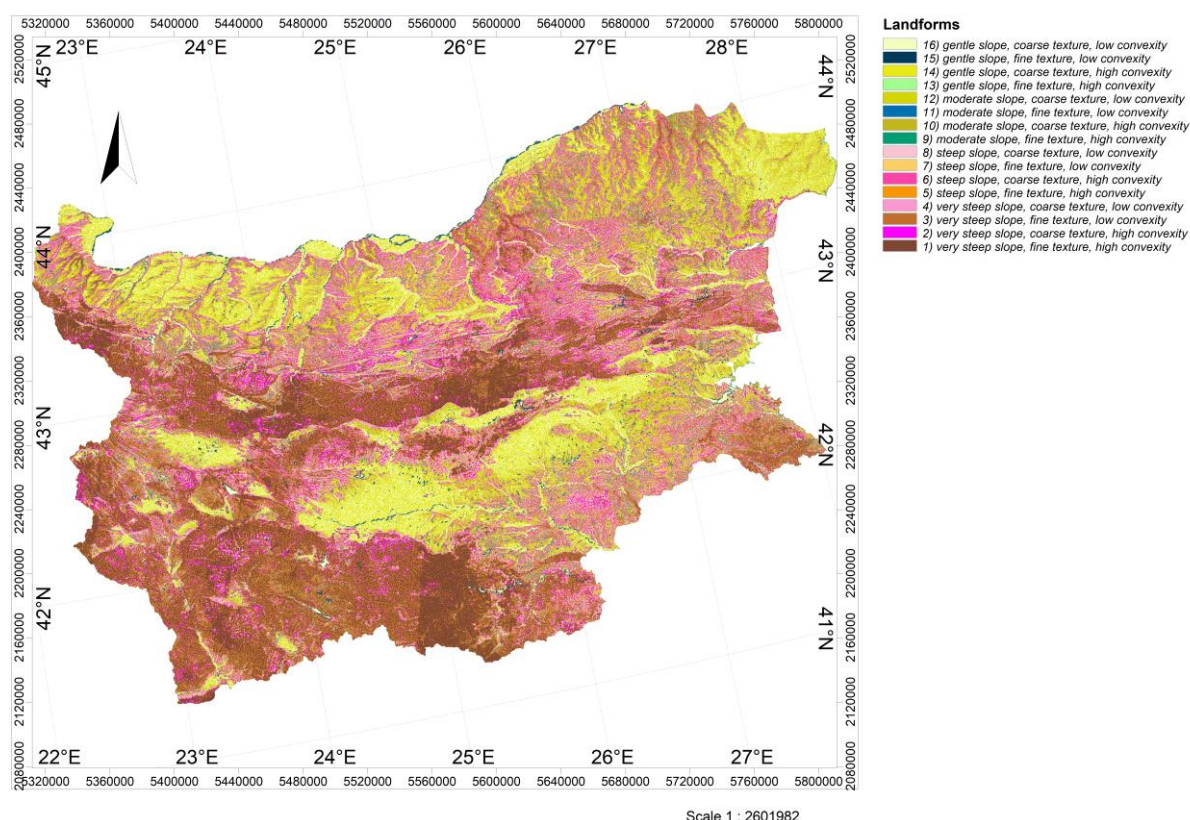


Fig. 2. Spatial distribution of terrain surface types within the study area

This study presents a morphometric classification of terrain types based on three key variables: slope gradient, surface texture, and surface convexity. A total of 16 distinct morphometric classes were identified and quantified. Each class was analysed in terms of its spatial extent, percentage of total coverage, and associated fractal dimension (D), a parameter reflecting surface complexity and geomorphological heterogeneity. The largest class by area is "very steep slope, fine texture, high convexity," covering 9,869.77 km², equivalent to 14.91% of the total area, with a high fractal dimension of 1.53. This suggests significant surface complexity, likely due to erosional and tectonic processes prevalent in such terrains. Similarly, classes with steep slopes and fine textures (e.g., Class 3 and Class 5) also demonstrate elevated D values (> 1.4), underscoring the influence of fine soil materials on terrain intricacy, particularly when combined with high slope gradients. Conversely, terrain types characterized by gentler slopes and fine textures exhibit substantially lower fractal dimensions. Notably, Class 13 ("gentle slope, fine texture, high convexity") has the lowest D value of 0.92, indicating a relatively smooth and homogeneous surface morphology. This is consistent with the expected reduced complexity in low-relief environments dominated by depositional processes or extensive weathering. Texture emerges as a key modifier of fractal dimension within similar slope and convexity categories. Coarse-textured classes generally show slightly lower D values than their fine-textured counterparts when slope and convexity are held constant. For instance, within the steep slope and high convexity group, fine-textured Class 5 has D = 1.44, while coarse-textured Class 6 shows a marginally higher D = 1.47, likely reflecting the roughness induced by larger grain sizes. Convexity also plays a substantial role, with high convexity conditions correlating with higher D values across most slope categories. This may reflect the increased micro-relief variation and drainage dissection associated with convex landforms. However, exceptions exist, indicating possible interactions between lithology, vegetation, and erosional regimes. In total, over 60% of the terrain falls within steep or very steep slope categories, which predominantly exhibit higher fractal dimensions (D>1.4), emphasizing the geomorphological dynamic nature of the landscape. Moderate and gentle slopes, although contributing a smaller proportion to the total area, provide important contrast through their generally lower D values and simpler surface geometry.

Geographically (Fig. 2), Terrain classes 1 through 4, characterized by very steep slopes with varying texture and convexity, are dominantly distributed across the high mountain systems—most notably in the Rila, Pirin, and western Rhodope Mountains. These classes collectively cover over 36% of the national territory, aligning with Bulgaria's alpine zones where rugged topography and high

elevation gradients prevail. Classes 5 to 8, representing steep slopes, are widespread in transitional mountainous regions such as Sredna Gora, the Eastern Rhodopes, and the Fore-Balkan. These areas demonstrate intermediate relief energy and serve as morphological corridors between lowland basins and high mountains. With a combined area share of roughly 26%, they are pivotal in Bulgaria's orographic structure. Moderate slope classes (9 to 12) show a more dispersed distribution, frequently occurring in dissected hilly terrains and fluvial margins across the Danubian Plateau and western Upper Thracian Lowland. These zones exhibit a balance between structural control and erosional shaping, hosting both agricultural use and semi-natural landscapes. Gentle slope classes (13 to 16), indicative of flat to gently rolling relief, dominate the country's major lowlands—namely the Danubian Plain, the Upper Thracian Lowland, and portions of the Burgas and Dobrudzha coastal plains. These areas, comprising approximately 19% of the territory, are essential for intensive land use and infrastructure due to their minimal relief constraints.

In conclusion, the spatial distribution of relief classes in Bulgaria reflects a complex interplay of tectonic uplift, lithological resistance, and surface processes. The 16 Iwahashi–Pike classes not only map topographic diversity with quantitative precision but also correlate strongly with the country's established geomorphological regions. This framework enhances regional planning, landscape ecology, and natural hazard assessment across Bulgaria's varied terrain.

Conclusion

In the present study, using unsupervised nested-means algorithm, a classification of local terrain was made. Sixteen terrain classes were identified and extracted. The results obtained confirm that the terrain surface within the study area is variable. The analysis reveals a clear correlation between terrain slope, soil texture, and surface convexity with fractal dimension, serving as a proxy for geomorphological complexity. Steep and fine-textured terrains, especially under high convexity, tend to be the most complex, whereas gentle, fine-textured surfaces are the smoothest. These findings have significant implications for erosion modelling, land use planning, and landscape evolution studies. Such an approach provides broader opportunities for geomorphological research and offers new insights into contemporary geodynamics by integrating internal and external processes of terrain formation.

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